Book of Abstracts

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Gas Discharge Plasmas and Their Applications

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Institute of High Current Electronics SB RAS
National Research Tomsk Polytechnic University
Tomsk Scientific Center
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PULSE VOLUME DISCHARGES IN HIGH PRESSURE GASES

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Interest in self-sustained volume discharge (SSVD) was largely provoked by the development of electric-discharge lasers that operate at sub-atmospheric and super atmospheric pressure. A necessary condition for obtaining SSVD is the presence of preionization and the homogeneity of the electric field in the discharge gap (DG). This ensures the homogenization of ionization processes in the active volume. However, this condition is not sufficient due to the instability of the discharge. The report will address the causes of instability and the various methods of their suppression both at the stage of formation, and at the stage of SSVD burning.

Powerful electrophysical devices require stable operation with a pulse repetition frequency of 1 kHz or with the discharge volume of nearly 100 liters. Self-sustained discharge in such cases should be quasi-continuous or it should have a burning period of 10 μs. For these purposes the fundamental problem is the complete suppression of plasma irregularities in volume self-sustained discharge. Unlike conventional SSVD it can be called a razor-homogeneous self-sustained discharge. In this paper we propose a new approach to the suppression of plasma irregularities and instabilities in SSVD. The physical model used to calculate the dependence of the boundary concentration of initial electrons n_0 on the field strength E in the DG for producing extremely homogeneous SSVD is suggested (see fig. 1).

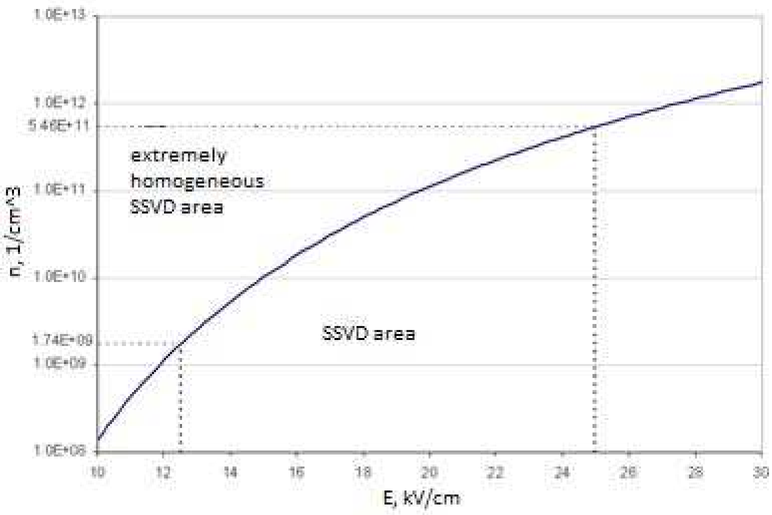

Fig. 1. Calculated dependence of boundary concentration of initial electrons n_0 on the field strength E in the DG for producing extremely homogeneous SSVD in the mix of CO2:N2:He = 1:2:3 at p = 1 atm.

SSVD with optimum energy input, when all the stored electrical energy is dissipated in the plasma during first half-period of discharge current pulse, is of utmost practical interest. Conditions for such SSVD with optimum energy input are formulated. They are: 1) $n_0^{min} < n_0 < n_0^{max}$; 2) $U_0 = 2U_{qs}$; 3) $w < w_{th}$, where for the mix of atmospheric pressure (CO2:N2:He = 1:2:3) $n_0^{min} = 5.5 \times 10^{11}$ cm^{-3}, $n_0^{max} = 10^{13}$ cm^{-3}, U_0 is a output voltage of the pump generator, U_{qs} is a quasi-stationary discharge voltage, w_{th} = 0.4-0.5 J/(cm^{3}atm) is a threshold specific energy input.

There were experimentally obtained SSVDs in mixtures of CO2:N2:He for discharge volume of 60 liters with the space between the electrodes of 18.5 cm at pressures up to 2 atm. In a mixture of CO2:N2:He=1:2:3 at atmospheric pressure the discharge duration was about 10 μs with full energy input of 10 kJ. These parameters values were limited by experimental setup and are not the utmost one.

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PSEUDOSPARK SWITCHES IN TRIPLE-PULSE MODULATOR FOR 20-MeV, 2-kA LINEAR INDUCTION ACCELERATOR POWER SUPPLY

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A 2-MeV, 2-kA Linear Induction Accelerator LIA-2 was built and is in routine operation [1,2]. Accelerator's high voltage system consists of 48 pulsed modulators, each of them supplies a couple of accelerating gaps with two pulses of 200 ns duration at peak voltage of 21 kV and variable delay between pulses from 2 to 100 µs. The main principles of the pulsed system will be used in a 20-MeV, 2-kA triple-pulse Linear Induction Accelerator which development is in progress now. A special role in a modulator operation is performed by TPI-type pseudospark switches. These devices are known for their fast high current commutation, small dimensions, low heat release along with unordinary reverse recovery [3]. Test results of TPI-type pseudosparks 10 kA current commutation at the anode voltages up to 45 kV are presented. Improved diode characteristics of the pseudospark switches taken at reverse voltage up to 25 kV applied in 0.1-20 µs after 5-10 kA forward current commutation are analyzed.

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BLACK SURFACE COATINGS DEPOSITED BY PLASMA CHEMICAL OXIDATION (PCO)

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This paper presents the results of our investigations concerning the production of black and super black layers by application of plasma chemical oxidation (PCO) and plasma coatings (APCVD) under atmospheric conditions. Plasma chemical oxidation (PCO), also known as Micro- arc- oxidation (MAO), or plasma electrolytic oxidation (PEO) is a electro - chemical and a plasma – chemical surface treatment for light metal alloys. The properties of the layers produced can be varied within wide margins by chosing corresponding electrolytic solutions. So it is possible to produce also black layers with very good resistance to irradiation, temperature and corrosion. In combination with atmospheric plasma or flame - pyrolitic coating (so-called PYROSIL) it is possible further to reduce the coefficient of absorption in the visible and NIR range and thus you can get super black layers.

The main condition to obtain these super black layers is based on the layering of surface roughness effects in three different ranges. First, the surface of the substrate is strongly roughened by mechanical or chemical processes und afterthat coated with a black ceramic coating according to the PCO-method . This gives an overlay of two different orders of magnitude of the obtained roughness values. Second, another range of roughness value in the nanometer range is superposed with the deposition of an only some nanometer thick SiOx-coating by using the process of plasma or flame coating under atmospheric pressure.

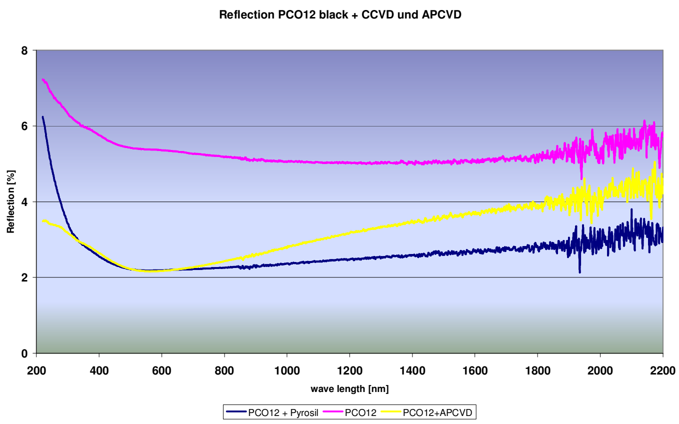

Fig. 1. The figure shows the reflection of black surfaces of PCO surface with additional APCVD and Pyrosil coatings

For optical devices these layers are already applied to components made of aluminium and magnesium alloys. Further applications are in the coating of opto-mechanical components for laser technology with a high damage threshold. Corresponding examples will be presented.

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PLASMA TECHNOLOGY OF SILICATE MELTS OBTAINING[1]

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Complex physicochemical processes occur in melting silicates prior to the mixture melting due to the diffusion in the solid phase. Some of its fine dispersion components possess a large contact area. Such phenomena as chemical composition distribution, gas bubble removal, and silicate melt homogenization are observed under the influence of highly concentrated heat flows and ohmic heating due to the melt conductivity enabled by diffusion processes.

Plasma technologies used in production of high-temperature silicate melts provide consistently high temperatures converting the original silicate materials to a molten state. A uniform chemical composition of the melt product depends on the melting temperature and time of the raw material. The higher melting temperature and longer melting time, the more intensive will be the failure of silicate compositions and their approach to the real structure of oxide melts. A failure of long-range order zones in a melt results in its more considerable disorder.

This paper mainly focuses on the investigation of plasma-chemical processes in a plasma generator during the production of high-temperature silicate melts.

The melt was obtained from basaltic rock located in the Kemerovo region, oil-shale combustion gases in Dalian Province (China), ashes from the combined heat and power plant in Seversk (Tomsk region) obtained from hardcoal combustion, and silica sand from Tuganskoe deposit (Tomsk region).

Experiments on melting processes of silica sand were carried out in the electro-plasma apparatus [1] equipped with a worm feeder that eliminates blowing of fine particles out of the melting zone.

After the experimental production of high-temperature silicate melts using the low-temperature plasma, the infrared spectroscopy was used to analyze the internal and intermolecular interactions and the different chemical bonds formed in preliminary grinded raw materials and melts produced therefrom [2-4].

The infrared spectroscopy analysis shows that the original materials are non-uniform due to their physicochemical system comprising different oxides that is supported by the mineralogical analysis, while melt products are uniform and ordered. In other words, the low-temperature plasma suggested for the production of silicate melt provides its complete homogenization.

Thus, the results obtained in this experiment allow drawing a conclusion about the structural uniformness of raw materials and melts produced therefrom [5-7].

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INVERSION OF THE POLARITY EFFECT IN A NANOSECOND PULSE DISCHARGE INITIATED BY RUNAWAY ELECTRONS[1]

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At the breakdown of gas gaps in a quasistatic electric field the effect polarity is observed [1]. In the same conditions, the breakdown voltage at negative polarity is more than at positive one. However, in a nanosecond pulse discharge the inversion of the polarity effect is observed. At some experimental conditions the inversion of the polarity effect was observed in [2, 3]. Data about observation of the inversion of the polarity effect in air, nitrogen, sulfur hexafluoride and sulfur hexafluoride with small (2.5%) nitrogen admixture at a pressure range of 0.013-0.3 MPa are presented in present paper. Nanosecond voltage pulses produced by the RADAN-200 pulser was applied to a gap with "point-plane" geometry. Interelectrode distance was 13 mm. The voltage was measured with a capacitive divider placed upstream of the discharge gap in a transmission line. Discharge current was measured with a shunt made of chip-resistors. The differences between the breakdown voltage at positive polarity relatively one at negative polarity are presented in fig. 1. It is seen, that increasing pressure of gases leads to decrease the differences of the breakdown voltage.

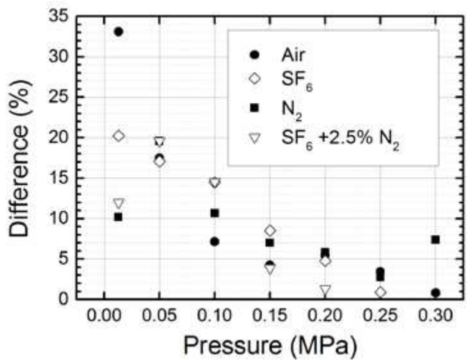

Fig. 1. The differences in the breakdown voltage at positive polarity relatively one at negative polarity in air, nitrogen, sulfur hexafluoride and sulfur hexafluoride with small (2.5%) nitrogen admixture at a pressure range of 0.013-0.3 MPa

From the waveforms of discharge current, it was found that at positive polarity the conduction current is registered later than at negative one. However an ionization wave velocity at positive polarity is more than at negative one. Therefore, it was suggested that at positive polarity on arrival of the ionization wave front at the plane cathode, efficient electron emission is retarded due to low electric field strength near the plane cathode. Consequently, the delay of rise in the discharge current is due to the delayed formation of explosive emission centers (bright spots) on the plane cathode.

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RUNAWAY ELECTRONS PREIONIZED DIFFUSE DISCHARGES AND THEIR APPLICATION [1]

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The electron beams and diffuse (volume) discharges in gases have a wide application in various fields of science and technology [1]. There are different ways and devices to obtain pulsed diffuse discharges at atmospheric pressure and higher; most of them use additional sources of short-wave radiation, including X-rays, electron beams, and radioactive radiation [2]. The present paper summarizes research results on runaway electron preionized diffuse discharges (REP diffuse discharge or shortly REP DD) in both single and repetitive pulsed mode. The REP DDs are initiated high voltage pulses due to the generation of runaway electrons and x-ray in an inhomogeneous electric field [3-5].

At the REP DD, the anode is influenced by the plasma of a dense nanosecond discharge with the specific input power up to hundreds of megawatt per a cubic centimeter, by the SAEB, shock wave and optical radiation from discharge plasma of various spectral ranges, including UV and VUV. This allows forecasting the REP DD application for modification and cleaning of metal surfaces in different technological processes as well as for the dielectric surface modification and cleaning at a definite anode design [6, 7].

This paper presets the results of an experimental investigation of the modified near-surface layers of a steel, Ti, Al, copper and AlBe plates upon the action of plasma of a REP DD in air, CO_2 and nitrogen at atmospheric pressure. The paper also reports data on the effect of different parameters on REP DDs (voltage pulse amplitude and duration, voltage rise time, gas kind and pressure, pulse repetition frequency, interelectrode gap width).

In the work, two high-voltage pulsers were used. The RADAN-220 pulser generated the voltage pulses of negative and positive polarity with an amplitude of ~250 kV (in the open-circuit regime), a FWHM of ~2 ns (on a matched load), and a leading front width of ~0.5 ns. The pulse-periodic NPG-15/2000N pulser of the negative-polarity generated a high-resistance load (1-10 kOhm) voltage pulses of the amplitude up to 35 kV, voltage rise time of ~3 ns and FWHM of 6 ns. The experiments were performed using a gap with the plane anode and a cathode with a small radius of curvature. The samples were irradiated in a periodic pulse regime at a pulse repetition rate of 1 (RADAN-220 pulser) and 500 Hz (NPG-15/2000N pulser).

It is shown that this type of discharge is formed both at negative and positive polarity of electrodes of small curvature radius. Either a cathode or an anode, or both can have a small curvature radius. The formation of a REP DD does occur at increased pressures: in nitrogen at up to 5 atm; in helium, at up to 15 atm. During the formation of a REP DD, supershort avalanches electron beam (SAEB) and X-rays are detected. The role of characteristic radiation in the formation of a REP DD is discussed [8]. It is shown that the SAEBs are generated in the first breakdown phase when the gap is bridged by an ionization wave.

It is established that the surface layer of the discharge-treated the steel, AlBe, Al, Ti and copper plates is cleaned from carbon contaminations. The oxygen penetrates up to a depth of about 50 nm was obtained. It has been found that the treatment of a copper and steel surface by this type of discharge increases the hardness of the surface layer of copper and steel.

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GAS-DISCHARGE PLASMA DYNAMICS UNDER HIGH CURRENT PULSE

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The axially-symmetrical plasma compression in pulsed strong magnetic field is used for creation of high-power radiation sources (Z-pinch, plasmafilled diode, and so on). The initial plasma bridge represents a cylindrical section with radius R and length l, which is filled by highly ionized plasma with uniform mass density $\rho = m_i n$, where m_i is the ion mass, n is the plasma concentration. In the magnetic piston approach, the plasma radial displacement for linearly increasing current $I(t) = \dot{I}t$ is descibed by the well-known equation [1, 2] $\frac{d}{d\tau}\left[(1-x^2)\frac{dx}{d\tau}\right] = -\frac{\tau^2}{x}$, where $x = r(t)/R$, $\tau = t/t_0$, $t_0 = R(\pi\rho)^{1/4}(c/\dot{I})^{1/2}$, c is the velocity of light. At the point in time $\tau_{comp} \approx 3/2$, the magnetic piston reaches the system axes and the plasma velocity rises unrestrictedly. During the compression time $t_{comp} = \tau_{comp} t_0$ the current increases to $I_{comp} = \left(81\pi\rho c^2/16\right)^{1/4}\left(\dot{I}R^2\right)^{1/2}$.

With perfect plasma conductivity, the energy balance can be written as $W_{in} = W_B + W_K + W_T$, where W_{in} is the input electromagnetic energy through the surface with radius R, W_B is the magnetic field energy in the plasma free volume, W_K and W_T are the kinetic and thermal plasma energy. The input energy is $W_{in}(t) = \int_0^t P(r=R,t')dt'$, where $P(r=R,t) = clRE_{ax}(r=R,t)B(r=R,t)/2$ is the radial energy flux for the azimuthal magnetic field $B(r=R,t) = 2I(t)/cR$ and the induced axial electric field $E_{ax}(r=R,t) = \frac{\partial}{c\partial t}\int_{r(t)}^{R} B(r',t)dr'$). The energy stored in the magnetic field is $W_B(t) = l\int_{r(t)}^{R} B^2(r',t)r'dr'/4$; the plasma kinetic energy is $W_K(t) = \pi\rho l[R^2 - r^2(t)]\dot{r}^2(t)/2$.

For the dependence $x(\tau)$, the energy partition can be expressed as $W_{in} = \frac{8}{9}\frac{lI_{comp}^2}{c^2}\int_0^{\tau}\left[\tau'|\dot{x}|/x + \ln x^{-1}\right]\tau' d\tau'$, $W_B = \frac{4}{9}\frac{lI_{comp}^2}{c^2}\tau^2\ln x^{-1}$, $W_K = \frac{2}{9}\frac{lI_{comp}^2}{c^2}(1-x^2)\dot{x}^2$. The thermal energy is equal to $W_T = W_{in} - W_B - W_K$. These expressions allow to calculate the energy distribution depending on the magnetic piston position $r_{mp}/R = 1 - x(\tau)$. In the beginning of current pulse, the energy partition coincides with that, which is realized in coaxial plasma opening switch: $W_B/W_{in} = 2/3$, $W_K/W_{in} = 2/9$, $W_T/W_{in} = 1/9$ [3]. It is quite natural, because initially the piston moves with almost constant acceleration [2]. Later on, there is some decrease in W_B/W_{in}, W_T/W_{in}. On the contrary, the ratio W_K/W_{in} increases as the plasma is accelerated. As a result, the ratio W_T/W_K decreases approximately five times. Such dynamics in W_T/W_K demands of careful account at designing of multimegaampere drivers even in the ideal piston approach. Other major circumstance is suppression of the current channel conduction crosswise the strong magnetic field. Such suppression takes place in plasma opening switches [4, 5]. For axially-symmetrical plasma aggregation, this issue becomes more significant because the sharp increase in Joule heating can restrict the plasma compression degree as the current channel comes nearer to an axis.

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BREAKDOWN STRENGTH OF HYDROGEN IN SUBNANOSECOND SCALE[1]

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In this paper the data on the breakdown voltages (U_{br}) of hydrogen diodes depending on the gas pressure (p) and the degree of the discharge gap overvoltage were obtained in subnanosecond range. The experiments were carried out in a uniform electric field. The radius of stainless steel cathode and anode was one sm. Pure hydrogen was used as the test gas in all experiments. Hydrogen now is often used in high-pressure gas dischargers with high impulse frequency. The pressure of hydrogen was changed within from atmospheric to 60 atm. The voltage pulse with the amplitude of 102 ± 2 kV, full width at half maximum of about 380-400 ps, and the front of about 250 ps at the level of 0.1-0.9 from amplitude was applied to the studied gas gap. In this case the voltage rise rate at the pulse front was up to 3.3×10^{14} V/s. Experiment started under minimum width of the discharge gap d = 0.15 mm. Then d increased with step of 0.1 - 0.2 mm under fixed pressure of the gas until the discharge gap stopped to breakdown. Than the experiment was repeated under higher pressure. Received data were built in coordinates $U_{br}(d)$ and $U_{br}(pd)$.

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BREAKDOWN FORMATION TIME OF SUBNANOSECOND DISCHARGE IN HYDROGEN AT HIGH PRESSURES[1]

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In this paper the experimental results of registration of the breakdown formation time (t_{form}) in hydrogen diodes with different width of the discharge gap are given. The experiments were carried out in a uniform electric field. Pure hydrogen was used as the test gas in all experiments. The voltage pulse, with the amplitude of 102 ± 2 kV, full width at half maximum of about 380-400 ps, and the front of about 250 ps at the level of 0.1-0.9 from amplitude was applied to the studied gas gap. In this case the voltage rise rate at the pulse front was up to 3.3×10^{14} V/s. During all experiments, described in this paper, the parameters of voltage pulse have not changed. The breakdown of the hydrogen gap takes place at the front of the pulse in the conditions of the increased voltages. The dependences of the breakdown formation time for different pressures (p) of hydrogen and the degree of the discharge gap overvoltage were obtained. Received data were also built in coordinates E_{br}/p and $t_{form}p$. Here E_{br} is an electrostatic intensity in the gap in the moment of breakdown.

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THE METHOD OF THE BREAKDOWN SPEED INCREASING IN SUBNANOSECOND HIGH PRESSURE GAS DISCHARGES[1]

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In this paper the dependences of the breakdown time (t_{br}) of subnanosecond hydrogen diodes with different width (d) of the discharge gap are given in coordinates E_{br}/p and $t_{br}p$. Here E_{br} is an electrostatic intensity in the gap in the moment of breakdown and p is a hydrogen pressure. The pressure of hydrogen was changed within from atmospheric to 60 atm. Comparison of the obtained results with the dependences $E_{br}(d)$ [1] allows to determine the intervals of pressure and the width of the discharge gap where the breakdown speed is essentially increased. The recommendations for the designing of high-speed subnanosecond gas discharges are given.

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CALCULATION OF A RADIAL DISTRIBUTION PARAMETERS OF A GLOW DISCHARGE IN A FIELD OF AN ACOUSTIC WAVE

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In [1] presented a self-consistent model of the positive column of a glow discharge in the tube with the influence of the acoustic oscillations. This model allows for calculation of basic parameters of the glow discharge in the field of the acoustic wave. Accounting of acoustic oscillations in the plasma glow discharge was performed using vortex so called acoustic streaming. Vortices appears due to the boundary layer near the walls, where the velocity is reduced from the value in the acoustic wave in the middle of the tube to zero at the wall of the tube. And a strong temperature gradient along the radius of the discharge pipe.

In a standing acoustic wave field generated acoustic streaming. The radial direction of the velocity in the vortex can be represented as follows (in cylindrical coordinates)

$$u_r = -\frac{u_a^2}{10c_0}\frac{R^2}{\delta^2}\frac{r}{\lambda}\left(1-\frac{r^2}{R^2}\right)\cos 2kx\,, \tag{1}$$

where u_a is the parameter characterizing the temperature inhomogeneity of the medium, R is the tube's radius, c_0 is the speed at which the acoustic wave travels in an undistorted medium, δ is the size of the boundary layer, λ is wavelength, k is wave vector [2].

A simplified model of the spatial structure of the positive column of a glow discharge with a cylindrical symmetry with the influence of acoustic streaming can be formulated on the basis of the system of equations: balance equation for the concentration of charged particles, energy balance equation of neutral particles, the equation of state of the gas, the equation for the discharge current i. Solving the system of equations can be obtained distribution along the radius of the glow discharge parameters such as the concentration of charged particles, temperature, electric field E:

$$n(r) = n_0 \exp\left(-\frac{r\left(\sqrt{u_r^2-4\nu_i D_a}-u_r\right)}{2D_a}\right)\Phi(a,b,\xi)\,, \tag{2}$$

$$T(r) = -\int_0^r\left(\frac{R^2}{\chi}\exp\left(\frac{\rho c_p u_r R r}{\chi}\right)\int_0^r j(r)E(r)\exp\left(\frac{\rho c_p u_r r}{\chi}\right) r\,dr\right)dr + T_0\,, \tag{3}$$

$$E_r = -\frac{(D_e-u_r)}{\mu_e}\frac{d}{dr}\ln\left(n_0\exp\left(-\frac{r\left(\sqrt{u_r^2-4\nu_i D_a}-u_r\right)}{2D_a}\right)\Phi(a,b,\xi)\right), \tag{4}$$

where n_0 is electron density on the axis of symmetry, где ν_i is the ionization frequency, which is a function of the electric field E, D_a is the ambipolar diffusion coefficient, $\Phi(a,b,\xi) = \frac{\Gamma(b)}{\Gamma(a)\Gamma(a-b)}\int_0^1 e^{\xi t} t^{a-1}(1-t)^{b-a-1}\,dt$ is special function of Kummer [3], $\Gamma(r) = \int_0^\infty e^{-t} t^{r-1} dt$ is gamma function, $a = \left(\sqrt{u_r^2-4\nu_i D_a}-u_r\right)\Big/ 2\sqrt{u_r^2-4\nu_i D_a}$, $b=1$, $\xi = r\sqrt{u_r^2-4\nu_i D_a}\Big/ D_a$, T_0 – temperature on the discharge axis.

Thus, the presence of acoustic streaming leads to a redistribution of plasma parameters of the glow discharge along the radius discharge chamber.

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REGULARITIES OF MUTUAL INFLUENCE OF VACUUM AND GAS ARC DISCHARGES ON ITS MAIN CHARACTERISTICS AT JOINT GENERATION OF PLASMA IN LARGE VACUUM VOLUMES

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In considerable vacuum volumes (> 0,3 m^3) dependences of tension of burning of vacuum and gas arc discharges on current of gas and vacuum arc discharges respectively are investigated and regularities of their mutual influence at each other are revealed. It is shown that with a pressure of nitrogen of equal 0,1 Pas tension of burning of the gas arc discharge changes from 120 to 95 V at change of current of the vacuum arc discharge twice (from 70 to 150 A). Thus in other modes of such expressed dependence it isn't observed. Growth of current of the gas discharge, in turn, practically doesn't influence tension of burning of the vacuum arc discharge, however considerably reduces quantity of its spontaneous switch off that provides stability of generation of the mixed gas-metal plasma in the working volume of the vacuum camera. Besides, dependences of key parameters of the mixed gas-metal plasma on the size of currents of discharges and pressure of working gases at joint generation of low-temperature plasma were investigated.

THE FEATURES OF BREAKDOWN OF HIGH-VOLTAGE NANOSECOND DISCHARGE INITIATED WITH RUNAWAY ELECTRONS IN A NONUNIFORM ELECTRIC FIELD [1]

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Currently, increased attention is paid to the pulse and pulse-periodic discharges in the dense gases initiated with runaway electrons under conditions of an inhomogeneous electric field distribution. The main feature of such discharges is a generation in a gap of runaway electrons and X-ray, affected on a breakdown. These processes was shown in [1-4] to provide the formation of diffuse discharges at the excitation of gas medium by high-voltage nanosecond pulses of both polarities. The increased interest in the study of runaway electron preionized diffuse discharge (REP DD) is due to the presence of a number of unresolved fundamental problems in this area of gas discharge physics. Among them are the process of the breakdown and discharge formation, refinement the mechanism of generation of runaway electrons and others, as well as opportunities of wide practical application of the high-pressure non-equilibrium low-temperature plasma, in particular, for cleaning, oxidation and hardening of metal surfaces [4].

The objective of this work is to study the initial phase of a breakdown in an inhomogeneous electric field in the gases at pressure of 0.013-0.7 MPa during the REP DD formation.

Investigation of breakdown was carried out by means of registration of waveforms of discharge plasma radiation intensity from different areas along of the longitudinal axis of discharge gap, voltage pulses and current through the gap. Discharge chamber with a strong nonuniform distribution of electric field intensity was filled with pure nitrogen (N_2) or mixture of sulfur hexafluoride (SF_6) with 2.5% N_2 admixture. The voltage pulse produced with the RADAN-220 pulser was applied through a short transmission line to an electrode with small radius of curvature. The spatial and time resolution of the registration system of radiation was ~1 mm and 100 ps, respectively. The duration of breakdown stage depending on the gas pressure can vary from tens to several hundred picoseconds. Therefore, high-pressure gases were used to increase the breakdown stage duration and decrease the effective lifetime of the $C^3\Pi_u$ state. It permitted to obtain more accurate information about the time evolution of radiation intensity from different discharge gap areas.

Experiments were carried out at the nitrogen pressure of 0.013-0.7 MPa, as well as in mixture of SF_6 with 2.5% N_2 at the pressure of 0.013-0.25 MPa. Delay of start of the radiation from the different areas along of the longitudinal axis of discharge gap relative to the onset of voltage pulse was found to be the function of a nitrogen/mixture pressure, time and distance from the potential electrode, as well.

The analysis of experimental data was based on equations, describing the relation between experimental data and values that depend on the local electric field strength. It was concluded, that the high-voltage breakdown of the gap with a nonuniform electric field distribution at elevated gas pressures and subnanosecond rise time of voltage pulse is occurred owing to the ionization wave characterized by amplification of the electric field strength in the area of its front. The average velocity of ionization wave is ~$(2.1\text{-}6.5)\cdot 10^7$ m/s in mixture of SF_6 with 2.5% N_2 admixture at pressures of 0.05-0.25 MPa and ~(0.5-1.3) 10^8 m/s at nitrogen pressures of 0.1-0.3 MPa at negative polarity of electrode with small radius of curvature Practically simultaneous increasing of the radiation intensity in areas near the grounded electrode is observed. This fact indicates to the possibility of changing the breakdown mechanism in this part of the discharge gap.

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THE OPTICAL EMISSION SPECTROSCOPY OF PULSED AND PULSE-PERIODIC DISCHARGES INITIATED WITH RUNAWAY ELECTRONS [1]

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Currently a lot of attention is given to study diffuse pulse and pulse-periodic discharges in dense gases preionized with runaway electrons (REP DD) under conditions of an inhomogeneous electric field distribution [1-3]. The main feature of such discharges is a generation in a gap of runaway electrons and X-ray, affected on a breakdown. These processes was shown to provide the formation of diffuse discharges at the excitation of gas medium by high-voltage nanosecond pulses of both polarities.

Determination of the main parameters of REP DD plasma is of both scientific and practical interest. The knowledge of the density *Ne* and electron temperature *Te*, gas temperature *Tg*, and reduced electric field strength *E/N*, where *E* is the electric field strength and *N* is the particle density, is important for general plasma characterization and verification of theoretical models of the REP DD plasma. Reliable data on these parameters can be used for calculating the rates of different plasma chemical processes and estimating the amplitude-time, spectral, and energy characteristics of the REP DD plasma light emission.

In practice, diffuse discharges at atmospheric gas pressure can be used for generation of chemically active plasma. Such plasma is in demand, for example, in surface modification of solids, surface cleaning and sterilization, decomposition of organic compounds, and waste processing. The data on the plasma parameters are also important for developing other modern technologies based on homo- and heterophase plasma chemical processes.

At present, there are known about several publications concerning the determination of REP DD plasma parameters with optical emission spectroscopy techniques [4-7]. The method of the Stark broadening of spectral lines was used in [4-7] for measuring the values of *Ne* in the helium, hydrogen and nitrogen plasma. In addition, the values of *Te* and *E/N* in the plasma of pulsed discharge of atmospheric pressure nitrogen were measured [7].

This study aims at determining with optical emission spectroscopy techniques values of *Ne, Te*, *Tg* and *E/N* in a plasma of REP DD operated in atmospheric-pressure nitrogen in the pulsed and pulse-periodic modes.

The high-voltage pulsers RADAN-220 (voltage pulse amplitude up to ~250 kV and the half-amplitude duration of ~2 ns for a matched load with the front duration of ~0.5 ns) and FPG-60 (voltage pulse amplitude on a high resistance load up to 60 kV and voltage pulse rise time of 2÷3 ns at a pulse repetition rate up to 2 kHz) were used for REP DD excitation of atmospheric pressure nitrogen in pulsed and pulse-periodic modes, respectively. The measurements of *Te* and *E/N* in plasma of REP DD were carried out both in pulse-periodic (~2 kHz) and pulsed modes with method, based on the radiative-collisional model [8]. In the first case the time average values of *Te* and *E/N* was found to be of ~2 eV and ~270 Td, respectively. The same results were obtained in the case of pulsed excitation.

The optical technique based on the relative radiation intensity of rotation structure of electronic-vibrational molecular transitions was used for *Tg* measurements. Values of *Tg* was found to be of ~ 380 ºK and of ~ 820 ºK at pulsed and pulse-periodic modes, respectively.

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CALCULATION OF THE HELIUM SPECTRUM EMITTED BY PLASMA OF CURRENT SHEETS[1]

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A study of emission spectra of atoms in alternating electric fields is a topical problem of modern physics, because, in addition to a quasi-stationary ionic microfield, alternating electric fields of different polarization can be generated in plasma. In particular, an appearance of the circularly- or elliptically polarized alternating electric field in plasma current sheets was revealed in experiments with the current sheet CS-3D device [1]. Plasma parameters of current sheets obtained in [1] were $N_e \sim 10^{16}$ cm^{-3} and $T_e \approx T_i \approx 2$ eV. An analysis of atomic or ionic spectral lines emitted under the impact of the electric field allows us to determine temperature and velocities of ions, plasma density and strength of the electric field into a discharge. Such analysis requires theoretical computations of atomic and ionic emission spectra in electric fields.

In this work, the method of the energy matrix diagonalization of an atom in the electric field [2] was used for calculating spectroscopic characteristics of the helium atom. This method is free from limitations of perturbation theory and suitable for calculating emission spectra of atoms and ions in an alternating electric field with the strength and frequency changing in a wide range. In the framework of the suggested method, the wave functions and energies of an atom in a circularly polarized electric field are determined by diagonalization of the energy matrix of an atom in the electric field with elements

$$Q_{mn} = E_n^{(0)}\delta_{mn} - \omega < \varphi_m^{(0)} \left| J_z \right| \varphi_n^{(0)} > \pm F < \varphi_m^{(0)} \left| D_x \right| \varphi_n^{(0)} > \qquad (1)$$

where $\varphi_n^{(0)}$ and $E_n^{(0)}$ are the wave function and energy of the n-th atomic state in the absence of external electric field, F and ω are the strength and frequency of the external electric field, and D_x is the x-component of the dipole moment operator. The wave functions and energies of an atom determined by diagonalization of the energy matrix with elements (1) are used for calculating spontaneous transition probabilities between the Stark states JM and $J'M'$. These transition probabilities are calculated using the formula

$$A(JM \to J'M') = \frac{4\omega^3_{JM,J'M'}}{3c^3} \sum_q \left| \sum_{ij} C_i^{(JM)*} C_j^{(J'M')} (-1)^{J_i - M_i} \begin{pmatrix} J_i & 1 & J_j \\ -M_i & q & M_j \end{pmatrix} < \gamma_i J_i \| D \| \gamma_j J_j > \right|^2 \qquad (2)$$

where $\omega_{JM,J'M'}$ are frequency of the transition between the Stark states JM and $J'M'$. Algorithm of the method of the energy matrix diagonalization of an atom in the electric field was implemented in the software package StarkD.

Within the framework of the suggested method, the behavior of the Stark components for singlet and triplet $D_J - P_{J'}$ and $P_J - S_{J'}$ spectral lines was studied. For these lines, the dependences of the Stark component shifts and transition probabilities between magnetic sublevels on the electric field strength and frequency were investigated. The electric field strength changed from 0 to 120 kV/cm and the electric field frequency was 10^3 MHz. Chosen parameters of the electric field correspond to the strength F~100 kV/cm and frequency ω~10^3 MHz of the circularly polarized electric field, which is generated in a plasma current sheet in the experimental device CS-3D. The validity of the results obtained was confirmed by the excellent agreement of our calculated results with experimental data [1] for the $3^1D_2 - 2^1P_1$ (λ=667.8 нм) spectral line of the He atom.

The calculated results have allowed us to clarify mechanisms of forming the helium spectrum emitted by plasma of current sheets. These results, obtained for the first time, are of interest from the theoretical viewpoint and have practical applications in Stark spectroscopy, plasma physics and astrophysics.

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PARTICLE-IN-CELL SIMULATION OF BREAKDOWN DYNAMIC IN GAS-FILLED DIODE WITH HIGHLY NONUNIFORM ELECTRIC FIELD[1]

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In the article there was done the representation of the results that were received in numerical PIC modeling of the breakdown development in the gas-filled diode with highly inhomogeneous electric field.

On the base of the simulation in the electrostatic model there was provided the research of the initial stage of the breakdown development and the formation of runaway electron beam. Different mechanisms of the runaway electron beam formation were analyzed and the results of the numerical modeling of the breakdown development in the geometry with highly inhomogeneous electric field in the electromagnetic approach are represented. The mechanisms of gaining energy by the electrons of the beam and the connection of the energy of the beam's electrons with the voltage on the diode were also determined. The mechanism of short circuit of the electrode gap during the development of the pulsed breakdown in highly inhomogeneous electric field was analyzed.

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RESEARCH ON THE ELECTRICAL CHARACTERISTICS OF THE PULSED DISCHARGE IN SALINE SOLUTIONS [1]

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Most of the metallogenic belt of metal ores are in the orogenic belt, the conventional seismic exploration techniques by using dynamite source, vibroseis, airgun or the sparker are not suitable for this seismic exploration. The phased array sparker was developed for this application. The system mainly consists of 100 pulse power module, 100 diacharging electrodes and a time sequence controller. By control the discharging time sequence of the power modules, the seismic wave could be focused in a certain direction, the signal-to-noise ratio can be increased, and the deep depth seismic profile can be obtained. Each power module includes an isolated diode, a capacitor with a stored energy of 2k J and a thyristor discharge switch. Due to the limitation of the environment (lack of water resource), the discharging electrodes was designed to be a hermetical chamber pre-filled with saline solution. The discharging electrodes were used to convert the elecric energy into the seismic wave energy. The experimental study on the electrical characteristics of single module were conducted under different parameters(includes discharging mode, voltage, number of positive electrode, electrode gap disctance, etc).

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POWER AND RESOURCE CHARACTERISTICS OF THE STEAM-WATER PLASMATRON

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Results of experimental studies of the arc plasmatron for steam heating to the temperature of up to 300 ± 50°C are presented. The structural layout of plasma generator with the tubular copper electrodes does not require the use of foreign gaseous media (such as the protective medium of argon or nitrogen). The current-voltage characteristics of arc are descending and they are summarized in the criterial form. It is shown that the thermal efficiency of this plasmatron is higher than when working on air and it is about 0.7.

To achieve the optimal temperature conditions in the discharge chamber of plasmatron, the system of indirect cooling of the composite copper-steel electrode was calculated using the ANSYS software package. The engineering solutions and conditions of electrode water-cooling determining minimization of specific erosion of the copper anode were detected.

For the developed construction of the steam plasmatron of 80 - 100-kW power, the estimated operation life of electrodes at the arc current of 200-300 is 300 hours.

SUBNANOSECOND HIGH-VOLTAGE GAS BREAKDOWN IN SHARPLY-NONUNIFORM ELECTRIC FIELD [1]

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High-voltage nanosecond discharges in sharply-nonuniform electric field and related phenomena – the runaway electron beams and X-rays have recently been extensively studied by a number of research groups. However, the question of physical processes taking place in the gas-filled diode during the development of breakdown under the high overvoltage discharge gap is not completely resolved today. Due to the short duration of the breakdown stage (hundreds of picoseconds), numerical simulation is the best method for solving this problem.

This work presents the results of numerical simulation of the breakdown development in the gas-filled diode at the voltages >100 kV and at the pressures below atmospheric, carried out on the basis of experimental data.

During the experiments, the waveforms of discharge currents, the currents of runaway electron beam and the voltage at the gas-filled diode at different pressures in the region of units-tens of Torr were obtained. For numerical calculations, we used two-dimensional axisymmetric PIC KARAT codes [1] and XOOPIC [2].

The results of simulation are in good agreement with the data obtained in the course of the experiments and allow reconstructing the dynamics of the processes in the studied conditions on a qualitative level.

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THE FORMATION AND TRANSPORT OF LARGE CROSS-SECTION BEAMS IN THE LOW-PRESSURE GAS[1]

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This work theoretically and experimentally investigates the formation and transport of large cross-section beams in the low-pressure gas, the discharge plasma characteristics and the basic mechanisms of energy loss in the electron source with plasma emitter and generated beam output into the atmosphere through a thin stainless foil (Fig. 1.). In such source, the electron beam is a superposition of elementary beams formed by separate emission structures, the plasma boundary is stabilized a fine-wire grid. The fraction of extracted current from the accelerating gap into the atmosphere reaches 75% emission current. In experiments with an accelerating voltage of 200 kV and emission current of 16 A and pulse duration of 40 μs into the atmosphere was extracted about 4 kW (more than 60%) of the beam average power in the accelerating gap with a geometric transparency of the foil support grid exit window of 56%. The further increase of average beam power was limited high-voltage power supplies.

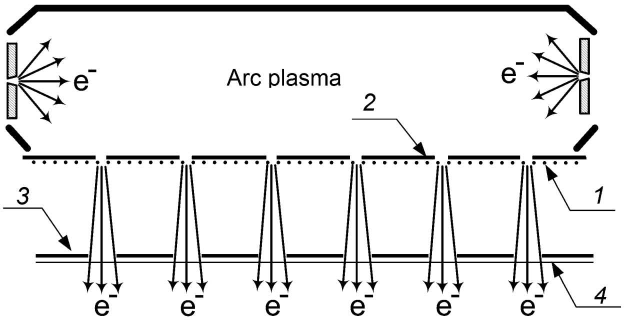

Fig. 1. Scheme of electron source with plasma emitter: 1 – emission grid, 2 – mask, 3 – support grid, 4 – foil

This work also leads the numerical study of the discharge plasma generation, formation and beam transport. It is shown that the characteristics of the discharge plasma (concentration, temperature and the plasma potential) depend on the resistance in the circuit of the hollow anode of the discharge system and the mask surface area (Fig. 2). The studies based on the theoretical model show that the main beam energy loss is associated with the ion current appearing due to the gas ionization by electron beam in accelerating gap as well as the ionization by electron beam of desorbed working gas on the surfaces of the output foil and the support grid. The processes associated with the ion current from the accelerating gap and leading to a local increase of the plasma concentration in a result of ion-electron emission from the anode surface were considered. We also investigate the possibility of uniformity control of beam density by changing of mask geometry.

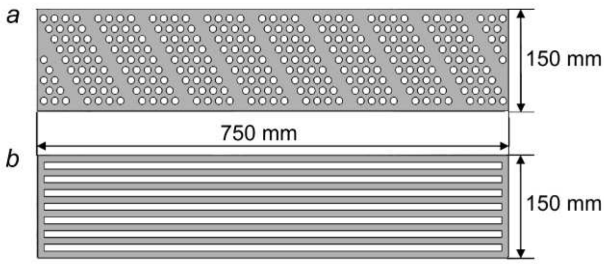

Fig. 2. Mask geometries

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UNIFORM AND FILAMENTARY MODES OF PULSED DBD IN AIR

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The experimental investigation of pulsed dielectric barrier discharge (DBD) in atmospheric air was carried out. The discharge was initiated by tailor-made generator of unipolar rectangle pulses. The uniform and filamentary modes of pulsed DBD were realized in atmospheric air for various dielectric barrier materials in plane-parallel electrode configuration without using of preionization sources. The optical data were collected by means of photomultiplier tube and standard commercial photo camera.

It was found the strong correlation between discharge mode and resistance of the external circuit [1]. In addition, the dependence of a discharge form on a pulse repetition rate was observed under condition of the constant series resistor value [2].

The uniform discharge mode developed as synchronous ionization of discharge gap medium and characterized by solitary bell-shaped current pulse on the rise and fall edges of applied voltage. This picture took place at relatively low circuit resistance values and frequencies. At high values of circuit resistance the ionization processes starts asynchronous and current signal disintegrates into separate pulses. Hereby the filamentary mode is realized.

It is possible to achieve the filamentary discharge mode via pulse repetition rate increasing at constant circuit resistance value. It is remarkable that the current signal in this case was also solitary bell-shaped current pulse.

There were not observed any strong borders of mode presence area. Noteworthy that for some kinds of dielectric material the gas discharge didn`t always appear at the rising edge of the voltage pulse. The observed delay is much higher than the rise time, but the uniform mode is realized. So, it is reasonable to claim that a rate of the electrical field rise in the discharge gap does not play a determinative role for the discharge mode. In the burst mode the random delay of the discharge appearance is observed only for the first pulse from the burst. There is no delay of the discharge current pulse in the subsequent pulses of the burst they appear synchronically with the voltage rise.

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FEATURES OF PLASMA SUSTAINING IN THE POSITIVE COLUMN OF GLIDING GLOW DISCHARGE IN AIR FLOW[1]

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Currently, the low-current atmospheric pressure discharges in a gas flow attract considerable attention. The systems for obtaining these discharges generally consist of two specially configured electrodes allowing the gas flowing through the discharge gap. The well-known example of such system is the so-called "gliding arc" used in this work.

In [1, 2] it was demonstrated that at a low average current (less than 0.5A) the atmospheric-pressure discharge typically burns in normal glow mode. The reduced electric field in the positive column of gliding glow discharge has to provide the column sustainment due to gas ionization. In our previous paper [2] we estimated the reduced electric field value as $E/p_{eff} \approx 10$ V/cm·Torr, that is rather low as compared, for example, to the data presented in [3, 4]. The paper describes the results of the investigation of the plasma parameters in the constricted positive column of gliding glow discharge in air flow at atmospheric pressure. The research methodology was previously proposed by us in [2].

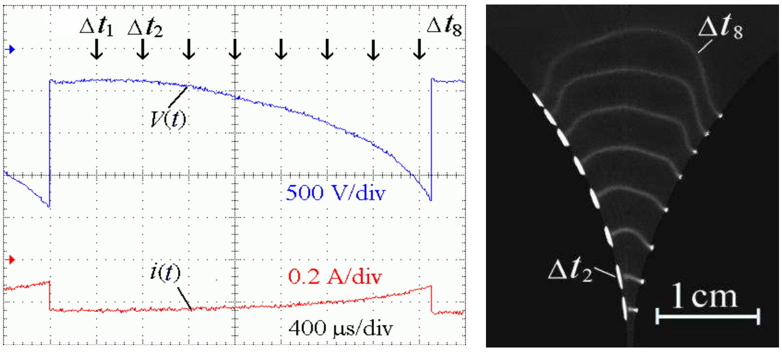

Fig. 1. Voltage and current waveforms jointly with CCD frames are used for estimation the parameters of gliding glow discharge. The output voltage of power supply $V_0 = 3.4$ kV, average discharge current is about 200 mA with ballast resistor $R_b = 13$ kΩ. The air flow is directed from the bottom upwards. The instants of expositions from Δt_1 to Δt_8 with exposition time for each frame $\Delta t = 20$ μs are shown by arrows.

In different conditions, at the average current about 0.2A an average electric field in the positive column of gliding glow discharge is (300–550) V/cm. On the basis of experimental data, the plasma parameters of positive column were estimated. The estimations demonstrate, that for $E/p_{eff} = 20$ V/cm·Torr the value of the gas temperature in the positive column T_{pc} is about 10000K. This value seems to be rather high for such type of discharges. In suggestion $E/p_{eff} = 10$ V/cm·Torr the value of T_{pc} is about 4200K, which is in agreement with experimental data. So, that the value of $E/p_{eff} \approx 10$ V/cm·Torr is probably sufficient for plasma sustaining in the positive column of the glow discharge in air flow.

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TWO-ELECTRODE GAS SWITCH WITH ELECTRODYNAMICAL ACCELERATION OF A DISCHARGE CHANNEL[1]

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High voltage, high current, and high coulomb transfer closing switches are required for many high power pulsed systems [1, 2]. There are a few alternatives for closing switches, for example ignitrons, vacuum switches, solid state switches, high pressure gas switches (spark gaps), and some others. The most popular closing switches up to date are spark gaps due to relatively simple design, robustness, easily field maintenance and repair. Main drawback of spark gaps is limited lifetime, which is related directly or indirectly to erosion of the electrodes. Multichannel switches and switches with moving arc have been proposed to prevent the electrodes erosion. Three-electrode switches, where a spark channel is initiated in a three-electrode layout and then the spark accelerates due to electro-dynamical force and moves along two extended electrodes, were investigated by Kovalchuk et al. [2]. It was found in [2] after extended tests (22000 shots) that for the 240 kA, 24 kV, 70 C switch main erosion occurs on a triggering electrode. In this report we present switch that consists of connected in serises two electrode spark gap with electrodynamic aceeleration of a spark channel and saturating inductor. The switch operates at atmopheric pressure. One turn saturating inductor consists of ten cores, which are winded up by transformer steel strip of 18 mm width and 50 µm thickness, with insulating 10 µm mylar tape between turns.There is no triggering electrode in such switch. Very wide operation range has been observed in tests: from 1 kV to 20 kV (at 50 kV sekf-breakdown voltage) with submicrosecond stability. It has also been shown (see Table 1) that energy loss in switch is very high at low charging voltages (~20-25% from the energy, stored in a capacitor bank at voltage below 2 kV) but does not exceed 4% at voltage higher than 15 kV, at operation on the level of ≈ 36% from sekf-breakdown voltage.

Spark gap is designed for 24 kV charging voltage, at a current up to 250 kA, and ~70 C total charge transfer. In this paper we present design of this spark gap, inductor and trigger generator, describe the test bed shematics and present results of the tests.

Table. 1: Uch – charging voltage on bank, I0 – load current, W0 – initial bank energy, δW – energy loss in switch.

Uch, kV	I0, кA	W0, kJ	δW, kJ	δW, %
1,2	11,6	2,3	0,586	25,4
2,6	26,1	10,7	1,76	16,4
5,2	52,6	42,03	4,1	9,7
10,4	103	166,6	10,88	6,58
15,4	153,2	365,86	14,9	4,08
20,4	202	643,3	22,14	3,44

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THE THRESHOLD EFFECT FOR SOME PHYSICAL PARAMETERS OF ADRE PLASMA BY SPORE BACTERIA DECONTAMINATION

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The role of runaway electrons density and energy values in ADRE-plasma (Atmospheric Discharge with Runaway Electrons) for different kind of applications is an actual question at present time. One of the most effective area of ADRE-plasma application is bacteria decontamination in air at atmospheric pressure and room temperature. Basic difference between general kinds of low-temperature atmospheric gas-discharge plasma interaction mechanisms with bacteria on solid-state surfaces and mechanisms of such surfaces sterilization by ADRE-plasma consists of available at the last plasma enough great number of "runaway" electrons with energy from several volts to several hundred kiloelectronvolts (in comparison with typical average energy of electrons in standard kinds of plasma at the level of 2-5 eV) [1-3]. Such runaway electrons have enough energy to inter-react with micro-organisms on a solid surface as by direct collision with biologically awake molecules of a microorganism (the mechanism of direct influence), and by formation of reactions products (radiolysis of water, etc. – the mechanisms of indirect influence) which then inter-react with biologically awake molecules of microorganisms [4-5].

Table 1. Results of ADRE-plasma interaction with vegetative and spore form bacteria by different plasma processing time

№ of the ample	Type of the bacterium	Treatment duration, sec	Sterility result
1	Staphylococcus Aureus	0 (control sample)	unsterile
2	Staphylococcus Aureus	30	unsterile
3	Staphylococcus Aureus	60	unsterile
4	Staphylococcus Aureus	90	sterile
5	Staphylococcus Aureus	180	sterile
6	Licheniformis Subtilis	0 (control sample)	unsterile
7	Licheniformis Subtilis	600	unsterile
8	Licheniformis Subtilis	900	sterile
9	Licheniformis Subtilis	1800	sterile
10	Licheniformis Subtilis	2700	sterile

The threshold effect [5] for specific average current of runaway electrons in ADRE-plasma by spore form bacteria decontamination have been studied at present paper. Two different ADRE-plasma parameter sets were used for bacteria decontamination in atmospheric air. One of results is presenting in the Table 1. First 5 samples have been seeded by vegetative form bacteria Staphylococcus Aureus with concentration 1 Mln/ml. The samples # 6-10 have been seeded by spore form of bacteria Licheniformis Subtilis with the same concentration (standard level for medical sterilization verification). The analysis of first 5 samples decontamination by ADRE-plasma with low current of runaway electrons and high average power of ADRE-plasma shows the enough good effectiveness of decontamination after 90 seconds of treatment. But for spore form bacteria the same parameters made the unsterile result only. The sterilization of spore form bacteria after 15 min treatment was made by ADRE-plasma with low average power but high specific current of runaway electrons (samples #8-10). Such result is unavailable by general types of atmospheric plasma.

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SPATIAL PROFILES OF THE CATHODE REGION PARAMETERS IN A STRONGLY CONSTRICTED ATMOSPHERIC PRESSURE GLOW DISCHARGE

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In low pressure glow discharges, the definition of constricted positive column is connected with a relation of its transverse dimension relative to a discharge tube diameter. Dimensions of cathode fall were unimportant in this case. However in high-current atmospheric pressure glow discharges, when discharge chamber walls are far from discharge axis and transverse dimensions of cathode region are in centimeter scale, a degree of positive column contraction should determine by relation of its diameter relative to a negative glow dimension. In connection to this, as it is shown in [1], positive column at gap of 10 mm and at current of 1 A is diffuse in nitrogen APGD, slightly constricted in helium one and is strongly constricted in argon one.

Creation of the APGD with diffuse positive column at large gap and high current is a hard challenge even in helium. As it is shown in Fig. 1(*a*) for the flat electrodes of large areas, a diffuse positive column at current of 1 A can be obtained at gaps less than 5 mm. At larger gaps it is constricted.

The significant heat release there is in the APGDs at high current leading to heating of electrodes. Positive column in the case of uncooled cathode is more constricted relative to the negative glow than in the

(*a*) (*b*) (*c*)

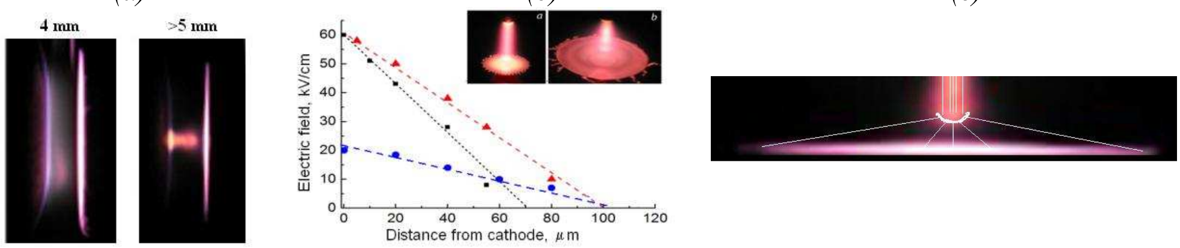

Fig. 1. (*a*) Images of the diffuse and constricted helium APGD at a current of 1 A; (*b*) Longitudinal electric field profiles in a cathode fall for cooled (squares, inset *a* above) and uncooled (triangles, circles, inset *b* above) cathodes. Square and triangle symbols correspond to axial profiles, the circles – at a distance of 8 mm from the axis; (*c*) Spatial profile of currents in cathode region

case of cooled cathode (see insets in fig. 1(*b*)). As it is shown in [2], the excess on about 400 K an uncooled cathode temperature over temperature of cooled one leads to the increase in the interelectrode voltage by 70–80 V for a constant discharge current of 1 A. This voltage increase is caused by a cathode fall voltage increase due to an increase in the cathode fall layer thickness at the discharge axis (Fig. 1(*b*)). Moreover, a radial dependence of electric field strength in the cathode fall is appeared. However, explanations of these two facts have not been received.

This report presents further investigations of these phenomena. It is established that an additional cathode heating by external heat source decreases the interelectrode voltage. Radially limited heat flow from a strongly constricted positive column to a cathode results in inhomogeneous distribution of the reduced electric field along the cathode surface – it decreases radially. Gas heating at the edge of cathode fall is mainly due to a heat transfer from hot cathode and a current flow here. Spatial profile of currents in cathode region is discussed (Fig. 1, (c)). The parameters of the cathode region in the diffuse APGD more or less fit the scaling laws at the periphery and mismatch at the center of the cathode region. As it is known, the cathode fall voltage is defined in preference by a secondary electron emission coefficient. In connection to this, the increases of cathode fall voltage at cathode heating by discharge current at the discharge axis and its decreases at the cathode sheath edge can not be explained by the oxide films formation and different contribution of metastables in the effective secondary electron emission coefficient.

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THE MODE TRANSLATION OF TRICHEL DISCHARGE

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The trichel pulse is a typical kind of negative corona current observed in electronegative gases with a highly regular form[1]. Many researchers have studied the mean current and the current-voltage characteristic of trichel pulse, yet the stochastic properties of the pulses have barely been investigated[2]. In this paper, a series of experiments were carried out in needle-plate discharge to investigate the detailed characteristics of trichel pulses including the amplitude, the rising time, the falling time and the interval of pulses using statistical methods.

An experimental setup of needle-plate negative corona discharge is designed in this paper. Both stainless steel point and plate electrodes are fixed on a shelf which is insulated from the ground. The radius of the needle is 0.2mm while the plate is 50mm*100mm. The gap space between the electrodes is set to 17mm. A high negative dc voltage from 0 to -20kV is applied to the needle electrode and the plane is connected to ground through a sampling resistor which is 2kΩ. All experiments are carried up in ambient air at room temperature.

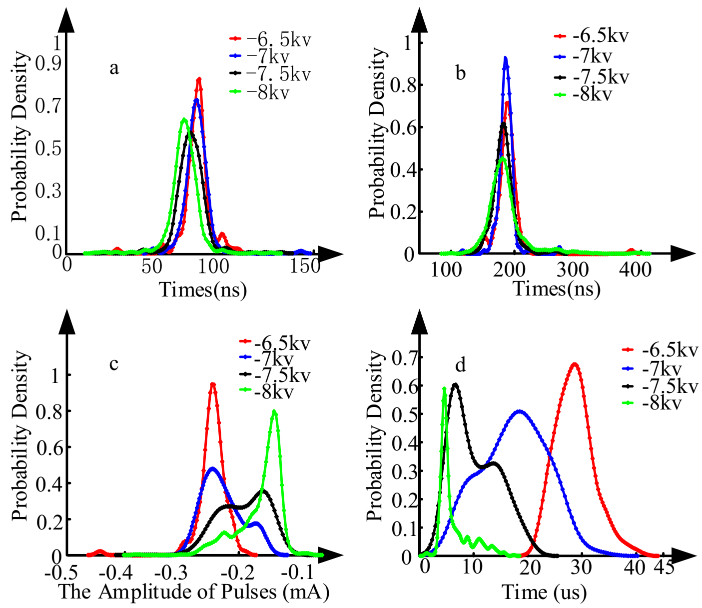

FIG.1 the probability density of parameters. a). the probability density of the rising time. b). the probability density of the falling time. c). the probability density of the amplitude of pulses. d). the probability density of the interval of pulses

FIG.1 shows the probability density of parameters mentioned above of pulses measured in 3ms with the voltage -6.5kv, -7kv, -7.5kv, -8kv and the number of pulses are 115, 202, 483, 732 respectively. The rising time of pulses are all about 75ns, and slightly reduce with the voltage increasing. The falling time are almost the same at 200ns when the voltage is different. When voltage is -6.5kv, the amplitude of pulses are almost -0.25mA, and -0.15mA while the voltage is -8kv. However, there are both -0.25mA and -0.15mA pulses when voltage is -7kv and -7.5kv,especially as the voltage increases from -7kv to -7.5kv, the regime amplitudes of pulses transfer from -0.25mA to -0.15mA. As the voltage increasing, the interval becomes smaller and transfer from 30us to 5us.According the probability density of the amplitude of pulses, the results shows that there a process of mode translation as the voltage increasing. The rising time and the falling time are basically the same between the different modes, while the amplitude of pulses has a mutation with the voltage increasing. According to the theory of negative corona discharge, we suggest that the reason to this phenomenon is that the dissipate way of negative ions which is the cause of trichel pulses have changed as the voltage increasing.

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INFLUENCE OF MAGNETIC FIELD TO DC CORONA DISCHARGE

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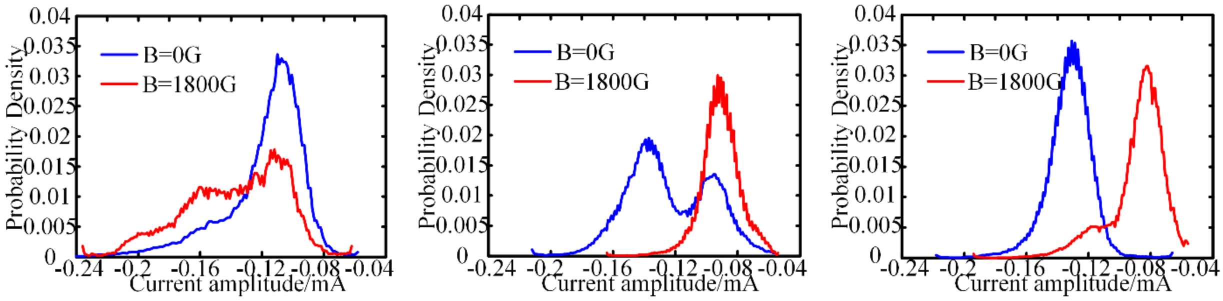
Nowadays, corona discharge at atmosphere exhibit a wide range of applications such as surface modification of materials, biotechnology and so on. The magnet enhancement corona discharges have been demonstrated in previous studies[1]. Corona discharge is a random process[2], in this paper, by using of statistical methods, the peak of discharge current is selected as a statistical element. We are focusing on the influence of magnetic field to the corona.

The discharge cell consists in a needle-to-plate electrodes arrangement, which are made of stainless steel. The discharge electrode is 50mm long, the diameter is 0.2mm, the grounded plate is 60mm*100mm. The discharge gap is fixed to 5mm. The magnetic field generated by two permanent magnets, keeping the distance between two magnetic poles is 20mm, the maximum magnetic flux density of the parallel magnetic field is 1800G, and the entire discharge area is wrapped in a magnetic field, the magnetic field is perpendicular to the discharge direction. The DC power source is regulated and continuously variable from 0 to 10kV. The applied voltage is measured by using the high-voltage probe (P6015a), through a 2K non-inductive resistor, the discharge current is converted into the voltage signal. The discharge signal is recorded by DPO3104 Tektronix digital storage oscilloscope.



(a) U=4.60kV (b) U=4.90kV (c) U=5.40kV

Figure 1 Statistical characteristics of the discharge current amplitude under different voltage

The current waveforms sustained 3ms are selected as a sample. Under different voltage amplitudes, the number of pulses are 1337, 2324, 2576. The statistical characteristics of the discharge current amplitude are shown in Fig.1. When U=4.60kV, under the condition of B=0G, the curve of current amplitude distribution have a peak point, nearly Imax=-0.11mA; when B=1800G, the current amplitudes distributed in a wide range; With the increase of the voltage, U=4.90kV, when B= 0G, the curve of current amplitude distribution have two peak points, and when B=1800G, only one peak point exists. When the voltage is 5.40kV, the peak of discharge current reduced slightly under the condition of B=1800G, and when the magnetic flux density is 0G, there are only one peak point. As shown by the statistical characteristics, under the condition of magnetic field, the current amplitudes distribution is changed, and the movement of current peak is delayed. In conclusion, the magnetic field can influence the stage of corona discharge, and also can make the corona discharge current pulse amplitude stabilize.

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THE EXPERIMENTAL STUDIES OF THE ELECTRO-EROSION PROCESSES ON PLASMATRON ELECTRODE WITH A MOVING ELECTRIC ARC

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The paper presents the results of experimental studies of a moving arc plasma torch electrodes. The results of investigation of heating and electrode erosion under the influence of high-current arc moving. Researches erosion traces on the surface of the plasma torch electrodes, resulting electromagnetic and thermal effects of the moving arc. The influence of the velocity of the moving arc V_d on the shape and size of these traces, in the range V_d = 7÷130m/s. The solve the problem by improving the efficiency of plasma generators.

THE GLOW DISCHARGE WITH A TRANSVERSE SUPERSONIC FLOW IN A BOUNDED REGION OF THE INTERELECTRODE SPACE

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The effect of supersonic gas flow on the characteristics of a glow discharge. The cases of gas flow near the anode, cathode and near the middle of the area in the interelectrode space. It is shown that the organization of a supersonic flow in a limited region of the interelectrode space to create a different concentration of the neutral gas particles in different regions between anode and cathode. As a consequence, in different areas of the interelectrode space there are different conditions of discharge. Studied the current-voltage characteristics of such discharges and the potential distribution along the discharge region.

NON-STATIONARY PLASMA PROCESSES AT VACUUM DISCHARGE IN DEPENDENCE ON SURFACE PROPERTIES AND EXTERNAL ACTION [1]

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The vacuum discharge implies a formation of plasma from the electrode material for a large current transfer. It consists of three stages – vacuum breakdown, vacuum spark, and vacuum arc [1-3]. The basic feature of all these stages is the formation of the explosive electron emission (EEE) pulses – ectons that arise from microscopic Explosive Centers at the cathode and are responsible for an electron emission current of a large density and large magnitude.

One can propose that the EEE being similar to the *boiling*, whereas the electron emission on a common type being similar to the slow *evaporation*. As the intensity of bubbles formation at boiling depends on how low is the particle number (the pressure) above the surface, similarly the intensity of EEE pulses – ectons formation being larger the larger the electrical current is desirable to be transferred. Ignition of the EEE pulses, their decay, and the consequent self-sustaining is of strong interest.

A two-step model of initiation of the explosive pulse under the external action has been proposed that implies (i) the dense primary erosion plasma production and (ii) the intense electron emission buildup that results in the electrical explosion [4]. It has been found that the threshold energy flux to the surface, being of about 100 MW/cm^2 for a ‘clean’ surface, reduces substantially for the surface covered by ‘easily eroding layers’, such as nanowires and metal films [5-7]. It is worth noting that the similar value of critical energy flux (few Watts per μm^2) has been found for a vacuum breakdown in modern radiofrequency accelerating structure [8].

We have proposed a model for determining the influence of the relative content of deuterium in a zirconium cathode on the properties of vacuum-arc plasma [9]. It has been shown that the occlusion of deuterium in the cathode leads to an additional energy consumption for its ionization and to the related decrease in the average charge of cathode material ions in the discharge plasma. Deuterium in the cathode spot is fully ionized, and the drift velocity of deuterium ions almost coincides with that of ions of the cathode material due to a large collision frequency at near-cathode region.

A model has been proposed for evaluation of the average ion-charge of the vacuum-arc plasma in dependence on the compound-cathode composition. It has been demonstrated for the cathodes of $Ti_{1-x}Al_x$ that increase of Al-component results in increase of aluminum ion average charge and in decrease in that for the titanium.

According to the modelling results the ignition of a new explosive electron emission centers at the dense ($\sim 10^{20}$ cm^{-3}) cathode spot plasma action onto the surface micro-relief arises within nanosecond time-scale, and depends in most on the thermal properties of the compound cathode.

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INFLUENCE OF THE SYSTEM Z-NONUNIFORMITY ON PLASMA CHANNEL FORMATION WHEN TRANSPORTING A LOW-ENERGY HIGH-INTENSITY ELECTRON BEAM IN THE LOW-PRESSURE GAS[1]

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For efficient use of low-energy electron beams for technological purposes there is a need of their transportation to a target. For this purpose plasma channel pre-created by external sources is used or the beam is injected into a neutral gas creating plasma channel independently.

In this work the question of plasma channel formation by a low-energy electron beam is considered when filling a drift tube with argon or helium with gas pressure range 0.02..0.2 Pa. Investigations are carried out on the basis of a mathematical model [1, 2] including ionization processes, current and charge neutralization when passing high-current electron beam in inert gases of low pressure in the absence and in the presence of an external magnetic field B_z. In addition, the model is supplemented by the system z-nonuniformity that allows determining influence of gaz density z-gradient on the plasma channel formation.

Research of plasma channel parameters is performed for electron beams with experimental current pulse [3]. The plasma channel parameters relations on the system geometry, the external magnetic field, gas pressure and gas type are determined on the basis of numerical calculations. The influence of the system z-nonuniformity on plasma channel formation is investigated.

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RESEARCH OF TRANSPORTATION EFFICIENCY OF LOW-ENERGY HIGH-CURRENT ELECTRON BEAM IN PLASMA CHANNEL IN EXTERNAL MAGNETIC FIELD[1]

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Effective high current (5-20 kA) and low energy (tens of keV) electrons beam transportation is possible only with almost complete charging neutralization. It is also necessary to use quite high current neutralization for elimination beam self-pinching effect. The research is based on the self-consistent mathematical model that takes into account beam and plasma particles dynamic, current and charge neutralization of electron beam and examines the transportation of electron beam into a chamber with low-pressure plasma in magnetic field. A numerical study was conducted with using particle in cell (PIC) method. The study was performed at various parameters of the system: the rise time and the magnitude of the beam current, gas pressure and plasma density and geometry of the system. Regularities of local virtual cathode field generated by the beam in the plasma channel, as well as ranges of parameters that let transportation beam with minimal losses, depending on the external magnetic field were determined through a series of numerical studies. In addition, the assessment of the impact of the plasma ion mobility during the transition period and during steady beam was performed.

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STREAMER DISCHARGES OPERATING ALONG THIN LIQUID SURFACE [1]

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Effectiveness for non-thermal plasma activation of liquids substantially depends on type of electrical discharge used for this purpose. That is why the development of new types of electrical discharges interacting with a liquid is of great interest for practioners and scientists dealing with a plasma-liquid interplaying. Taking this in mind, the specific issues that will be discussed in this report are as follows:

1) electrical discharge in gas bubbles surrounded by a liquid;
2) multi-pin electrical discharge above a liquid influenced by a strong mechanical vibration;
3) pulsed-periodical discharge extending for a long distance above liquid due to impact of airflow;
4) generation of long surface streamers spreading above a liquid.

Short information related to approaches 2) and 4) is presented below.

Approach 2). The water surface under mechanical vibration is strongly disturbed and similar to a sea surface during a storm. Streamers choose the shortest way between HV pin and water surface. Because of that they strike predominantly the wave tops but not wave valleys. The sketch illustrating chaotic distribution of the streamers over strongly disturbed water is shown in Fig. 1. It follows from this figure that HV pins work not always simultaneously. Nevertheless the experiment showed that the averaged electric power consumed by AC streamer discharge above vibrating water is higher compared with that for a discharge above the tranquil water.

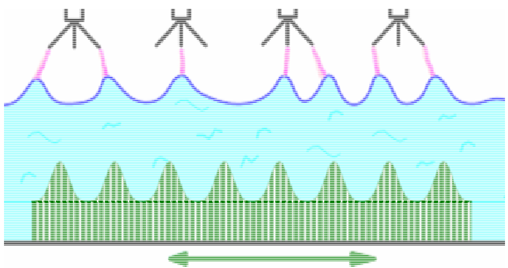

Fig.1. Sketch illustrating a chaotic distribution of streamers generated by a multi-pin electrode above water surface strongly disturbed by mechanical vibration in transverse direction.

Approach 4). A conductive liquid can exhibit dielectric properties but only for short time $t_* \leq (\varepsilon \cdot \varepsilon_0/\sigma_l)\cdot(\partial \ln E(t)/\partial \ln t)$, where ε, σ_l and $E(t)$ are the dielectric permittivity, conductivity and electric field strength in liquid, respectively. As a rule for the pulsed discharge over a liquid, surface streamers cease their propagation after time t_*. A reason is that the conductive current in a liquid "switches on" after time t_* and shunts the electric current inside the streamer. This shunting leads to decreasing the voltage drop V_s along the streamer. The streamer will stop if the V_s is lower than it is necessary for streamer's propagation. Typical length of the surface streamer on water does not exceed 1 cm. The mentioned above scenario happens in pulsed discharges, if streamer slides above surface of a deep liquid: $h_l > h_c\cdot\sqrt{(\sigma_s/\sigma_l)}$, where h_l and h_c are the depth of a liquid and diameter of the streamer; σ_s is the streamer conductivity. However streamers can propagate over liquid at $t>t_*$ as well, if the depth of liquid is not large: $h_l < h_s\cdot\sqrt{(\sigma_s/\sigma_l)}$. In this case, there is no full shunting of streamer by thin layer of conductive liquid. Taking this in mind, we were able to realize the extended (up to 10 cm) and multiple surface streamers propagating over thin layer of a liquid.

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RESEARCH OF DIFFUSION AND MECHANICAL WAVES INTERACTION UNDER CONDITIONS OF METAL SURFACE TREATMENT WITH PARTICLE FLUXES[1]

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Due to material processing with charged particle fluxes, the purposeful change of the surface layer material state is possible, thus improving its operating abilities. Achievement of important results requires a detailed study of the processes occurring during processing. Surface treatment is accompanied by different physical and chemical factors that affect each other and influence the formed macroscopic properties of work materials. The role of each separate factor can't be experimentally investigated. Therefore, the computer simulation has a big significance for this research. The paper is aimed at investigating the nature of interaction of two different scale processes - impurity diffusion and mechanical stress wave propagation under the action of a single pulse.

A coupled isothermal model at the initial stage of a solid body surface treatment with particle flux (dimensionless variables):

$$\tau_r \frac{\partial^2 C}{\partial \tau^2} + \frac{\partial C}{\partial \tau} = \frac{\partial}{\partial \xi}\left[f(C)\frac{\partial C}{\partial \xi}\right] - \omega\gamma\frac{\partial}{\partial \xi}\left[C\frac{\partial S}{\partial \xi}\right], \tag{1}$$

$$\frac{\partial^2 S}{\partial \tau^2} + \gamma\frac{\partial^2 C}{\partial \tau^2} = \frac{\partial^2 S}{\partial \xi^2}, \tag{2}$$

$$S = e - \gamma(C - C_0). \tag{3}$$

$$\xi = 0:\ \mathbf{J} = \beta\varphi(\tau),\ S = S_0\varphi(\tau),\ \xi \to \infty:\ C = 0,\ S = 0, \tag{4}$$

$$\tau = 0:\ C = 0,\ S = 0,\ \frac{\partial C}{\partial \tau} = 0,\ \frac{\partial S}{\partial \tau} = 0, \tag{5}$$

Detailed explanation of the transition to (1)-(5) described in [1, 2]. Also in these papers are shown the influence of model parameters on concentration and diffusion waves distribution.

Interesting phenomena can be observed when form of the function $f(C)$ is change. Profiles of both waves not only accelerated but also "overturned" (Fig. 1).

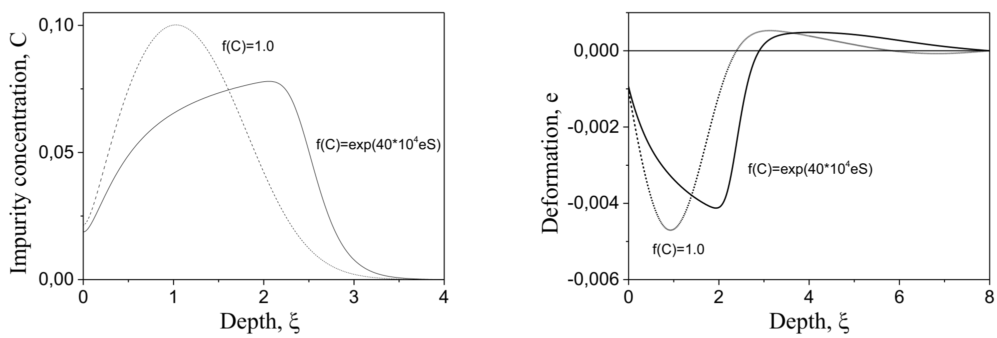

Fig. 1. Influence of the function $f(C)$ form on the distribution of the implanted impurity and deformation wave. Times, $\tau = 8.0$.

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PLASMA EFFECTS AT IRRADIATION OF LIF AND NAF CRYSTALS BY FEMTOSECOND LASER PULSES

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The irradiation of transparent crystals by femtosecond laser pulses has wide research interest and use in the creation various micro and nano - structures, such as optical data carriers, wave guides, etc. [1, 2].

High laser intensity in focal volume causes nonlinear absorption of laser energy by the crystal through multiphoton ionization, ionization of tunneling and avalanche ionization. Due to these processes the density of nonlinear excited electrons in a conduction band increases. Electrons of conduction band form plasma which influences structural changes in a crystal.

Ti:Sapphire laser pulses with energy 0,5 mJ, duration 30 fs, repetition rate 1 kHz induced channels with the color centers and destructions in LiF and NaF (Fig. 1).

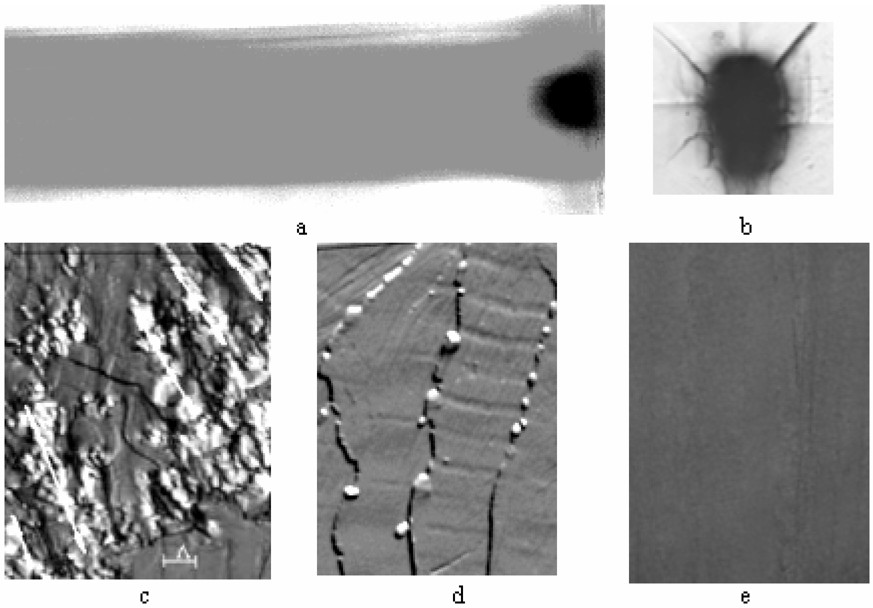

Fig. 1. a - the channel 1 cm length, 200 microns wide, induced by femtosecond laser pulses in NaF (a dark spot on the right – the self-focusing area coinciding with geometrical focus); b – cross section of the channel in NaF (geometrical focus on a crystal surface); c, d – destructions in focal area made by femtosecond laser pulses in LiF crystal; e – unirradiated LiF

Cracks are formed mainly in <110> and <100> directions (Fig. 1b) in the cross section of the femtosecond channel. The temperature increases in the focus due to transfer of energy from the photo-excited electrons of electron plasma to a lattice in a crystal. The shock wave is generated because of it. Cracks are formed due to generation of a shock wave.

Destructions in Fig. 1c represent the melting areas self-organized in the directions of the bands shown by white arrows. Distance between bands about 800 nm. Polarized dependent formation of nanostructures is connected with the high light intensity making electronic plasma density a close to critical. Due to disintegration of an initial electromagnetic wave on the Langmuir and acoustic waves the interaction of electronic plasma wave with incident light wave occurs. The interference of waves and periodic modulation of electronic plasma concentration and structural changes in a crystal occur in result.

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HIGH ENERGY ELECTRONS BEHIND THE PLANE-GRID CATHODE AT SUBNANOSECOND DISCHARGE IN ATMOSPHERIC PRESSURE AIR [1]

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An interesting mode of runaway electron beam generation was realized in [1]. Bokhan and Sorokin demonstrated that in low-pressure neon and helium with a grid cathode, runaway electron beams can be generated moving backward from the anode (backward runaway electron beams). In the works reported in [2-5], a backward runaway electron beam was detected in atmospheric pressure air with increasing the voltage pulse amplitude and decreasing the voltage rise time.

In this work, the experiments was performed for examination of the conditions under which a runaway electron beam moves not only toward the anode but also backward (to the space downstream of the cathode). Furthermore, simulation of electric field distribution in "anode – grid cathode" and "anode – grid cathode – foil" gap was carried out.

In the experiments, a SLEP-150 generator was used which allowed us to obtain ~$6\cdot10^{10}$ electrons in atmospheric pressure air downstream of an Al foil anode 10 μm thick. For recording a backward runaway electron beam, a positive voltage pulse was applied to the high-voltage electrode of the gas diode. The amplitude of the voltage pulse in the incident wave was ~150 kV and its FWHM was ~1 ns. The voltage pulse rise time was determined by a peaking switch and was ~0.3 ps. The anode of the gas diode was 36 mm in diameter and was a flat disk 3 mm thick with rounded edges. The anode surface facing the cathode was made of aluminum, stainless steel or tantalum. The cathode was a grid of parallel ∅0.2-mm stainless steel wires stretched with a step of 4 mm on a flat steel ring 3 mm thick. On the other side of the ring, there was an Al foil reinforced with a grid of transparency 90 %. The electron beam was recorded by collectors of varying receiving part diameter located downstream of the 10-μm foil which was also fixed to the flange of the gas diode. The spacing between the grid and the foil was 3 mm and could be increased to 6, 9, and 12 mm using additional rings. With diaphragms, the pulse width of the backward runaway electron beam was measured at picosecond and subnanosecond time resolution. In the first case, the diameter of the collector receiving part was 3 mm and the time resolution was ~20 ps.

When recording the electron beam in the forward direction, the generator polarity was revered. The potential electrode was a cathode in the form of ∅0.2-mm parallel stainless wires stretched with a step of 4 mm on a ∅40-mm steel ring fixed to a flat disk. The anode, in this case, was a 10 μm thick Al foil. Aluminum foil filters of differing thickness made it possible to determine the electron beam attenuation.

On the bases of the conducted experiments and simulation, the following conclusions can be made:

1. Recording of fast electrons behind the cathode foil of the discharge gap containing inside the thin wires under the cathode potential indicates that these fast electrons are generated near the wire surfaces where electric field has its maximum strength. Simulation of electric field distribution have shown, that an electric field strength is reached ~10^6 V/cm around wires.
2. Short current pulse of the fast electrons indicates that they are formed in the initial stage of the breakdown and they are not the dissipated electrons, which have got beyond the cathode after the anode voltage drop.
3. Dependence of the total number of fast electrons on the anode material indicates that the bremsstrahlung X-radiation is of great importance already at the initial stage of the breakdown development when runaway electrons are formed.

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BLUE AND GREEN JETS IN LABORATORY DISCHARGES INITIATED BY RUNAWAY ELECTRONS[1]

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Spectral and amplitude-temporal characteristics of a plasma radiation of a nanosecond pulse-periodic discharge were investigated. Voltage pulses of negative polarity (amplitude is ~13 kV, FWHM is 10 ns, pulse rise time is 4 ns) produced by the NPG-15/2000N pulser were applied to an electrode (cathode) made of different metal (copper, aluminum, stainless steel). Pulse repetition rate was 60Hz. The cathode had a cone form. Diameter of cone base was 6 mm, and radius of curvature of cone apex was about 0.2 mm. Grounded electrode (anode) was a flat with diameter of 38 mm. Interelectrode distance was 2 and 3 mm. Discharge current was measured with a shut made of chip-resisters. Spectrum of optical radiation of a discharge plasma from different regions of the discharge gap was registered with spectrometers HR4000, Ocean Optics B.V., 1st: $\Delta\lambda = 330 - 425$ nm, 2nd: $\Delta\lambda = 200 - 305$ nm and EPP-2000C, Stellar-Net Inc., $\Delta\lambda = 192 - 850$ nm. Temporal characteristic of a discharge plasma radiation from different regions of the discharge gap was measured with monochromator MDR-23 and PMT-100. Discharge chamber was filled with air, nitrogen, argon.

Diffuse discharge is formed in all three gases at pressure up to 100 Torr. At pressure more than 200 Torr a spark channel is formed. Maximum pressure was 760 Torr. At using aluminum and copper cathode bright blue and green jets respectively are observed in a cathode surface at pressure of gases 30 and 50 Torr. At a pressure of more than 100 Torr the blue and green jets are observed only near apex of the cathode (Fig. 1). At using the cathode made of a stainless steel the blue jets are observed at a pressure more than 100 Torr. It was supposed that observed jets are formed due to explosion of microinhomogeneity on the cathode surface and electro-erosion of metal. As the results a vapor of metal are formed.

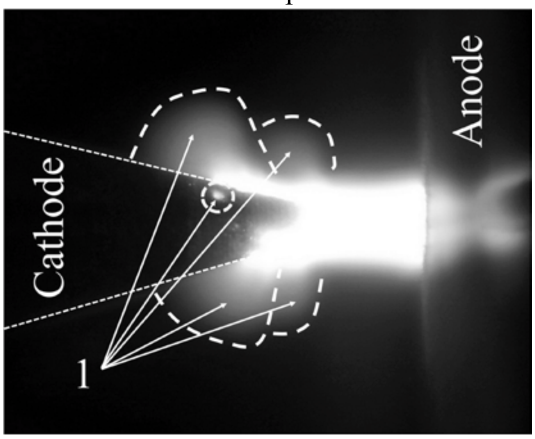

Fig. 1. Image of discharge in nitrogen at pressure of 200 Torr. Interelectrode distance is 2 mm. 1 – green jets. The exposure time is 1s

Spectral investigation have shown that green and blue color of jets is determined by radiation of atoms and ions of metal. It was registered radiation of intense line of AlI at a wavelength of 394.4 and 396.15 nm (upper level $3s^24s$ $^2S_{1/2}$ (3.14 eV) is common and lower level is $3s^23p$ $^2P^0_{1/2}$ (0 eV) и $3s^23p$ $^2P^0_{3/2}$ (0.014 eV) respectively [1]), as well as lines of CuI at wavelength of 510.55 nm (upper level is $3d^{10}4p$ $^2P^0_{3/2}$ (3.81 eV) and lower level is $3d^94s^2$ $^2D_{5/2}$ (1.39 eV) respectively [1]), 515.32, 521.8 nm (upper level $3d^{10}4d$ $^2D_{3/2}$ (6.19 eV) is common and lower level is $3d^{10}4p$ $^2P^0_{1/2}$ (3.79 eV) and $3d^{10}4p$ $^2P^0_{3/2}$ (3.82 eV) respectively [1]) and several hundred lines of FeI and FeII.

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[1] The work is performed in the framework of the Russian Science Foundation (the project #14-29-00052).

ON PLASMA JET FORMATION IN VACUUM ARC WITH COMPOSITE CATHODE[1]

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It is known [1] that ion angular distributions in the plasma jet of vacuum arc are different for the various ion species and ion charge states. In addition, the angular distribution of ions in the plasma arc with a pure (single component) cathode differs from the angular distribution for the same type of ions in an arc with a composite cathode [1].

The dependence of the angular distribution from the charge of the ion can be explained by the inhomogeneous distribution of electron temperature in the region of strong ionization in the vicinity of the cathode spot [2]. However, the dependence of the angular distribution on the composition of the cathode is difficult to explain as well. It is assumed that the angular distribution of ions in the plasma arc is formed under the influence of the mixing of the plasma jets from the individual cathode spots in the cathode group-spot. In order to study the mechanism of jet mixing a computer model based on hybrid model [3] was developed (Fig. 1). The calculations showed that some part of ions in the area of jet mixing acquires additional chaotic energy. This energy can be spent for widening of the common plasma jet in the area of low plasma density where ion-ion interaction is not able to equalize the velocities of ions of different types.

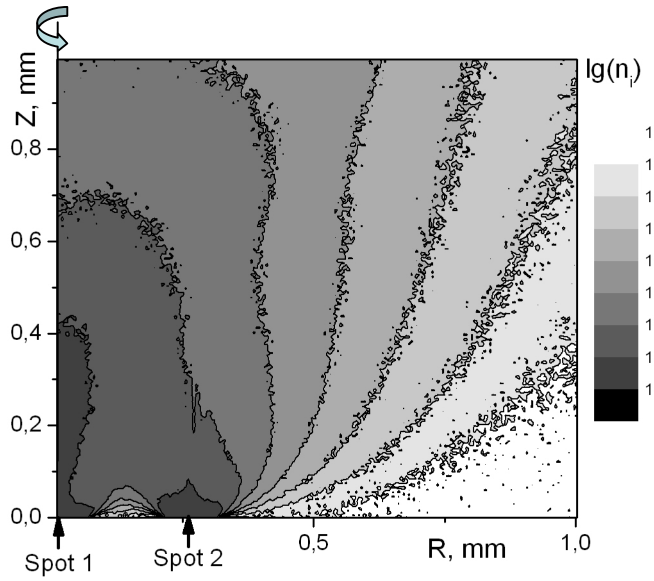

Fig. 1. An example of quasistationary ion density distribution in the case of mixing of jets coming from sopt1 and ring-shaped spot2, that mimic the group-spot; [density] – cm^{-3}, total current 500 A.

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NUMERICAL SIMULATION OF THE PLASMA LAYER NEAR THE CATHODE SPOT[1]

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The present paper is devoted to the kinetic (PIC MC) numerical simulation of the narrow near-cathode plasma layers in the vicinity of the vacuum arc cathode spot [1]. Theoretical researches of the cathode spots ([1]-[2] for example) have shown that two types of the self-sustained cathode spots are possible on the clean metal surface. The first type is so-called (0)-mode (in G. Ecker notation [2]), which is characterized by the surface temperature in the range of 3000–4000 K and the current density in the range of 10^5 - 10^6 A/cm2 ([2], [3]). This is a quasistationary mode. The most powerful energy source in this case is the ion flux from the plasma to the cathode. The second type of the cathode spot ((1)-mode by G. Ecker [2]) is the explosive nonstationary mode [1], which has typical current density more then 10^8 A/cm^2. The most powerful energy source in this case is the joule heating of subsurface metal layers.

Computer simulations made in the present work have shown that the additional heat source should play very important role when the current density is about 10^8 A/cm^2. This heat source is the electron back flux from the plasma to the cathode. The heat source increases with the surface temperature increase. This temperature dependence of the heat source leads to the developing of thermal instability. Thus, from this viewpoint, the cathode spots also should be nonstationary spots. This instability starts to develop at the current density, which is close to the current density of the joule thermal runaway. However, the new heating mechanism can significantly modify the timeline of the nonstationary cathode spot.

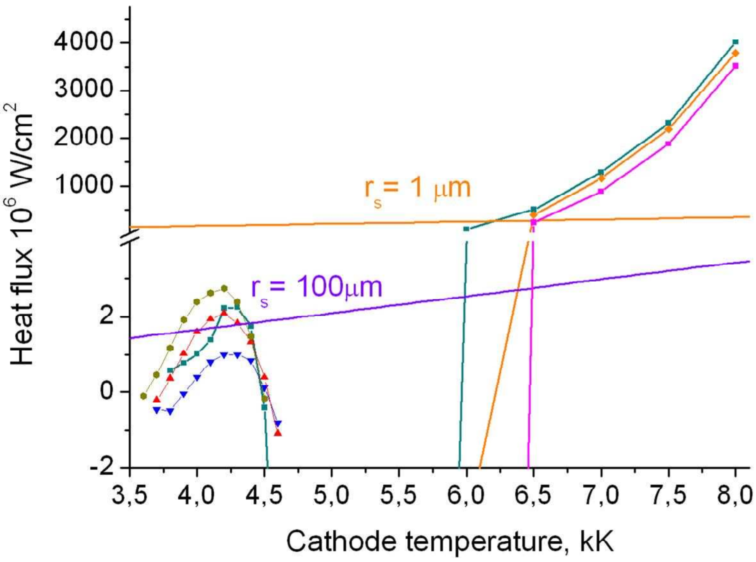

Fig. 1. Heat flux from plasma to cathode vs the cathode temperature. Dot+line – calculated heat flux for three different applied voltage: 15, 20 and 25 V; lines – necessary heat flux to support stationary temperature of spot with given radius on metal surface.

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SUPERSHORT AVALANCHE ELECTRON BEAMS AND X-RAY IN SF_6[1]

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In this work, the generation of a supershort avalanche electron beam (SAEB) and X-ray in SF_6 in an inhomogeneous electric field is studied on two generators with pulse rise times of 0.5 and 2 ns. The SAEB parameters in SF_6 are compared with those obtained in other gases (argon, air, nitrogen, and krypton), see also [1]. In the case of negative polarity of voltage pulse, a diffuse discharge in SF_6 was formed at pressures ranged from 0.05–0.2 MPa. Bright spots were only visible at the electrode with small curvature radius (tubular electrode). Figure 1 shows the waveforms of voltage pulses, current through gap and runaway electron beam behind foil (SAEB).

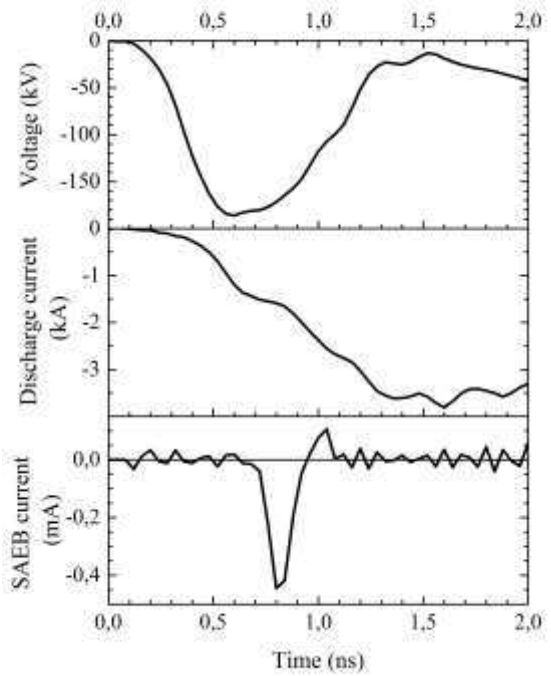

Fig. 1. Waveforms of voltage pulses (a), current through gap (b) and runaway electron beam behind foil (SAEB) (c). d = 13 mm. Pressure of SF_6: 0.05 MPa.

The waveforms were the average for approximately 30 pulses. All waveforms were synchronized in time with an accuracy of no longer than 0.2 ns. The SAEB was detected during the rise time of both the voltage pulse and discharge current. Similar sets of waveforms were obtained in SF_6 at other different pressures as well as in other gases and gas mixtures.

It is shown that the SAEB amplitude in SF_6 at pressures range from 0.05 to 0.2 MPa is commensurable with that in krypton and is much lower than that in air and nitrogen. It is found that in SF_6, SF_6 mixture with 2.5 % of nitrogen, and other gases, a runaway electrons preionized diffuse discharge (REP DD) is ignited not only at negative polarity but also at positive polarity of the electrode of small curvature radius. Furthermore, the velocity of the ionization wave front in SF_6 in an inhomogeneous electric field is studied. Experimental results show that the velocity of the ionization wave front in SF_6 is lower than that in air and nitrogen as well as such velocity decreases when the pressure increases from 0.05 to 0.3 MPa in all gases.

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BEAM PLASMA GENERATED IN DIELECTRIC HOLLOW: EXPERIMENTS AND SIMULATION[1]

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Fore-vacuum electron sources [1] have been employed successfully for such applications as electron beam welding of ceramics, modification the surface properties of non-conductive materials [2] and beam-produced metal and gaseous plasma generation [3]. The generation of electron beam-produced plasma inside the dielectric hollow is of considerable interest for plasma chemistry and sterilization purposes. The goal of this research is to show the possibility of beam plasma generation inside the dielectric cavity, present some special features of such plasmas, and to explain them using simulation. The experimental apparatus is shown in Fig. 1.

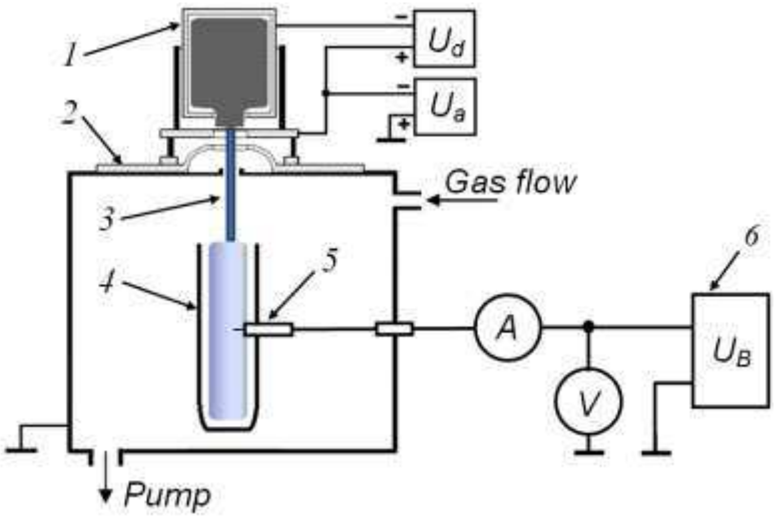

Fig. 1: Experimental apparatus: 1 – fore-vacuum plasma electron source, 2 – vacuum chamber, 3 – electron beam, 4 – dielectric cavity, 5 – Langmuir probe, 6 – probe bias voltage supply U_B. Ud, U_a – discharge and accelerating voltages power supplies, respectively.

.It is found that the density and electron temperature of beam plasma generated in dielectric hollow is greater than for the open beam plasma. As the test experiment, the hollow dielectric tube was replaced by floating metal cavity. It is observed that when the metal cavity was floated, the beam plasma parameters were nearly the same as in the quartz hollow, while when it was grounded, plasma parameters were similar to the case of open beam plasma. The balance model including secondary electron emission from cavity's surface and equations of energy balance, current continuity, ion balance and quasineutrality of plasma inside the cavity is proposed to explain the observed phenomena. Simulation shows the good agreement with experimental results.

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ELECTRODYNAMIC CHARACTERISTICS OF DUSTY PLASMA OF HIGH FREQUENCY TORCH DISCHARGE[1]

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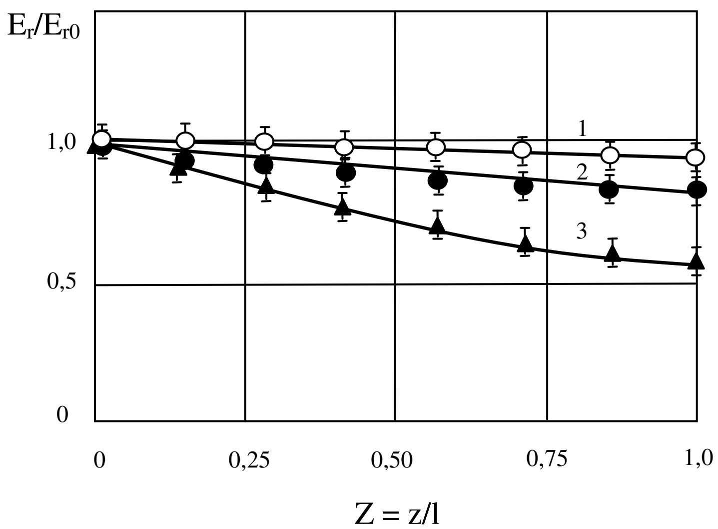
High-frequency torch discharge combustion proceeds due to [1] the dissipation of electromagnetic wave energy. Therefore, characteristics of the discharge are determined by characteristics of its electromagnetic field. When using a high-frequency torch discharge for practical purposes one needs to determine its characteristics providing that condensed phase is present in the discharge plasma.

In the present article we have determined the characteristics of the electromagnetic field of a dusty torch discharge burning in air. The discharge was dusty with dielectric and conductive materials using a pneumatic batcher. The dispersibility of the powders that were used equaled 30-50 microns. Characteristics of the electromagnetic field were measured by capacitive and inductive probes moving along the axis of the discharge.

An increase in electromagnetic field attenuation along the axis of the discharge dusty with a conductive material has been detected as a result of measurements. When the discharge was dusty with a dielectric material, electromagnetic field attenuation was insignificant. Typical axial distribution of the amplitude of the radial component of the torch discharge electric field is shown in fig.1. The axial coordinate is presented in the units of discharge filament (1) length.



The axial distribution of the electric field radial component of the torch discharge, burning in the air
1 - without the condensed phase; 2 - dielectric material; 3 - conducting material

We have also conducted measurements of the wavenumber for an electromagnetic wave propagating through the plasma of a dusty torch discharge. The measurements were made by comparing theoretical profiles of radial distribution of the radial component of the electric field with experimental data. It has been proved that the wavelength decreases if the discharge is covered in dust with a conductive material.

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THE STUDY OF THE ELECTRIC FIELD ARC COLUMN IN THE CHANNEL AC ARC PLASMA TORCH

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IPE RAS has created AC plasma generators for air and mixture of water steam with various gases for use in advanced plasma-chemical processes [1-3]. One of the most important features of this type of plasma torches is burning electrical arc outside the electric discharge chamber of the plasma torch in the flooded area of the internal volume of plasma chemical reactor. The lengths of electrical arcs in plasma such type may be up to 200cm. In this throughout the arcing from electrode to another electrode changes the mode of heat transfer of arc with environment and the modes of arc stabilization by gas flows. It leads to a change in electric field intensity.

This paper presents the study results of changes in the electrical field in the arc column of AC high voltage plasma torch using an adapted method of probe measurements.

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CHARACTERISTICS OF THE PULSED QUASI-STATIONARY NON-SELF-SUSTAINED GAS DISCHARGE WITH HOT FILAMENT CATHODE

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Electrode system and the basic characteristics (pulse shape and amplitude of the current and the discharge voltage, etc.) of non-self-sustained gas discharge with hot filament cathode when it functioned in a repetitively pulsed mode at a frequency of the voltage pulses and the discharge current of 5 kHz and pulse width of 50 µs are presented. Revealed that the pulse shape of the quasi-stationary discharge can develop high value of its pulse discharge current (300 A) at low (less than 20 V) average voltage of discharge burning. This result shows a high efficiency of the plasma generator operating in this mode, and will increase the continuous service time thermionic cathode filament and of the plasma generator as a whole.

AIRFLOW EFFECT ON DBD UNIFORMITY IN ATMOSPHERIC AIR

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The study of a gas flow effect on the dielectric barrier discharge (DBD) homogeneity was conducted on a base of comparison of the DBD emission brightness in a cross section of a discharge gap (DG) with the reference curve brightness distribution of the homogeneous isotropic radiation, obtained taking into account electrodes shape [1]. The pulsed DBD was realized in a 2 mm air gap under atmospheric pressure between two round-cross-section electrodes, one of which was covered with 2 mm-plate of alumina ceramics [2].

Waveforms of the voltage applied to the electrodes with frequency of 30 Hz (V_{in}) and corresponding discharge currents (I) for two cases: with airflow (3,6 l/min, dotted lines) and without it (solid lines) are presented in figure 1.

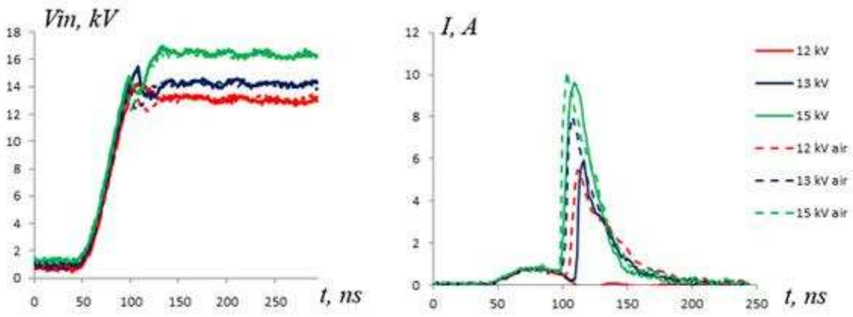

Fig. 1. Waveforms of the voltage applied to the electrodes of the DG and corresponding current discharge pulses for two cases: with airflow (dotted line) and without it (solid line) at different voltage amplitudes of DC power supply [2], 2 mm–air gap, P = 1 atm.

The waveforms show that the discharge is initiated at lower voltages when using airflow. The amplitudes of the discharge currents are higher in this case either. However at 15 kV discharge currents are almost the same, but the emission of the DBD is different. Figure 2 shows the brightness distributions of the DBD in a cross section of the DG at two voltage amplitudes 13 kV and 15 kV with the use of gas flow and without it and the reference brightness normalized curves *l(ai)*, imposed on them.

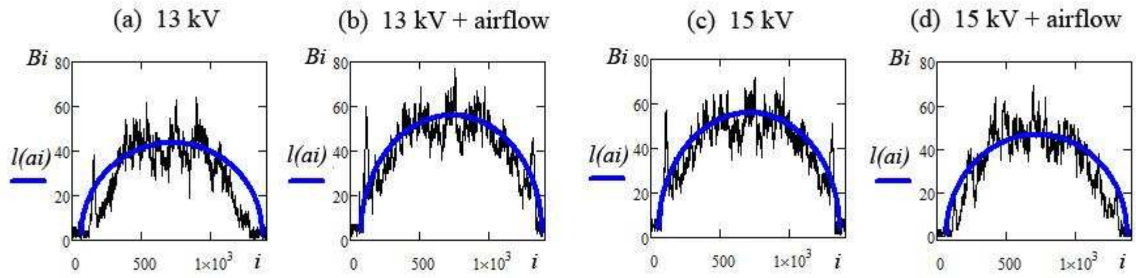

Fig. 2. Distributions of DBD emission brightness in a central layer (10 μm) of the DG cross section. 2 mm air gap, P = 1 atm.

The voltage of 13 kV is a "borderline" for the existence of the DBD without airflow, as evidenced by incomplete filling the DG (fig. 2a). At 13 kV despite the similarity of the DBD brightness distribution with the reference line, there are some obvious peaks on the DBD brightness curves, even in the case of the air flow discharge (fig. 2b). At 15 kV the DBD is stable for any case, but the airflow discharge is more homogeneous (fig. 2d). There are visible filaments on the edges of the distribution of the DBD emission brightness without airflow (fig. 2c).

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A STUDY OF HIGH-FREQUENCY CURRENT PULSATIONS IN THE GAS DISCHARGE WITH CONTACT TO LIQUID ELECTROLYTE

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History of electric discharges in contact with the liquid, has more than a hundred years. However, despite the long history and sufficiently extensive use of in applied problems, they have been studied to date not fully, especially in small spatial and temporal intervals. One of the properties that appear in minor intervals is the presence of high-frequency current pulsations. They are fixed at currents that make up the hundreds of milliamps or more [1,2].

In this work experimentally investigated electrical discharges in atmospheric pressure between the liquid electrolyte and metal electrodes in different combinations and in various embodiments the polarity of their connection to the power supply. The studies were carried out using a digital oscilloscope AKIP-15/1 with a bandwidth of 25 MHz. Analysis of current oscillations was carried out using the fast Fourier transform of the same oscilloscope in the megahertz frequency range. Signal to register the discharge current was voltage drop across the shunt resistance of 0,01 Ω. It is revealed that the emergence of high-frequency current pulsations is accompanied by phenomena of dispersion and erosion of the electrodes.

The presence of sputtering and erosion of the electrodes was determined by visual characteristics, and emission spectrum. Record of the spectrum of the radiation was carried out on fiber-optic spectrometer AvaSpec-3648 in the visible range. For example, in the case of copper cathode on the origin of the erosion process indicated the following factors. First, on the surface of the cathode remained traces of erosion. Secondly, in the plasma column was observed green luminescence characteristic of the vapors of copper, and, thirdly, in the emission spectrum of the gas discharge was recorded spectral lines of an atom of copper.

As the liquid electrolyte used was a solution of sodium chloride in distilled water. Its electrical conductivity was 10 mS/cm. Feature of liquid-phase electrode was the fact that the frequency spectrum of the signals from the discharge current is abruptly changed when changing the polarity of the electrolytic electrode. In combination electrodes "liquid electrolyte - hafnium" when feeding the electrolyte positive potential, current pulsations were so weakened that they become virtually indistinguishable from the noise signals.

Experiments have shown that the spraying liquid electrolyte cathode is enhanced at higher discharge currents. Visualization of the sputtering process promoted the use of electrolytes with lower specific electric conductivity. The influence of these factors on the sputtering process is shown on instant photography discharge. At their favorable combination of the photographs clearly highlighted in yellow "bubbles" that are likely to represent a spherical formations, formed as a result of falling droplets of electrolyte in the discharge gap.

Based on the obtained experimental data, in the study assumes that the main cause of the high-frequency current pulsations in electric discharges in contact with liquid electrolytes, is the spraying of the electrolyte and the entry of droplets in the discharge region. As a result, abrupt thermal degradation of liquid droplets of electrolyte are released in a large number of ions, which leads to a local increase in concentration of charge carriers. Therefore, occur quick-variable fluctuations of the electric conductivity of the interelectrode space and formed current pulsations with different frequencies and amplitudes.

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LOW-CURRENT ELECTRIC ARC IN THE OPEN AIR BETWEEN THE END OF THE CATHODE AND LONG VERTICAL ANODE

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The first experiments, by results of which formed the term "electric arc", were made more than two hundred years ago (Petrov, Davy and Ritter) [1,2]. To date, an open electric arc in the high-current combustion mode is studied in sufficient detail. Low-current modes of combustion remain almost unnoticed.

In this work, we investigate the properties of an electric arc in the open air at currents less than 1 A. Rod cathode is mounted horizontal. The anode is cylindrical rods and flat plates. They were installed either vertically or with a certain angle opposite end of the cathode. Under the influence of buoyancy force, discharge channel was stretched upwards. In this case, the reference point to the anode was also raised. Lengthening the discharge channel has led to increased stresses. Since the output voltage of the power supply was constant, the discharge current decreases. With the increase of the distance l between the end of the cathode and the anode of the discharge goes into a pulsating mode. Oscillograms of the current and voltage characteristic of this mode are shown in Fig.

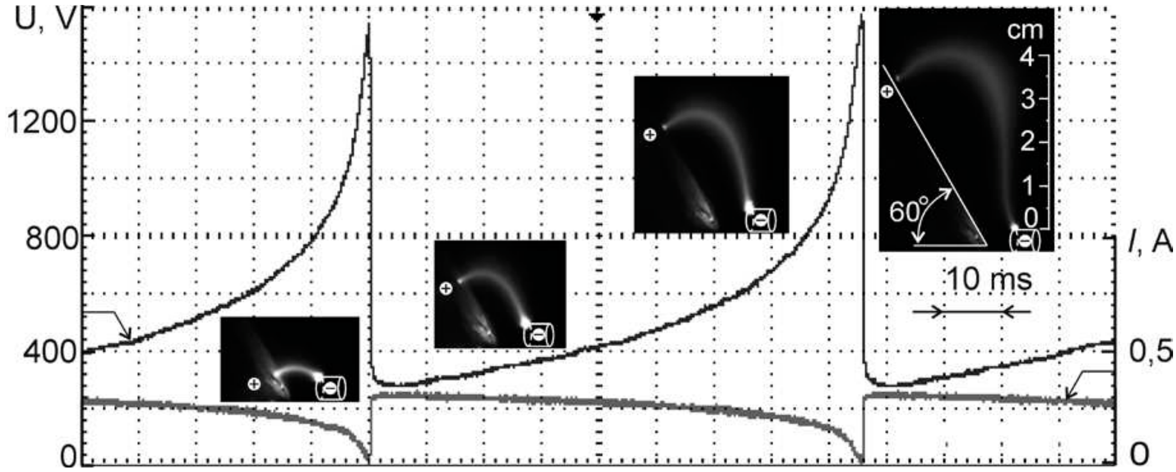

Fig. Oscillograms of voltage and current. Cathode – hafnium, anode - copper plate, the inclination angle of 60 °. l = 6 mm.

The geometry of the discharge has been studied for an instant photographs taken high-speed camera. The discharge was pronounced channel as a thin cord with aureole. The length of the discharge channel reaches up to 10 cm.

As shown by the experiments, the occurrence of a pulsating mode depends on the parameters l and I. The critical value of l, which is corresponding to the pulsating mode, increased after increasing I. For example, at I = 0,2 A (maximum value) it was 6-7 mm, and at I = 0,7 A are 10-11 mm. The pulsating mode occurs when currents of more than 0,2 A. When l is less than 4 mm discharge burning in the horizontal direction and the movement of the anode spot was not observed. The height of the anode spot and the amplitude of its movements in pulsating combustion mode increased with increasing current.

The peculiarity of these discharges is that the electric field strength it is much higher than in the high-current open arc. In the pulsated mode it exceeds 100 V/cm, whereas in the open carbon arc at I = 200 A is in the range of 10-20 V/cm, at comparable values of l (in the range 3-10 mm) [2].

In practice, the combustion mode with regular self-oscillation can be used in surface modification processes, and other solid metal conductors, in particular graphite.

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BENDING OF A PATHS OF A CATHODE STREAMER AND SPARK LEADER IN RUNAWAY ELECTRON PREIONIZED DIFFUSE DISCHARGES [1]

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Currently, increased attention is paid to the study of streamer breakdown of the dense gases [1-5]. Most recently, it was reported that a positive streamer could propagate at a near right angle to background electric field lines along the trace of enhanced preionization created by a KrF excimer laser [6]. In the study cited, the pulses produced by the laser had a wavelength of 248 nm and a pulse energy of ~1 mJ with a pulse duration of ~20 ns and the maximum repetition frequency of 10 Hz. The laser beam was shaped by four shutters to a quasi-rectangular beam. This beam propagated through a vacuum chamber filled with different nitrogen–oxygen mixtures with a tip electrode positioned 103 mm from the cathode plane. The laser beam was aligned to the symmetry plane, which included the electrode tip. The ionization density was about 8×10^8 cm $^{-3}$ in pure nitrogen at 0.1 MPa for the laser operated at full power, and it was too low to modify the electric field. Numerical simulation that presented in Ebert's work confirmed experimental observation [6].

Preionization can also be provided by runaway electrons (RAEs). The RAEs are more likely to be generated in a discharge gap when a high-voltage-nanosecond-pulse is applied to an electrode with a small radius of curvature. Moreover, X-ray radiation would appear due to both collisions between RAEs and gas molecules, and bremsstrahlung between the dense plasma front and the metal foil. Therefore, the gas in the gap is preionized by RAEs and X-rays, resulting in the appearance of a runaway-electron-preionized diffuse discharge. However, it can be transformed to a spark. Therefore, a positive streamer and cathode-directed spark leader may be produced in the preionized gap. We suppose that at these conditions, a positive streamer could also propagate nearly perpendicular to the background electric field. Therefore, the objective of our study is to investigate the formation of a positive streamer and cathode-directed spark leader in a runaway-electron-preionized diffuse discharge to confirm the existence of their bent paths in this type of discharge.

The experimental setup used in the experiment was described in [7]. The pressure of air or sulfur hexafluoride ranged from 0.02 MPa to 0.25 MPa. The grounded plane electrode was at a distance of 13 or 16 mm from the potential tubular electrode, made of a stainless steel foil of thickness 100 μm. Experiments were performed in a single pulse mode at positive and negative polarities of the RADAN-220 pulser.

Typical discharge images of the runaway-electron-preionized diffuse discharge taken in our experiments reveal that a positive streamer and cathode-directed spark leader can propagate at an angle to the background electric field lines. It could be explained by the nonsimultaneous and inhomogeneous increase in electron density during the runaway-electron-preionized diffuse discharge formation. The increase rates of the electron density are different in different regions of the discharge volume preionized by RAEs and X-rays. Thus, an electron density gradient arises in the discharge plasma, resulting in an electrical field component whose direction differs from that of the background electric field and bent paths of the positive streamer and cathode-directed spark leader. However, such phenomenon is observed only in part of the pulses (about 5%–50% of the total number of pulses in a 16-mm air gap at a pressure of 0.08–0.1 MPa).

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RESEARCH OF SPIRAL FORM OF ARC POST OF HIGH-FREQUENCY ARC DISCHARGE

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At research of high-frequency (HF) arc discharge it was educed in a stabilizing channel, that like the arcs of direct-current, a discharge can exist in two forms: as a direct cylindrical arc post (CAP) and spiral arc post (SAP).

Study in a number of works [1-3] spiral form of arcs of direct-current showed that principal reason resulting in a spiral is "current is convection instability". Presence of such factors as high pressure, and considerable charges gas, the large diameter of the stabilizing channel, as compared to the diameter of discharge, facilitates a transition to SAP.

For HF arc discharge, in the investigational in hired range of the modes of operations of arc discharge and geometrical parameters of plasma generator, the basic form of existence was a spiral form of arc.

Discharge in form CAP it was succeeded to investigate only in the special construction of plasma generator with rotating discharge tube for the case without the expense of gas arc. Thus, HF an arc in a cylindrical form existed only at the small currents of discharge, to 0,9-1 A. At the increase of current of discharge HF an arc passed to the brightly expressed spiral form.

The border value of current at that there is a transition HF arcs to the spiral form appeared below, than for the arcs of direct-current. In [1] the border value of current was certain for different gases depending on the charges of gas and diameter of discharge tube. For nitrogen in case of arc without the expense of gas of value of border current lie within the limits of 5-10 A. Thus, border of stability HF arcs to spiral indignations appeared in 5-10 times less than, than for the arcs of direct-current.

Because HF an arc discharge in case of arc without the expense of gas was in immobile gas in absence external magnetic-field, then transition from the form of CAP to SAP, at the increase of current confirmed, what for HF arcs "current is convection instability" is characteristic.

The analysis of foto got with SAP allowed to estimate the sizes of spiral arc discharge. For without the expense of gas HF arc discharge in mid air at pressure equal to atmospheric ($p = 10^5$Pa) and diameter of discharge tube of $17 \cdot 10^{-3}$m it is got, that a diameter of spiral of $d_B = (12 \pm 1) \cdot 10^{-3}$m and step of spiral of $a_в = (0,1 \pm 0,025)$m.

Substantial influences on parameters SAP a turbulent gas stream, at flowing of gas stream through the post of arc. In order of effect these influences are comparable with forces defiant "current is convection instability". The united action over of a turbulent gas stream and spiral instability is brought to considerable fluctuations of parameters of SAP: diameter of spiral of d_B and step of spiral of $a_в$.

The middle parameters of SAP for the range of changes of the modes of discharge and their the maximum possible deviation. The mean values of parameters of discharge were certain on results 63 experiments, for HF arcs in a tube long L=0,3m and by the internal diameter of $2R = 17 \cdot 10^{-3}$m. The measured value of diameter of spiral, for the indicated range of the modes, made $d_B = (4,8 \pm 1,1) \cdot 10^{-3}$ m and step of spiral discharge - $a_в = (58,1 \pm 13,3) \cdot 10^{-3}$ m.

A diameter of discharge for the same range of the modes of operations of discharge and indicated geometry of plasma generator $d_p = (2,6 \pm 0,5) \cdot 10^{-3}$ m.

Coming from the measured values of diameter of spiral, step of spiral and diameter of discharge, lengthening of discharge $\Delta L = (\pi \cdot d_B \cdot L)/a_в$ is expected. Putting the got values of d_B and $a_в$, and taking into account that length of discharge interval of L = 0,3 m, we will find $\Delta L \cong 0,08$ m. Lengthening of discharge rather significantly and at the calculation of tension of electric-field it is required to take into account in the discharge of him.

Study of distribution of parameters of SAP along an axis HF arc discharge showed that their establishment took place in the distance 1 -1,5 diameters of discharge channel from a central electrode. In future, at a movement along the axis of discharge, the middle parameters of spiral form of discharge are saved. This circumstance was taken into account at measuring of temperatures in the sections of discharge and at establishment of homogeneity of dissipation of electric power on length of post HF arcs.

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A THEORETICAL STUDY OF SPECTRAL LINE INTENSITIES OF THE HE ATOM IN AN ALTERNATING CIRCULAR ELECTRIC FIELD[1]

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A study of atomic emission spectra excited by alternating electric fields is necessary for solving problems of plasma physics. Spectroscopic methods are very efficient in the determination of plasma parameters, such as ion and electron temperatures, plasma density and the electric field strength into a discharge. To estimate plasma parameters from emission spectra, one needs to calculate the positions of the Stark components of spectral lines, transition probabilities between the Stark states, the intensities of the Stark components of spectral lines and their profiles. In order to calculate all of these spectroscopic characteristics of atoms in the electric field, it is necessary to use a reliable and efficient calculation method. Non-stationary perturbation theory, by virtue of its limitations, is unsuitable for calculating spectra emitted by low-temperature plasma.

In this work, the method of the energy matrix diagonalization of an atom in the electric field [1] was used for calculating the helium emission spectrum. This method is free from limitations of perturbation theory and suitable for calculating emission spectra of atoms and ions in an alternating electric field with the strength and frequency changing in a wide range. All computations were performed for the case of an alternating circularly polarized electric field. Electric fields of such polarization are generated in an inductive high-frequency discharge, in plasma of current sheets, light-emitting diodes and so on.

It is known, the intensities of the Stark components of spectral lines are calculated using the formula

$$I(JM \to J'M') = N_{JM} A(JM \to J'M')\omega_{JM,J'M'}\,, \tag{1}$$

where N_{JM} is the population of the magnetic sublevel JM, and $\omega_{JM,J'M'}$ is the frequency of the transition between the Stark states JM and $J'M'$. In the framework of our theoretical approach, $\omega_{JM,J'M'}$ is determined by diagonalization of the energy matrix of an atom in the electric field, and spontaneous transition probabilities between the Stark states JM and $J'M'$ are calculated using the formula

$$A(JM \to J'M') = \frac{4\omega^3_{JM,J'M'}}{3c^3}\sum_q \left|\sum_{ij} C_i^{(JM)*} C_j^{(J'M')} (-1)^{J_i - M_i} \begin{pmatrix} J_i & 1 & J_j \\ -M_i & q & M_j \end{pmatrix} < \gamma_i J_i \| D \| \gamma_j J_j > \right|^2 \tag{2}$$

It should be noted, in the case of low-temperature plasma, magnetic sublevels can be considered as uniformly populated ones. It means that the intensities of the Stark components, and, consequently, spectral line intensities are specified only by the transition frequencies $\omega_{JM,J'M'}$ and spontaneous transition probabilities $A(JM \to J'M')$, calculated by the method of the energy matrix diagonalization of an atom in the electric field. Our calculation results have shown that in the case of weak interaction of the Stark states, an increase in the electric field strength leads to decreasing spectral line intensities of the helium atom, and spectral lines remains sufficiently narrow. If interaction of the Stark states is strong, the intensities of spectral lines can increase with the electric field strength, and these lines have noticeable Stark broadening. The dependence of spectral line intensities on the electric field frequency has more complicated character owing to the presence of resonance-like effects in the behavior of Stark components under the change in the electric field frequency. These effects appear owing to the Stark state interactions in the electric field.

The calculated results have allowed us to reveal the reasons for changing the intensity of atomic spectral lines in the electric field. First of all, the results obtained are of interest from the theoretical viewpoint. In addition, they can be used in practical applications, in particular, for diagnostics of laboratory and space plasma. Finally, our results can be useful in technologies of construction of new radiation sources.

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MODELING OF PULSED PLASMA MOVEMENT IN CONICAL INDUCTOR

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Induction vapor and gas ionizers are often used in the art of physical vapor deposition (PVD) of coatings in order to generate so called inductively-couples plasma. The plasma species are employed for evaporation by heating or sputtering of raw coating materials, for ion-kinetic assistance of forming the desired coating microstructures and providing chemical reactions for synthesis of complex coating compositions, for thermal effect on the substrates and cleaning the substrates prior to coating deposition. In recent years, pulse modes of plasma generation and ion impact on coating growth are of great interest because pulse modes expand the ranges of possible operation parameters, substrate materials and coatings.

After the excitation of current oscillations in the inductor, the plasma is generated within the inductor coil and plasma species move towards the surrounding walls and the substrate. Accordingly, the substrate ion current has the form of a pulse whose the face front is shifted in time relatively to the inductor current pulse. Fig. 1 depicts the example of dependences of the velocity of Al vapor plasma boundary movement in the substrate direction on the inductor current oscillation frequency *f* for two inductor voltage pulse amplitude values. Experimental curves were obtained by measuring the ion current pulse face front delays on Langmuir probes located at different distances from the inductor. The velocity is $(0,5 - 2,5)\times 10^4$ m/s. It can be assumed that the delay time of the ion current pulse is inversely proportional to the average velocity of the plasma boundary.

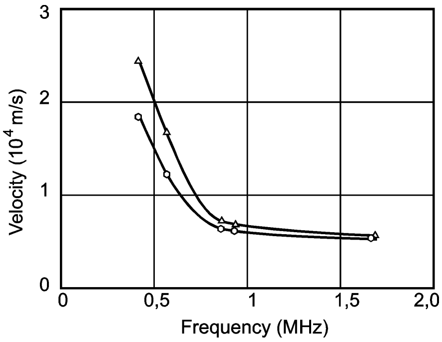

Fig. 1. Dependence of Al plasma boundary velocity on inductor current frequency: inductor voltage amplitude – 2.5 kV (lower curve) and 3.5 kV (upper curve)

In this contribution we also solve the mathematical problem on the plasma movement in the pulsed electromagnetic field of the conical inductor in order to identify the characteristics of the plasma movement. The problem is solved in the hydrodynamic approximation. The following expression is obtained for the plasma boundary velocity *V*:

$$V \approx \frac{\mu_0 e^2 \sin 2\Theta U^2}{32\pi m M R^2 L (2\pi f)^2} \frac{\nu}{\nu^2 + (2\pi f)^2},$$

where *e*, m – electron charge and mass, *M* – ion mass, μ_0 – magnetic constant, *R* – average inductor radius, *L* – inductor inductance, 2θ – vertex angle of the cone, ν – particle collision frequency. From the physical point of view, the plasma movement is due to the action of the radial component of the inductor magnetic field. When $\nu >> 2\pi f$, the extension plasma velocity *V* is directly proportional to the square of the inductor voltage amplitude and inversely proportional to the inductor current frequency. This is correlates with the experiments.

It is possible to calculate the probable Al ion energy ε of the directed movement within the plasma flow. When the velocity is 0.5×10^4 m/s, the energy ε is 3.5 eV; then at 1.0×10^4 m/s the ε value is 14 eV and at 2.5×10^4 m/s the ε value is 87.5 eV.

Thus, when the pulsed mode of inductor power supply is used, not only the generation of the ions of depositing material and working gas but also their acceleration towards the substrate can be obtained. This allows simplifying the coating apparatus with ion assisting.

THE EMISSION SPECTRUM OF THE RADIATION KR_2F AND KRF MOLECULES IN THE DISCHARGE PLASMA OF EXCIMER LASER[1]

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In this paper we present the results of experimental studies of the spectral composition of the discharge plasma in dense gases, including fluorides. For gas mixtures $Ne/Kr/F_2$ and $Ar/Kr/F_2$ experimentally studied emission transitions of excited molecules KrF* and Kr_2F*, emitting in the ultraviolet and visible spectral range. It is shown that with increasing content of Kr 10 to 400 mbar in the gas mixture increases the intensity of fluorescence molecules Kr_2F*. In excimer gas mixtures realized stable volume discharge during several periods of the pump current.

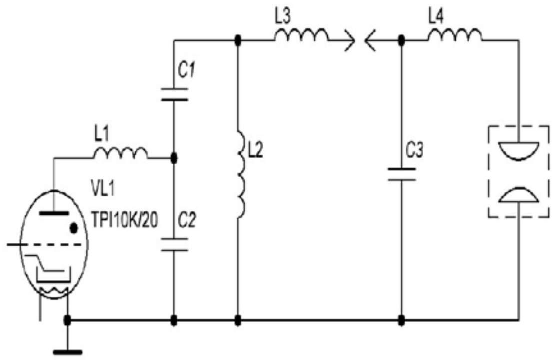

Fig.1. Schematic diagram of excitation circuit. C1= 80 nF, C2= 40 nF, C3= 22 nF, L1= 20 nH, L2= 0.15 mH, L3= 150 nH, L4 = 3 nH

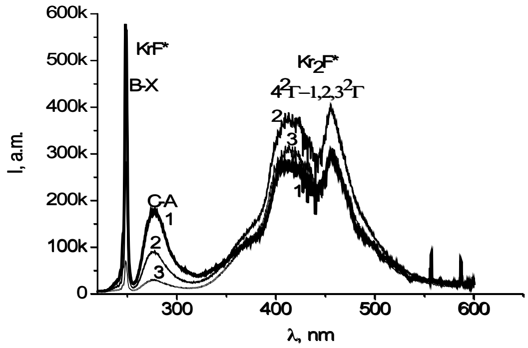

Fig. 2. The emission spectrum of the discharge. Mixture: Ar/Kr/F2 = 1000/400/1 mbar, P = 1.4 bar, U0 = 25 kV. The opening of the optical shutter for the time of discharge: 1– 0-50 ns; 2– 50-100 ns; 3–100-150 ns.

Generated plasma was pumped with generator based on a LC- inverter Fig. 1. Preionization of the discharge gap was carried out by UV - radiation that occurs at triggering spark gaps installed in the second loop of the circuit. Storage capacitors C1 and C2 and discharge capacitor C3 had the values of 100, 50 and 30 nF respectively. Thyratron TPI1-10k/20 was used as the commutator. The inductance of the first L2 and the second L3 discharge contours were 130 and 4 nH respectively. The length of the electrodes was 450 mm, the electrode gap - 25 mm. Electrodes were of cylindrical shape work surface with the radius of 60 mm. Figure 2 shows the emission spectrum of the discharge. Mixture: Ar/Kr/F2 = 1000/400/1 mbar, P = 1.4 bar, U_0 = 25 kV. The opening of the optical shutter for the time of discharge: 1– 0-50 ns; 2– 50-100 ns; 3–100-150 ns.

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INITIAL STAGES OF THE HIGH-CURRENT PULSED DISCHARGE IN SALINE SOLUTIONS[1]

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Last time a considerable interest has been generated in the direction that is associated with the pulsed electrical discharges in electrolyte or discharges in the saline solutions [1-3]. The low-current discharges are used in the so-called plasma scalpels in surgery , while the high-current discharges (the level of current up to several kiloamperes) are widely used in installations for underwater sound waves generation and so on [1-3].

There is the characteristic feature of the discharges in the electrolytes. In the initial stage, the gas cavities arise at the surface of active electrode. An increase in a voltage at the gap leads to the appearing a gas discharge plasma in the cavities. It was shown that the processes of the cavities and discharge formation and forms of the discharges burning have a significant effect on the character of the current flow in the electrolyte [1, 4]. This report focuses on investigation these processes in the high-current pulsed discharge.

Schematic of experimental arrangement is shown in figure 1. The discharge is sustained in the electrode system between active electrode *1* and the return electrode *2*. Diameter of the electrode *1* is 1.3 mm, l=8 mm, d=1 cm. The electrodes are placed in case *3* with saline solution (3 % NaCl). The case is equipped with the quartz windows that offer a possibility to take the discharge images and to obtain the time resolved waveforms of the discharge luminosity by means of photomultiplier. When the switch Sw was closed the voltage on the charged capacity C_0 was applied to the electrodes through the cable l_c. The voltage V_0 was up to 5 kV. The pulse duration and maximum current were approximately 2 ms and 4 kA. Current in the discharge gap was recorded using of the low-inductance shunt R_s and the oscilloscope Tektronix TDS 3032. Voltage at the gap was recorded between the point *A* and the electrode *2* using of probe P6139A.

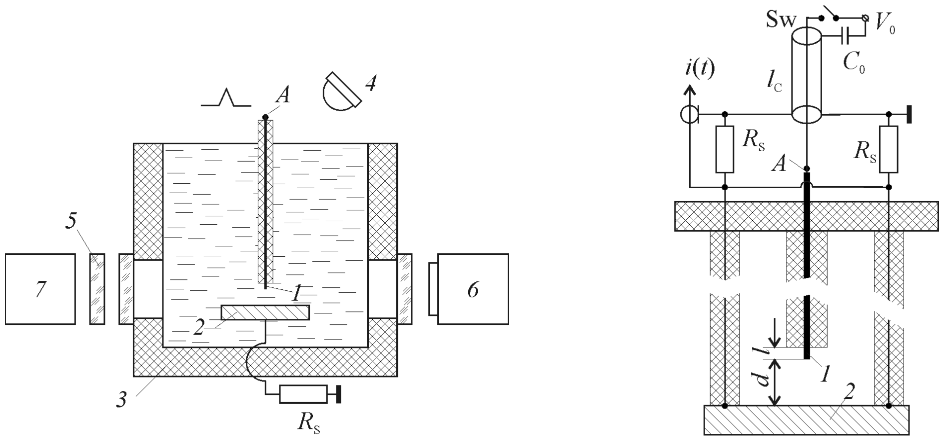

Fig. 1. Schematic of arrangement and sketch of electrode system: *1* – active electrode, *2* – return electrode, *3* – case, *4* – lighter, *5* – filter, *6* – camera, *7* – photomultiplier. C_0 = 40 μF, R_s = 0,01 Ω.

A set of experimental data to describe processes of the gas cavities and discharge formation was obtained. The mechanism of the gas discharge formation in the cavities is discussed. The forms of discharge combustion are analyzed.

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RECOVERY OF THE ELECTRIC STRENGTH IN A COLD CATHODE THYRATRON[1]

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The cold cathode thyratron (or the pseudospark switch) is considered as an advanced alternative to ignitrons and vacuum switches in facilities that require an extremely high current [1]. The triggering with a small jitter makes it possible to use the pseudospark switch instead of the classical thyratrons in the electric circuits with a fast current rise. In general, the principle of operation of the pseudospark switch resembles that for the classical thyratron. On the one hand, a usage of the cold cathode is quite definite advantage from the viewpoint of increasing the switching current [2, 3]. On the other hand, the problem of increasing the pulse repetition rate in the pseudospark switch is more severe than that in the thyratron with hot cathode.

The upper level of the pulse repetition rate in the switch is determined by the conditions when a characteristic recombination time for plasma in the gap becomes comparable with the time interval between the pulses. Then, residual plasma from a preceding discharge remains in the gap to the instant when a succeeding pulse arrives to the electrode thereby the pulsed breakdown voltage for the switch decreases [4].

One of the methods to enhance a limited value of the pulse repetition rate is based on the idea to extract the products of the preceding breakdown from the cathode cavity in the pause between the pulses. For this purpose a so-called blocking electrodes can be applicable [5]. These electrodes are intended to extract the electrons from the cathode cavity and to suppress the prebreakdown electron current in the main gap.

In this paper we investigate the method which allows extracting the plasma of the preceding discharge not only from the cathode cavity but also from the main gap of the switch (Fig. 1). Due to the voltage V_1 some current appears in the main gap and we are able to make diagnostics of this current in the pause between the pulses. On the one hand, this current is able to encourage a fast de-ionization of the gap. On the other hand, measuring the current allows us to judge of the process of de-ionization in the main gap.

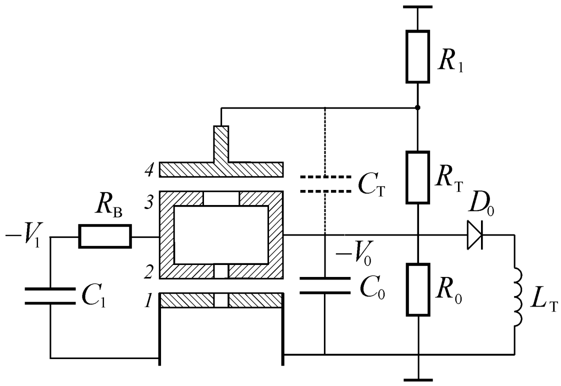

Fig. 1. Design of electrode system and electric circuit for investigation of recovery of the main gap. C_T is the spurious capacitance of the gap *3 – 4*; C_0 = 1 nF, R_0 = 70 kΩ, R_1 = 100 kΩ, R_B = 10 kΩ, R_T can be varied from 100 kΩ to $R_T = \infty$.

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EFFECT OF THE CATHODE EMISSIVITY ON THE REGIMES OF HOLLOW-CATHODE GLOW DISCHARGE[1]

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The pseudospark switch is considered as an advanced alternative to ignitrons and vacuum switches in facilities that require an extremely high current [1 – 4]. The principle of the switch operation resembles that of a classical thyratron with a grounded grid. However, in these type of switches a hot cathode is absent. Then the term “grounded-grid thyratron”, or the “cold cathode thyratron” is also used in the current literature [1, 5].

A range of operating pressures of the switch corresponds to the conditions of the left branch of the Paschen's curve when the electron free path for ionization is much in excess of the electrode separation. Under such conditions, the mechanism of the switch breakdown is not related to the development of classical electron avalanches that are initiated by single electrons. For both self-breakdown and external discharge triggering a considerable prebreakdown electron current is required to ignite a high current discharge in the main gap [1 – 4, 6]. For the external discharge triggering a prebreakdown current is provided due to a trigger unit, that is placed in the cathode cavity. The trigger unit is intended for generation of the trigger discharge plasma in the cathode cavity. The electron flow is extracted from this plasma in the main gap so that due to this electron current the main high current discharge is initiated [4].

Various types of trigger units are used in switch prototypes and the sealed-off switches [1, 5 – 7]. One of them is based on an auxiliary low-current hollow-cathode glow discharge. Conditions of the discharge burning are mainly determine the characteristics of the switch itself, particularly, breakdown voltage, jitter and pulse repetition rate. Therefore, the choice of the regime of an auxiliary discharge is of the great importance.

In this paper, the results of the investigations of effect of the cathode emissivity on the regimes of hollow-cathode glow discharge are presented. It is shown that the increase of the cathode emissivity due to the so-called high-emissivity tablet allow to essentially decrease discharge initiation and discharge burning voltages. The model of the current sustaining for the hollow-cathode discharge allowing some quantitative estimates has been developed. In the model, the generalized secondary emission coefficient that takes into account an external emission current is introduced. On basis of the model, the volt-ampere characteristics are interpreted. It is shown that the model is in a good agreement with the experiments.

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DIFFUSE AND SPARK DISCHAGES IN NONUNIFORM ELECTRIC FIELD AT PULSE REPETITION MODE AND THEIR INFLUENCE ON THE ANODE [1]

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The aim of the present work was to study the initial stages of the diffuse and spark discharge formation in the nonuniform electric field at the elevated and atmospheric pressures of air and nitrogen in a pulse-periodic mode by means of a CCD camera. The experiments were carried out in the conditions of generation of runaway electron beams and X-rays at the different voltage pulse rise-time and pulse repetition rate.

The experiments were carried out in a discharge chamber to which voltage pulses from two generators were applied via a cable. The NPG-15/2000N and FPG-60 high-voltage, pulse-periodic generators were used. The FPG-60 allowed forming the negative-polarity voltage pulses of the amplitude up to 60 kV, voltage rise time of ~2 ns and FWHM of 4-5 ns at a high-resistance load (1-10 kohm). The NPG-15/2000N generator has FWHM of the voltage pulse equal to ~6 ns at a matched load (75 ohm), the rise time at a level of 0.3–0.9 being ~2.5 ns. The NPG-15/2000N generator allowed forming the negative-polarity voltage pulses of the amplitude up to 35 kV and a repetition frequency of up to 3.5 kHz at a high-resistance load. In some experiments, a sharpening spark gap was installed between the generator NPG-15/2000N and the discharge chamber, due to which the duration of the voltage pulse rise time reduced to ~0.5 ns.

In the experiments, the amplitude of the incident voltage wave was usually equal to 10-20 kV. A sharp-edged cathode made in the form of a cone (No1) with an apex angle of 30° or a 6-mm-diameter tube (No2) with a wall thickness of 100 μm and a flat anode were used, see Fig. 1.

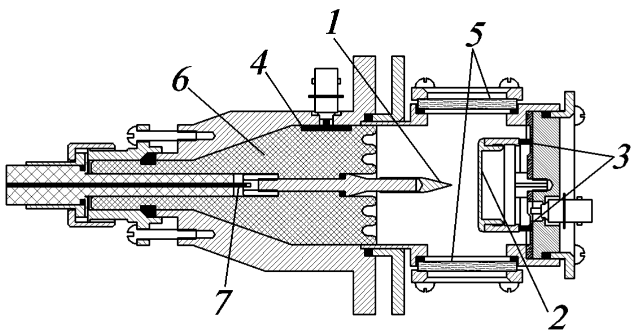

Fig. 1. Scheme of the working chamber: (*1*) cathode No1, (*2*) anode, (*3*) chip resistor shunt, (*4*) capacitive divider, (*5*) quartz windows, (*6*) insulator, and (*7*) high-voltage cable.

The voltage across the gap was measured with a capacitive divider while the discharge current was measured with a shunt connecting the anode with the chamber case. The interelectrode gap was 2-6 mm. The discharge was photographed with a HSFC-PRO four-channel CCD-camera. Due to the high (subnanosecond) timing accuracy of the pulse generator and CCD-camera, the photos of the gap glow during the first nanosecond after applying a voltage pulse to the gap were obtained as well.

The studies of a nanosecond discharge in air and nitrogen at elevated pressures have shown that at the negative polarity of the electrode with a small radius of curvature, the formation of the diffuse discharge takes no more than 1 ns. Under conditions of the above-described experiment, cathode spots can be formed during the time interval of ≤1 ns, see also [1]. After the bright spots appear on the cathode, the contracted channels propagation begins. Under the conditions of these experiments, at low pressures of air and nitrogen a supershort avalanche electron beam (SAEB) was recorded behind a thin-foil anode.

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PULSE-PERIODIC GENERATION OF X-RAY EMISSION AND SUPERSHORT AVALANCHE ELECTRON BEAMS IN NITROGEN [1]

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The aim of the present work was to study the supershort avalanche electron beam (SAEB) parameters and the X-ray exposure dose in the pulse-periodic mode of the discharge at different rise time of the voltage pulse, see also [1]. Information obtained in this study can be used to create pulse-periodic electron accelerators and X-ray sources with the subnanosecond pulse duration, as well as to better understand the formation mechanism of a diffuse discharge at elevated pressures. The second aim of this work was to detect SAEBs at the pulse repetition frequencies of higher than 1 kHz. This work continues the studies [2, 3], where SAEBs were obtained at the voltages of tens of kilovolts, helium pressure of ~100 Torr, and pulse repetition frequency of 1 kHz.

The experiments were carried out in a discharge chamber to which voltage pulses with the amplitude of up to 35 kV and repetition frequency of up to 3.5 kHz were supplied from an NPG_15/2000N generator via a 3-m-long cable. The FWHM of the voltage pulse at a matched load (75 Ω) was ~6 ns, the rise time at a level of 0.3-0.9 being ~2.5 ns. In some experiments, a sharpening spark gap was installed between the generator and the discharge chamber, due to which the rise time of the voltage pulse reduced to ~0.3 ns. Figure 1 shows the X-ray exposure dose as a function of the nitrogen pressure in the experiments with the sharpening spark gap.

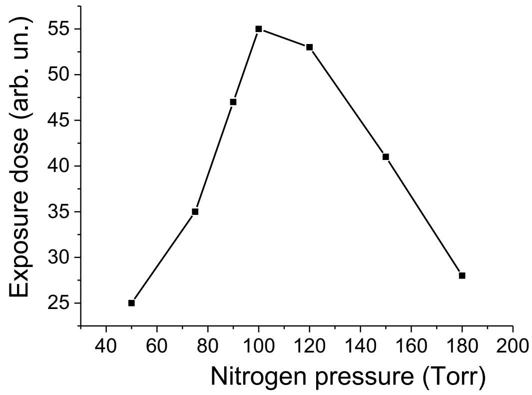

Fig. 1. X-ray exposure dose as a function of the nitrogen pressure in the experiments performed with the sharpening spark gap.

The exposure duration on the X-dosimeter for each point was 2 min at a repetition frequency of 500 Hz (6×10^4 pulses per point). The X-ray dose reached its maximum value at a nitrogen pressure of about 100 Torr. The SAEB amplitude at this pressure was half as large as that at a pressure of 40 Torr. The SAEB parameters depend in a complicated manner on the pulse repetition frequency, the pulse number, the operation time, and the amplitude and front duration of the voltage pulse. It is found that gas heating in the pulse-periodic mode can lead to increase of the number of runaway electrons in the e-beam by several times. At low energy depositions in the gas, SAEB generation was obtained at a pulse repetition frequency of 3.5 kHz. The largest number of SAEB electrons per pulse has been achieved at a repetition frequency of 3.5 kHz and generator voltage of 25 kV. The X-ray exposure dose in the pulse-periodic mode increases by more than one order of magnitude. It was stated that the SAEB duration depended on the decrease rate of the gap voltage and, in the pulse periodic mode, increases as compared to that of the single-pulse mode.

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SIMULATION OF THE CRATER AND LIQUID-METAL JET FORMATION ON THE CATHODE IN A VACUUM ARC[1]

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A microcrater is formed as a result of displacement of molten cathode metal from an explosive emission center (ecton) under the action of the pressure of the cathode spot plasma [1]. It is supposed [2-4] that the hydrodynamic processes occurring on the cathode play a key part in self-sustained operation of a vacuum arc. This is due to that the formation of liquid-metal jets and their subsequent explosion give rise to new explosive emission centers that ensure the operation of the cathode spot and of the discharge as a whole. In the present work, we simulate immediately the behavior of the molten metal during the crater formation and the initial stage of formation of liquid-metal jets, performing a self-consistent calculation of the molten metal area. To do this, a 2D axially symmetric hydrodynamic model has been developed which includes Navier–Stokes equations for an incompressible viscous fluid with a free surface and a heat conduction equation taking into account Joule heating and convective heat transfer. With the numerical model developed, we have investigated the space and time characteristics of the crater formation process depending on the current per cathode spot cell. The example of modelling of considered processes is presented in Fig. 1. Based of the simulation results, we can distinguish three different modes of the crater formation process: “no splashing”, “inertial splashing”, and “active splashing”.

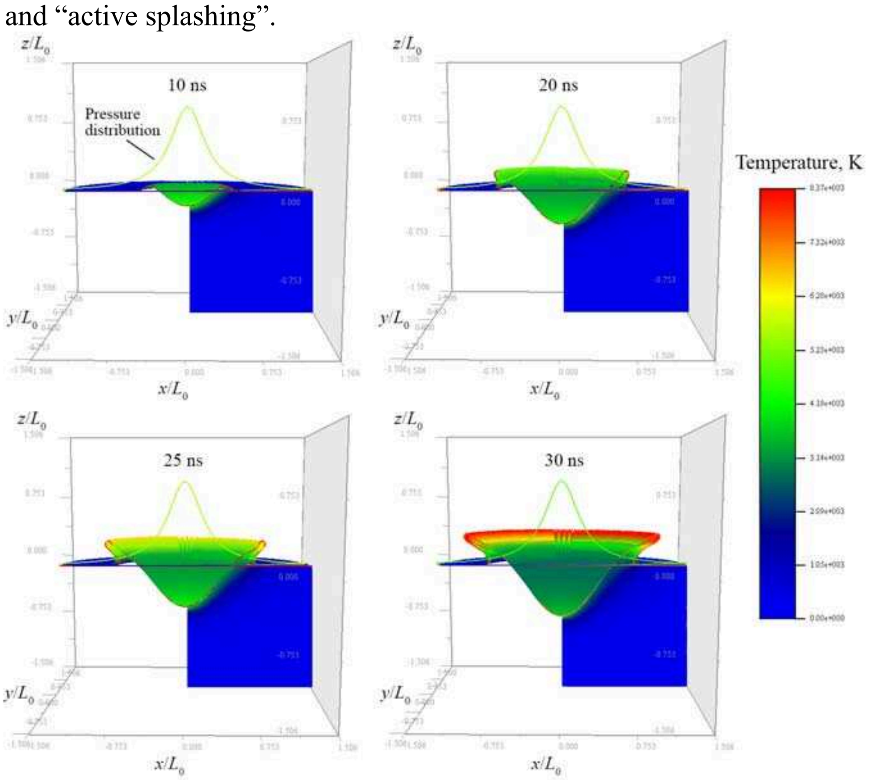

Fig. 1. Results of simulation of the crater and jet formation for a pressure $P = 4{\cdot}10^8$ Pa exerted by the reactive force.

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THE EMISSION CURRENT INCREASING IN THE PLASMA ELECTRON SOURCES BASED ON A LOW-PRESSURE ARC DISCHARGE [1]

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In the electron beam sources based on plasma cathode with the grid stabilization of the plasma emission boundary the anode (beam) plasma has a considerable influence on the limited parameters of the electron sources. This plasma acts as the anode plasma of the electron source and largely determines its main characteristics.

The paper describes the theoretical and experimental studies of the generation of the discharge plasma and considerable (up to twofold) increasing mode of the electron beam emission current in the plasma electron sources based on low-pressure arc discharge and the grid stabilization of the plasma emission boundary. The source works at an Ar pressure in the vacuum chamber p = 0.02–0.05 Pa, accelerating voltages of up to U = 10 kV, and longitudinal magnetic field of up to B_z = 0.1 T.

The positive reverse connection in the plasma electron source determines the simultaneous increasing of the discharge and emission currents, which can lead to disruption of the plasma cathode because of uncontrolled changes in the parameters of the electron beam generated by them and as a result, the breakdown of the accelerating gap.

It is experimentally shown that the polarity changing of the voltage U_d between cathode and grid electrode occurs in the electron beam emission mode. Theoretically, the numerical modeling shows that the plasma potential and the voltage U_d depends on the electric field penetrating from the accelerating gap of anode plasma through grid cells, on discharge current, gas pressure, grid geometric transparency and gas type.

It is shown that the basic mechanisms responding to the increasing of discharge current and emission current are associated with the secondary ion-electron emission of electrons in the plasma cathode and in transport channel on grid electrode, as well as with the presence of positive reverse connection between plasma cathode generation area and electron beam transport channel. It is theoretically and experimentally shown that the discharge current increasing depends on the power supply voltage, its resistance, the geometry of the grid, the accelerating gap and its applied high voltage.

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INVESTIGATION OF PULSED PLASMA SOURCES BASED ON VACUUM FLASHOVER DISCHARGE[1]

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Recently [1] it was revealed that vacuum flashover is source of multiple charged accelerated ions. In [1] high voltage short duration generator RADAN 150 [2] with fixed pulse parameters (150kV,4ns) was used. The mechanism of formation and acceleration of multiple ionized plasma flow remains unclear. This paper is devoted to experimental investigation of dependence of flashover plasma parameters on pulse amplitude, current and duration. Two type of generators were used. 1.The pulse cable generator with durations of pulse 5ns, 35ns, 50ns and 100ns. 2. RADAN generator with 150kV pulse amplitude and 5ns duration. High pressure polyethylene was used as dielectric. The discharge electrodes was made of copper. Two type of electrode arrangement were used: 1 coaxial 2 linear.. Anode –cathode gap was 1mm-50mkm for cable generator and 1cm for RADAN generator. The results of experiments shows, that there is no considerable dependence of ion energy and mass-charge composition on a pulse amplitude, electrode arrangement and interelectrode gap. Total ion charge generated by flashover discharge depends on discharge time and area of dielectric surface that discharge occurs on. There is straight dependence of ion energy on a ion charge. Time of ion charge composition formation establishing is about 5ns. Typical energy spectra are presented on Fig.1

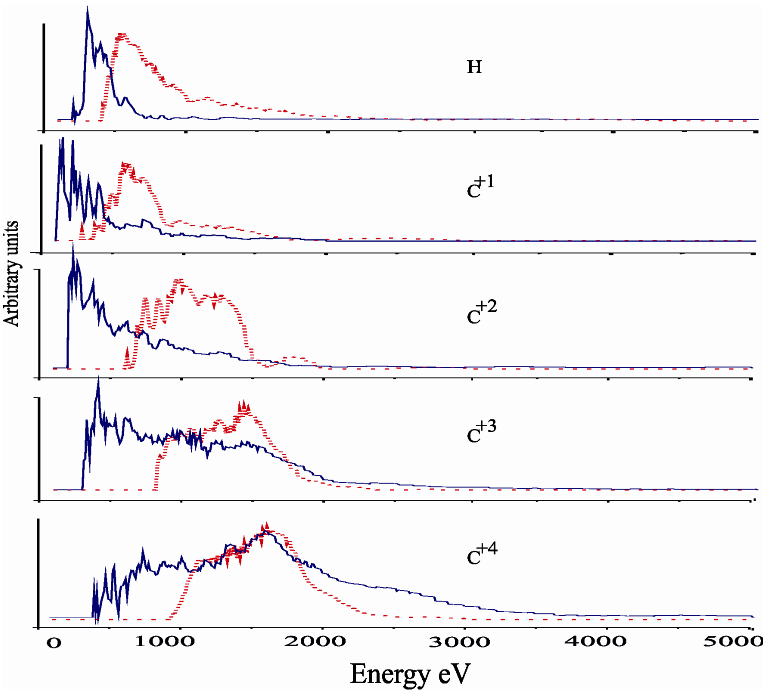

Fig. 1. Energy spectra/ Solid line -15kV/ 100ns, dotted line 150kV/5ns .

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LASER SHADOW IMAGING OF THE INITIATION OF VACUUM ARC CATHODE SPOT FRAGMENT[1]

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Laser shadowgraphy is a powerful instrument for the investigation of fast cathode processes in vacuum discharge. The first successful application of this technique was made in [1] where the authors observed the dense plasma objects of the size about 10 micrometers and lifetime of about 1-3 nanoseconds.

In our work the cathode processes at the cathode spot of vacuum arc of the current 5-100 A are investigated by the pulsed laser shadowgraphy technique. The aim of this investigation is to obtain data on the size and lifetime of the dense plasma of the ecton [2] process within cathode spot of vacuum discharge.

The second harmonic of pulsed Nd:YAG laser (532 nm) with pulse length 20 ns was used to obtain shadow images of discharge gap. Stemi 2000 microscope (refractor, glass optics) was used to obtain magnified image of electrodes at the entrance of whether CCD camera or ultra-high speed framing camera K001. Framing camera makes three frames with exposure 160 ps and inter-frame period about 200 ps.

Discharge was initiated at the cathode by high voltage trigger pulse 40 ns of duration applied to the auxiliary trigger pin made of tungsten. Cathode was the titanium wire and the wire tungsten anode was positioned 200 microns aside the discharge gap. Arc current was formed by 75 Ohm co-axial line in the anode circuit.

With CCD camera at current 25 A we have got pictures alike shown in Fig.1. at probability one case per approx. 20 shots. Actually this is open shutter picture taken with the exposure time equal to laser pulse duration 20 ns. The size of dense plasma object is 5-10 microns.

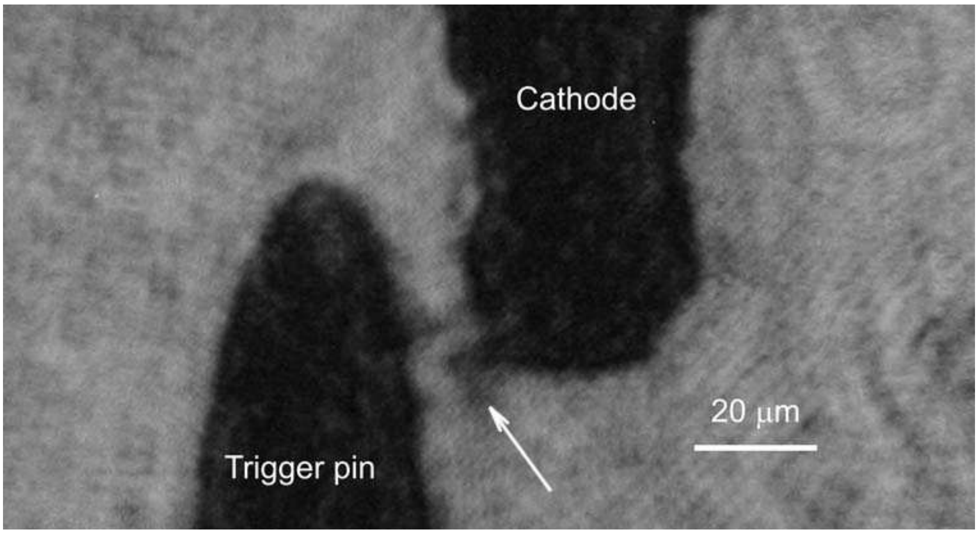

Fig. 1. Picture of dense plasma object (arrowed) at the cathode taken with CCD camera (open shutter, effective exposure is equal to laser pulse duration – 20 ns). Arc current 25 A.

With fast framing camera we have registered the dense plasma objects 5-10 micron of dimension at the cathode and the probability to get such objects was one case per approx. 100 shots. The three frame movie allows us to state that lifetime of dense plasma objects is about 350 ps. It should be noted that the quality of framing camera pictures is much lower than quality of CCD camera pictures.

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USING OF TWO X-PINH SYSTEMS FOR FINE FOILS EXPLOSION INVESTIGATION [1]

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The present work is devoted to studying of substances properties at high specific deposit energy using double-frame pulsed backlighting system [1]. The high specific deposit energy was reached at electrical conductor explosion (ECE). Fast mode of ECE was investigated. We performed the experiments with the Al, Cu, Ti and Ni foils.

Experiments were carried out on the experimental complex consisting of three current generators. One of generators *WEG-2* [2] provided explosion of the fine conductors. This generator has the capacitance of 250 nF, which was charged to voltage 10 to 30 kV. High-resistance divider measured voltage only on the subcircuit where the exploding conductor was assembled. The current derivative was measured with an inductive loop. The investigated conductor was mounted in special holder and the foil contacts with the electrodes were soldered.

Two other generators - radiographs *XPG-1* and *XPG-2* with X-pinch load were used as diagnostics [3]. When the generators were operated with a low inductance load, there current pulse amplitude was up to 300 kA at the pulse rise time of 180 ns. X-pinch produced by four Mo wires was a load for the radiographs. Using of x-pinch radiation the spatial image of exploded foil was registered. The image was registered on a film located behind the filter. The X-ray pulse power from X-pinches were registered using vacuum X-ray diodes that were located behind of kimfol film with thickness of 4 microns with aluminum coating with thickness of 0.4 microns.

The measurement of the current flowing through a conductor and voltage on the exploded conductor has allowed to determine the energy deposited in the conductor, delay time of the bubbles formation relative to the moment of current-cutoff and the time dependence of the vapor bubbles quantity.

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EXPERIMENTAL STUDY OF STRATA FORMATION DURING OF FOIL ELECTRICAL EXPLOSIONS IN VACUUM[1]

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The formation of the strata during fast explosion of metal foils at current densities of ~ 10^8 A/cm^2 has been studied experimentally. To observe the strata the soft x-ray radiation generated by an x-pinch were used.

The experiment on studying the process of stratification during the foil explosion (FE) was carried out in a setup consisting of three generators. The first generator *WEG-2* [1] was operated to initiate FEs, while two other generators - radiographs *XPG-1* and *XPG-2,* were used for diagnostics. The generator *WEG-2* represents RLC-contour, with capacity 250 nF, which was charged to voltage of 20 kV, and the current rate of 16 A/ns.

The test foil was fastened in a special holder with its contacts to the electrodes soldered.

The radiographs *XPG-1* and *XPG-2* [2] have the capacitance of 1mcF, the charge voltage of 43 kV, the current of 300 kA, and the current rise time of 180 ns. Four crossed molybdenum wires with diameter of 25 µm were used as a load. The delay between the operation of the *WEG-2* and *XPG* generators was set with the use of DPG trigger pulse generator; the operation jitter was 20 ns for the all generators. The delay between the operations was regulated in the range of 0.1 µs up to 1.3µs.

Fine foils of aluminum and cooper were used as conductors. The length of foil was 2 cm, the foil width was 1mm, and the foil thickness was 6 µm. In our experiments the shunting discharge develops at the metal explosion in the vacuum. Analysis of the experimental results suggests that the most probable reason for the stratification is the thermal instability.

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INFLUENCE OF THE ELECTRODES EROSION ON ARC DYNAMICS[1]

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High voltage, high current, and high coulomb transfer closing switches are required for many high power pulsed systems [1]. The most popular closing switches up to date are spark gaps due to relatively simple design, robustness, easily field maintenance and repair. Main drawback of spark gaps is limited lifetime, which is related directly or indirectly to erosion of the electrodes. Three-electrode switches, where a spark channel is initiated in a three-electrode layout and then the spark accelerates due to electro-dynamical force and moves along two extended electrodes, were introduced Kovalchuk et al. [2]. Arc motion in a rail gap channel in general can be described as moving current contour under action of accelerating magnetic force and aerodynamic drag of the medium, which acts on the rear plasma bridge surface. A simple and effective model has been developed by Kharlov [3] to study in complex both arc motion and electrodes erosion in linear or coaxial rail geometry in high pressure gas for high current and high charge transfer pulses. Self-consistent treatment of plasma motion and [1]electrodes heating has been employed. But in model [3] approximation with constant arc mass has been accepted, which is not very accurate assumption. In present report self-consistent electrodes ablation has been added into equation of motion in order to get comletely closed system of equations for the plasma motion and electrodes heating. Temperature dependence of main thermal parameters has been also taken into account in present paper. Stainless steel (Cr/Ni/Ti 18/10/0.6÷0.8), copper (Cu), chromium (Cr), tungsten (W), and molybdenum (Mo) have been considered here as the electrode materials, because these materials are widely used for manufacturing of electrodes. Good agreement with the experiment is observed in considered range of parameters.

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INFLUENCE OF A DENSE LOW-TEMPERATURE PLASMA ON B-DOT MEASUREMENTS[1]

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In experiments on high current generators for the implosion liner dynamic investigation and estimations of current flowing along a liner at different moments of time are used B-dots [1]. The extremely important conclusions about losses of current in the course of liners compression liners it is possible to conclude on the basis of signals from B-dots, using an assumption that the plasma surrounding loops does not influence the probes. To be convinced of the validity of this assumption we carried out a number of test experiments. In the experiments we compared signals from the B-dots received in absence and presence of dense low-temperature (T_e = 1.5 eV) plasmas. As a plasma source the plasma gun with an arch current at level 60 - 70 кA was used. The arc current is periodic with the period nearby 30 µs. For reception of the maximum concentration of plasma round tested B-dots in the experiments bismuth electrodes, possessing considerable erosion factor of electrodes were used. The maximum plasma density in the area of the B-dot measurements is about 1 mg/cm^3 at degree of ionization close to 1. The test signal had a half-cycle about 100 nanoseconds. Such time scale of test signals has been chosen in terms of characteristic times of liner compression.

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ION CHARGE STATE DISTRIBUTION FOR PLASMA OF VACUUM ARC WITH COMPOSITE CATHODE OF ALLOY OF LEAD AND TIN[1]

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We present research results on vacuum arc plasma produced with dual-component cathode made tin and lead alloys. The ion mass-to-charge-state spectra of the plasmas were studied by time-of-flight spectrometry. It is shown that the fractional composition of ions of each cathode components in the plasma flow from the cathode spot closely matches the fractional content of these components in the composite cathode. The charge state of ions of the cathode components is determined by the average electron temperature in the cathode spot plasma. The physical processes responsible for these changes in the ion charge state in dual-component-cathode vacuum arc plasma are discussed.

Because the elements comprising the investigated cathodes can differ in density, mass, ionization potential, and in other physical properties, studies of the ions composition produced by cathode spots can provide a large body of new and important experimental data, analysis of which can assist in developing physical model of the cathode spot phenomena. Research in the plasma physics of vacuum arcs with multicomponent cathodes is thus of both fundamental and applied interest. Practical interest in vacuum arc cathode spots follows in large part from the use of vacuum arc discharges for the generation of metal plasma, which in turn finds various technical applications. The vacuum-arc-produced metal plasma is used for example in vacuum arc ion sources (sometimes called *Mevva* ion sources, for *me*tal *v*apor *v*acuum *a*rc) [1] to form intense, energetic metal ion beams for ion implantation [2] and for particle accelerator injection, [3] in plasma generators for coating deposition [4]. Here we present results of our investigation the ion charge state distribution for plasma of vacuum arc with composite cathode of alloy of lead and tin.

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ESTIMATION OF ELECTRON ENERGY IN THE ELECTRON BEAM FORMED IN THE 95-KV 5-NS DISCHARGE AT THE LOW VACUUM CONDITION AND THE ATMOSPHERIC PRESSURE[1]

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In the earlier experiment [1] the electron beam in short-pulse discharge was detected via Thomson spectrometer at different background gas pressure. Unfortunately, signal intensity in the experiment become too low at the pressure increasing to 400 Pa. In this experiment we attempted to improve sensitivity of the particle detector, and to receive the electron beam signal at gas pressure level above 400 Pa.

Electron beam was detected in 95 kV discharge in air with 5 ns duration. During the experiment air pressure was varied from 1000 Pa up to the atmospheric pressure. The electron beam energy was estimated by electrostatic spectrometer with automated recording system. The method is similar to the Thomson parabolas method [1] without magnetic field deflection.

The anode was a tungsten grid made of 0.2 mm diameter wires. The cathode was a copper needle or a copper multi-wire composition with 3 mm diameter. The electrode separation was about 8 mm. As a voltage source we used a RADAN-150 generator.

The microchannel plate based detector was used in the spectrometer; the high-vacuum condition is necessary to operation of the detector. Thus the electron beam was injected from the discharge chamber to the spectrometer via aluminium membrane with 12 μm thickness.

Due to the low intensity of the electron beam signal, we had to limit the beam collimation; thus the signal spot diameter was too large to obtain a reliable energy distribution of the electrons. The spot had a round shape, and the shape remained undistorted with deflection electric field applying. This fact can indicate the monoenergetic spectrum of the electron beam. Energy of the beam was estimated by the deflection of the central point of the spot.

Characteristic energy of the electron beam was about 60 keV at the lower pressure level (10^3 - 10^4 Pa, and increased up to 75 keV with pressure increasing up to atmospheric pressure. The signal intensity decreased with the pressure increasing.

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PROPAGATION OF THE PULSED ELECTRON BEAM OF NANOSECOND DURATION IN GAS COMPOSITION OF HIGH PRESSURE[1]

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Investigation of the propagation of electron beams in different gas compositions are interesting both for the development of physical ideas phenomenon of multiple scattering, the formation of charged and excited particles, and for applied purposes, such as pulsed plasma chemical technology on the synthesis of nanoscale metal oxides [1-2], and pulse cleaning technology decontamination of industrial and domestic wastewater [3-4], and others. [5-6].

This article presents the results of the investigation of the propagation of an electron beam in the gas compositions of high pressure (300 and 760 Torr): sulfur hexafluoride and hydrogen, sulfur hexafluoride and nitrogen, sulfur hexafluoride and argon. The choice of the composition of gases is based on the fact that these gases are widely used in many industrial processes technologies as the working fluid. Experiments were done on the basis of laboratory accelerator TEU-500 [7]. The main parameters of the accelerator: the accelerating voltage of 500 kV; electron beam current of 10 kA; pulse width at half maximum of 60 ns; pulse energy of 200 J; pulse repetition rate of up to 5 pulses per second, the beam diameter of 5 cm. The output of the electron beam was carried out through the anode box, which is a supporting grid (with optical transparency of 95%) and aluminum foil thickness of 140 microns. The anode-cathode gap for all experiments was 13 mm. The stability of the accelerator controlled by the Rogowski coil and the capacitive voltage divider. Scatter in the values of current and voltage, registered with sensors did not exceed 5%. Pulsed electron beam was injected into a 40 cm metal drift tube. The drift tube is equipped with three reverse-current shunt with simultaneous detecting of signals. The obtained results of investigation permit the conclusion that the picture of the processes occurring in the interaction of an electron beam in the gas composition of high pressure is different from that observed in the propagation of the electron beam in the gas composition of low pressure (1 torr). Plasma produced in gas compositions by the electron beam has different characteristics (ion temperature, concentration, composition), which impact on the beam propagation characteristics in this plasma.

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ELECTROPHYSICAL PARAMETERS OF THE DISCHARGE UNDER TRIMETHYLSTEARYLAMMONIUM CHLORIDE AQUEOUS SOLUTION IN AIR AT ATMOSPHERIC PRESSURE[1]

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In this work, the results of electrophisical parameters measurements of the atmospheric pressure air discharge between copper anode and an aqueous solution of cathionic surfactant the trimethylstearylammonium chloride as cathode are presented. The ranges of the direct current were 20-100 mA. Solution concentrations was varied in the range of $5{\cdot}10^{-3}$-10 g/L (0,014-29 mmol/L), the interelectrode distance was $5{\cdot}10^{-3}$ m. The total voltage drop in the discharge system was measured using precision voltmeter Fluke 289. For the calculation of the current density the video registration of discharge geometry was carried out using digital camera. The distribution of potential in discharge has been measured by means of moving anode. On the base of these data the electrical field strength in plasma and cathode voltage drop has been found.

Electrical field strength for aqueous solution concentration of 5 mg/L with all the current range and for fixed current discharge of 40 mA with all range of concentrations was calculated. The electric field strength in the positive column of the discharge is about of 700 V, cathode voltage drop is in about 450 V. Both values don't actually depend on the concentration of surfactant solution and on the discharge current within the error.

Increase of the aqueous solution concentration lead to decrease of the cathode spot area.

Increase of the discharge current almost does not effect on current density that was calculated using known values of cathode spot area. The current density increases as result of the solution concentration rise in the range of 0,3-1,5 A/cm^2. Characteristics were obtained experimentally after 10 and 30 seconds after generation of the discharge. Current density after 30 seconds of the discharge burning is higher than the values that were obtained after 10 seconds.

Using optical emission spectroscopy the rotational temperatures of the N_2 molecules was obtained (Fig. 1). In our case the rotational temperature equal to the gas temperature, so the reduced electric field was calculated.

That values increases within 9-18 Td as solution concentration increase. Increase of the discharge current lead to weak decrease of the electrical field strength within 10-14 Td.

Using obtained experimental data the discharge model can be created.

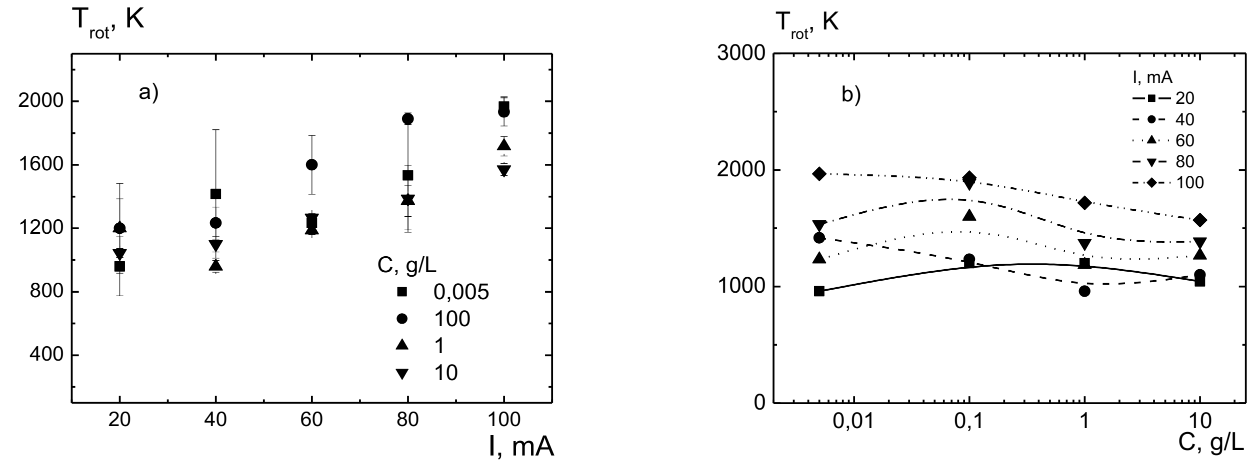

Figure 1. The rotational temperature of N_2 as a function of the discharge current (a) and function of the solution concentration (b).

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THE RUNAWAY ELECTRON BEAM FORMED IN A DISCHARGE AT ATMOSPHERIC PRESSURE

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A numerical simulation of a beam of runaway electrons formed from an individual emission zone on a cathode [1] has been performed for discharges in air of atmospheric pressure. The model is based on solving numerically two-dimensional equations of motion for the electrons [2] and allows one to describe the dynamics of the fast electrons injected from the surface [3] of the emission zone. In calculations it was supposed that the electric field at the surface of the emission zone is enhanced due to which conditions are realized for the electrons injected from the surface to switch into the mode of continuous acceleration. It is shown that the formation of a runaway electron beam in a highly overvolted discharge [1] is largely associated with avalanche-type processes and that the number of electrons of an avalanche reaches 50% of the total number of runaway electrons [2].

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NUMERICAL SIMULATION OF RUNAWAY ELECTRON BEAM GENERATION IN NON-HOMOGENIOUS GAS MEDIA WITH TUBE CATHODE[1]

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Using an electrode system with tube cathode is a "classical" method for runaway electron beam generation. During a discharge glowing the region near cathode heats essentially more than other regions of discharge. As a result, the temperature in this region is higher and molecular number density (N) is lower in comparison with other regions. This can increase E/N relation in addition to amplification of electric field (E) near edge of tube cathode and, therefore, increase amplitude of runaway electron current pulse. Such situation was observed experimentally in pulse periodic mode of runaway electron beam generation [1].

The study was performed with the well-known XOOPIC program package, which was applied earlier to simulate the formation of subnanosecond gas discharges and generation of runaway electrons in non-homogeneous gas media [2]. The program package is based on the particle-in-cell method used for simulation the motion of charged particles. The electromagnetic field in this code is calculated using Maxwell's equations. The interaction of charged particles with gas is simulated by the Monte Carlo method (model of individual collisions). A voltage pulse with a time of 235 ps was applied to the left end of the transmission line of length L = 23.5 cm. At the right end of this line, a diode with tube cathode was located. The hot region with low concentration of neutral molecules was located near the cathode.

We calculated oscillograms of voltage, currents of plasma and runaway electrons.

Calculated electron energy distributions for different concentrations of neutral molecules in hot region are shown in Fig.1.

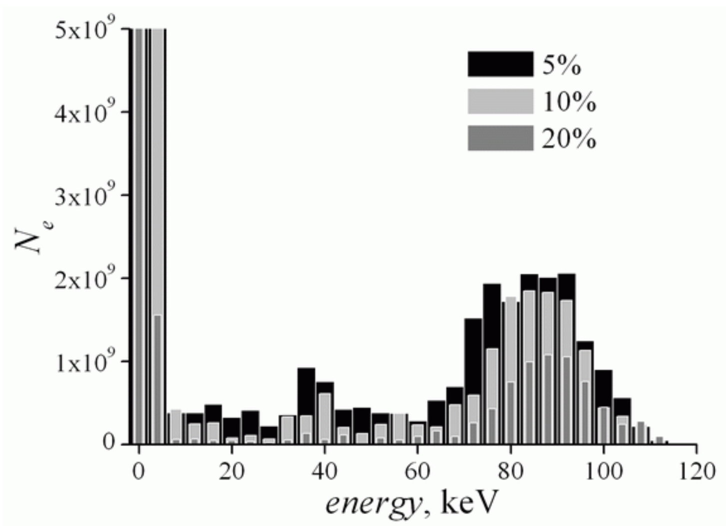

Fig. 1. Electron energy distributions for different concentrations of neutral molecules in hot region. (percentage of molecule concentration in surrounding gas media)

It can be seen, that decreasing of neutral molecules in hot region leads to increasing the part of runaway electrons especially in high-energy range (70-110 keV). At that, amplitude of runaway electron current increases also.

Thus, overheating in cathode layer of gas discharge plays a positive role for generation of runaway electrons.

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COMPARISON OF DIELECTRIC MATERIAL ON AR ATMOSPHERIC PRESSURENONEQUILIBRIUM PLASMA JETS WITH HEATED DIELECTRIC WALL[1]

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In this work, effect of dielectric temperature on atmospheric pressure nonequilibrium plasma jets (APNPJs) with different dielectric materials has been investigated[1]. In our experiments, a single-electrode plasma generation equipped with an AC power supply is applied. Two materials, 95% alumina ceramic and quartz are adopted as dielectric tube. To distinguish the APNPJ status from the argon flow rate, the three modes, laminar, transition and turbulent, are separated. Three amplitude voltages of 7, 8.5 and 10 kV are ued here for the excitation and sustaining of the discharge. It is found that, with the dielectric wall heated, the APNPJ length and volume are enhanced over a large range of flow rates with both ceramic and quartz tube. Contrast with the situation of quartz tube, the transition regions has a significant 'bulge' in ceramic tube with heated wall [see Fig. 1 (a)]. It is confirmed that the heating of discharge gas is responsible for the expansion of transition region[2]. For the case of high temperature in quartz tube, the peak length of plasma plume has even greater enhancement under different applied voltages. The maximum values of jet length with 7 kV applied voltage are 5.15 cm in quartz tube and 4.50 cm in ceramic tube, respectively. For both ceramic and quartz tube, obvious distinction of longest length versus applied voltage is disclosed between two different dielectric temperatures [see Fig. 1 (b)]. In room temperature, the trend of longest length versus applied voltage is upward, but it shows an entirely opposite tendency in high temperature. It is believed that the interaction between the dielectrics and plasmas is the dominant reason.

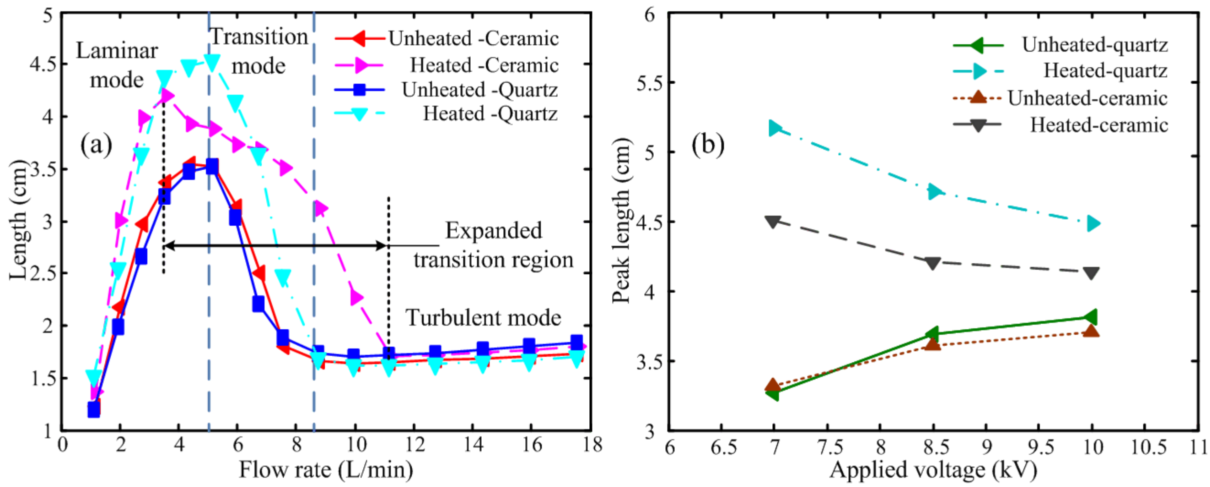

Fig. 1 (a): The plasma plume length versus Ar flow rate at applied voltage of 8.5 kV. (b): The peak length of plasma plume versus applied voltage.

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A FACILITY AND EXPERIMENTAL PROCEDURES FOR SECONDARY ARC TESTS OF SPACECRAFT EQUIPMENT[1]

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Secondary arc initiation in the electrical distribution (ED) of spacecrafts (SC) is much sensitive to the SC environment and a kind of primary discharge [1]. Standard procedures on secondary arc tests imply electrostatic discharge (ESD) as an only source of arcing. However, the problem of secondary arcing is actual also in equipment where ESD has no chance to happen.

To realize secondary arc tests, a facility and experimental procedure are developed. The experimental procedures includes items as follows:

– a method for simulation of the inner space of the spacecraft equipment;
– a method for simulation of initial arc discharge in the spacecraft equipment; and
– a method for investigation of the secondary arc probability the spacecraft equipment.

The facility allows one to carry out investigation under conditions being close to real ones at spacecrafts.

The results of experimental study are subject to be presented. Secondary arc probabilities are measured for residual atmosphere simulating LEO conditions in gas composition vs orbit altitude. The experimental arrangement includes also rare plasma and primary arc plasma. The source of primary arcs is fed by a low-voltage (100 V) power supply, simulating arc ignition by a fuse evaporated [2].

Experimental data obtained indicate the secondary arcing to be a result of the two-stage process. The volume discharge is initiated by the primary arc first, followed by secondary arcing. This finding is of importance in analysis of impact of space environment on operation of ED at SC. In particular, cavities in SC equipment must be analyzed on the matter of gas discharge initiated by a primary arc and serving as a source of arc distribution over long distances inside the SC equipment.

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INVESTIGATION OF STATIONARY AND PULSE TYPE LOW PRESSURE ARC DISCHARGE IN AXIAL MAGNETIC FIELD[1]

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At present, gas low-pressure arc discharges find wide application in plasma sources and also in sources of electron and ion beams with the plasma cathode.

Research of the low-pressure arc discharge with the hollow cathode in a stationary and pulse condition are presented in the paper.

The discharge operates as follows.

In the crossed electric fields of cathode fall and axial magnetic field created by the magnetic coil or a permanent magnet with induction 10-25 mT the cathode spot moves on a circular path in a maximum of the tangential component of a magnetic field on the internal surface of the cylindrical hollow cathode. Electrons emitted by the cathode spot and accelerated in cathode fall ionize the working gas, and cathode erosion products (microdrops, atoms and ions of metal) are subside inside the cathode cavity. The discharge between the hollow cathode and the hollow anode burns with voltage 30-50 V that is sufficient for stable burning of the gas discharge. The gas flaw was regulated within the limits of 3 to 100 mPa·m-3·s-1. At that, pressure in the field of the hollow anode varied from 2·10-2 Pa to 1 Pa.

Были проведены экспериментальные и теоретические исследования разряда на уровне тока до 200 А в стационарной форме и до 700 А в импульсах с длительностью от 10 до 250 микросекунд.

Experimental and theoretical investigations of the discharge at current up to 200 A in a stationary mode and up to 700 A in pulses condition with duration from 10 to 250 microseconds were carried out.

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STABLE PLASMA PRESSURE PROFILE PEAKING AT CONVEX-CONCAVE MAGNETIC FIELD LINES [1]

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The convective (flute-interchange) instability of the plasma is one of the basic features of the plasma dynamics in a non-uniform magnetic field [1-3], and in any magnetic configuration, the magnetic field lines are either convex or concave relative to the plasma. The plasma convective motion due to the **E**×**B** drift is of importance for the turbulent transport description of fusion plasmas [4-5] as well as for low-temperature plasma applications [6-7].

It is well known that plasma can be stabilized e.g. by confinement at ‘concave fields’ (cusp, min$B$) or by confinement at ‘convex’ field lines of a large field-line curvature, such that a gentle pressure decrease to the periphery insures the plasma stability without min$B$. Some critical pressure gradient maintains here similarly to that for a ‘sand hill’.

It has been found that a combination of the convex and the concave part of a field line provides a strong stabilizing action against convective (flute-interchange) plasma instability [8-9]. This results in internal peaking of the stable plasma pressure profile that is calculated from the collisionless kinetic stability criterion for any magnetic confinement system with combination of mirrors and cusps.

The simple ideal MHD description gives a strong variation in the stable pressure profile due to the strong variation in the specific volume $\int dl/B$: the critical profile being $p_{MHD} \propto (\int dl/B)^{-5/3}$. However, we have found that there is a strong variation in the stable pressure profile at regions of almost equal specific volume – near min $\int dl/B$, with curvature of alternating sign – with appropriate combination of the convex and concave field line parts.

The pressure peaking arises at the minimum of the second adiabatic invariant $J = \int v_{\|}\, dl$ that is located at the ‘middle’ of the mirror–cusp tandem transverse cross-section. The position of the minimum in J varies with the particle pitch angle that results in a shift of the peaking position depending on plasma anisotropy. This allows one to improve the stable peaked pressure profile in a convex–concave field by appropriately changing the plasma anisotropy over the trap cross-section.

To study this effect experimentally, a compact magnetic confinement device has been modified by adding an external current coil to fulfill the field-line curvature requirements. The reconstruction of the magnetic configuration according to the field measurements and critical convectively-stable plasma pressure profiles calculation in this experimental geometry have been performed.

Probe measurements of the spatial plasma distribution in the new magnetic configuration of alternating-sign field-line curvature have been performed.

The experimental results give some support for a conclusion that there is an increase in the ion saturation current at the region near the minimum of the specific volume min $\int$ dl/B. This region corresponds to average minimum in the second adiabatic invariant, J, and the kinetic description predicts the pressure peaking here due to reducing of charge separation by particle drift in alternating-sign curvature, whereas, MHD predicts minimum in the pressure gradient here. Thence, there is a slight trend to support the theory.

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PARTICLE-IN-CELL SIMULATION OF THE RUNAWAY ELECTRONS AVALANCHES IN EXPERIMENTAL SET-UP[1]

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The results of numerical simulation of the breakdown and forming of avalanches of runaway electrons in nitrogen with atmospheric pressure in the geometry when the electric field distribution in most of the electrode gap is aligned cathode geometry (Fig.1.) are presented. Dynamics of the electric field distribution in the course of such breakdown was received. It was shown that in the plane of the anode can be fixed two separated time high energy electron beam.

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DIAGNOSTICS OF PLASMA JET IN LOW-CURRENT NONSTEADY STATE PLASMATRON[1]

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In the last years, a considerable interest has been generated in the nonequilibrium atmospheric pressure glow type discharges in a gas flow [1]. One of the electrode configurations for obtaining such a discharge corresponds to the classical coaxial plasmatron (Fig. 1). Typical diameter of the plasmatron anode nozzle is of about 0.5 cm, a gas flow rate in the experiments G(air) = (0.05 – 0.5) g/s, and an average discharge current in plasmatron can be varied from 0.2 A and less [2, 3].

In the above conditions, the discharge current is mainly carried by plasma column *3*. The discharge burns in a glow form with the occasional transitions from glow to spark [2, 3]. However, due to a vortex gas flow, the background weakly ionized gas appears in the plasmatron nozzle. This weakly ionized gas forms the plasma torch (plasma jet) inside the nozzle and at the exit of plasmatron. A small fraction of discharge current also closes to anode *2* via the plasma torch. The goal of the paper is to estimate the parameters of the plasma jet at the plasmatron exit.

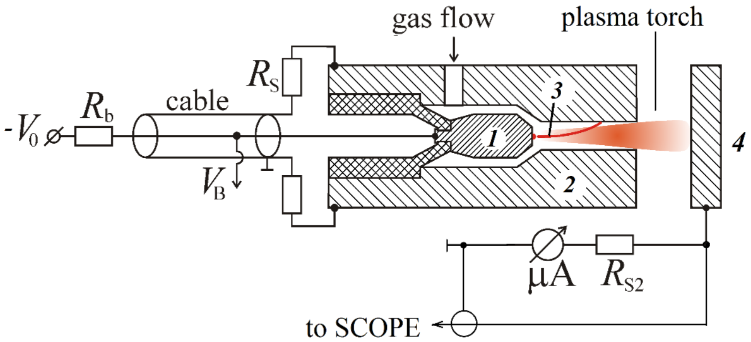

Fig. 1. Schematic of the low-current nonsteady state plasmatron for obtaining the plasma jet (plasma torch) in air. *1*–cathode of the plasmatron, *2*– anode nozzle, *3* – plasma column, *4* – probe for measuring a current flowing via the plasma torch, V_0 – voltage of dc power supply, R_b – ballast resistor, R_S – current shunt for recording a current to the anode nozzle, R_{S2} – current shunt for recording a current to the probe.

As noted above, the plasma jet forms out of the plasmatron nozzle due to gas flow. For the discharge in air, the charged particles in the jet are the positive and the negative ions. Then the jet represents a flow of weakly ionized gas, which contains a certain concentration of the charged particles N. Total flow of the charged particles λ can be written as

$$\lambda = NvS = NG/\rho, \tag{1}$$

where v – gas velocity at the plasmatron exit, ρ – neutral particle density, S – area of the plasmatron nozzle.

With a purpose of diagnostics of the plasma jet, an additional probe *4* is used and a current to this probe is measured. When a current to electrode *4* is available, we can say that a kind of nonself-sustained discharge burns between the electrodes *1* and *4*. Most simple regime for the current to electrode *4* corresponds to the so-called saturation current. For this regime, a current of negative ions to electrode *4* is determined by (1), and the same current of the positive ions flows to electrode *4*.

The concentration of charged particles has been estimated with a usage of (1) for different regimes of discharge in plasmatron and for different designs of probe *4*. In typical conditions of the discharge in plasmatron (i = 0.1 A, G = 0.1 g/s) we measured the nonself-sustained current to probe *4* at a level of 1 μA. The corresponding density of the charged particles in the jet was of about 10^{10} cm^{-3}.

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ELECTRON BEAM INJECTION INTO A LONG AIR GAP POWERED BY 0.8 MV VOLTAGE PULSE

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Despite on the long history of researches atmospheric discharges attract attention as before. Significant advance in the experimental techniques allows one define reliably electric fields in the atmosphere, find out strong correlation of power x-ray bursts, radio-frequency emission and cosmic air showers with thunderstorm discharges [1, 2]. These papers also present an unified approach which explains a lot of experimental data. This approach is called runaway electron breakdown (RB) [3]. Nowadays RB is under intensive investigations using laboratory devices, because of higher reproducibility of the laboratory discharges in comparison with natural ones. Wide experiments over the world are being performed both at subnanosecond voltage pulse rise times and at microsecond ones. In the first case short gaps (few mm) are used at high overvoltage $E \approx$ (100 - 300) кV/cm. In the second case long gaps are exploited at the mean electric field lower than static breakdown electric field of ≈ 30 kV/cm.

Existence of the run-away electrons in such discharges is evident. But reliable proofs of the run-away electron avalanche growth are not the case. The most advanced is results of the experiments [4] where run away avalanche resulted in gap breakdown was proofed at applied electric field 250 kV/cm and subnanosecond voltage rise time.

This paper is devoted to describe results of the experiments on influence of the 150 kV electron beam injection into the 50 cm long atmosphere gap with non-uniform electric field with average field of 16 kV/cm. The experiments have been performed on the Marx generator of the ERG installation (P.N.Lebedev Physical Institute) modified with output oil-air insulator [5].

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OPERATION OF AN OIL-FILLED MARX GENERATOR WITH AN OIL-AIR OUTPUT INSULATOR FOR ATHMOSPHERE LONG SPARK INVESTIGATIONS[1]

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A new phenomenon called the runaway breakdown (RB) was predicted in 1992 [1]. In this type of breakdown, the runaway electrons with energy of several hundred keV and higher play the main role in the development of the electron avalanche that forms finally a current-carrying channel. It is assumed that the RB namely is realized in lightning. A long distance of runaway electron avalanche growth is typical; therefore, the RB can be realized in long high-pressure discharges. First of all, interest in high-pressure gas discharges in long gaps raises from the RB research.

Oil-filled Marx generators provide significantly lower size of the installation as compared with open air Marxes. Moreover the oil-filled Marxes could lower an electromagnetic noise level and have no dependence on atmospheric conditions. These circumstances stipulate an interest in using of the oil-filled Marxes for long air spark laboratory experiments.

High-pressure gas discharges are under investigations at the P.N. Lebedev Physical Institute of the Russian Academy of Sciences (see, for example, [2,3]), using the experimental facility built around the Marx of the ÉRG electron relativistic generator. In this installation, the Marx generator with total accumulated energy up to 60 kJ is used as a voltage source. A voltage pulse through an oil-air output insulator is applied to an axially symmetric two-electrode gap mounted in a cylindrical discharge chamber with an open end. The Marx provides a voltage rise up to 900 kV for 150-200 ns. The working gas is air at atmospheric pressure.

The output oil-air insulator is a key part of the experimental installation. This paper is devoted to detail description of the insulator design and some features of its operation.

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EFFECT OF THE DISCHARGE CIRCUIT AND SPARK GAP PARAMETERS ON ENERGY LOSS IN A NANOSECOND SPARK GAP SWITCH

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The paper presents the results of tests of a capacitor-switch assembly operating onto a low-impedance load. The parameters varied in the tests were the operating pressure, main gap in the switch, and load impedance. Based on the obtained experimental data, dependences of the energy loss in switching on the varied parameters were constructed. Comparative analysis of the experimental and numerical simulation [1] data was performed.

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INVESTIGATION OF ELECTROOPTICAL BREAKDOWN THRESHOLD IN GAS MIXTURES OF COMPLEX CHEMICAL COMPOSITION [1]

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Initiation of pulsed breakdown of gases investigated for a long time, and spark discharge in a DC or low frequency electric field is perhaps the most studied and frequently used in the technique. Despite this, studies of electrical discharges are ongoing and are aimed primarily at finding ways to increase their energy efficiency (e.g. for lighting and lightning protection), including through the application of combined effects. So, to date, investigated various combinations of constant, low, high [1] and microwave electric fields and light fields [2, 3], including in combination with various sources of seed electrons [4, 5]. And in most cases the vector fields for the combined effect were collinear (radiation distributed along the electric field).

In this paper first briefly presents the results of experimental studies combined (electrooptical) breakdown of gases (He, Ne, Ar, Kr) under low vacuum (p~10^1–10^5 PA) under the simultaneous interection of nanosecond laser pulses(λ~213, 266, 355, 532, 1064 nm, $\tau_{0,5}$~18 ns, I_0~10^9–10^{11} J/cm^2) and a constant electric (E~0-13,2 kV/cm) fields. In the experiments, the radiation is focused by a quartz lens (F~150 mm in spot diameter of ~ 0.12 mm in the electrode gap (d~3 – 10 mm) formed by a movable copper electrodes one of which was applied a positive potential to U~5 kV (second electrode was grounded).

Feature electrical and optical breakdown of gases is that the minima thresholds occur in the area of ~10^2-10^3 PA and ~10^6-10^7 PA, respectively [6]. In addition to the optimum, for each mode of breakdown, there are also areas where the most energy efficient is the combined effect. Analysis of mechanisms of electric and optical breakdown suggests the existence of synergistic effects when combined with the impacts associated with the peculiarities of formation of seed electrons and their acceleration under various modes and conditions of exposure [7].

Experimentally determined thresholds optical, electrical and combined electro-optical breakdown for noble gases and their binary and triple mixtures with different ratio of components. Investigated the possibility of reciprocal reductions in breakdown thresholds in simultaneous optical and electrical effects on the gas, and the possibility of lowering the thresholds of the combined breakdown of the main gas at other gas additives.

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FEATURES OF PLASMA GENERATION BY RIBBON ELECTRON BEAM IN FORVACUUM PRESSURE RANGE[1]

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Low energy intense ion fluxes is of great interest for the processing technology of flat surfaces of large area. The most promising source of such flows is a plasma, created by an ribbon electron beam [1].

In the mode of paired collision ribbon electron beam allows to create a plasma surface [2] area of several tens of square centimeters with plasma concentration up to 10^{10} cm^{-3}, which is not enough for some applications. The present study investigates the possibility of obtaining more dense plasma in the fore-vacuum pressures through the implementation of collective interactions, i.e., generation of beam-plasma discharge (BPD).

Experiments have shown the presence two modes of the ribbon beam transportation in the pressure range 5-10 Pa. When a beam current of 200 mA, pressure 5-7 Pa and an accelerating voltage of 1.5 kV, the electron beam in the field of transport is characterized by a uniform purple glow plasma produced when the beam passes through the residual atmosphere of the vacuum chamber (Fig. 2a). When exceeding the beam current or gas pressure certain threshold value at a distance of about ten centimeters from the electron source the violet color, accompanying the electron beam, is replaced by a bright pink, while the rest of the beam path is purple (Fig. 2b).

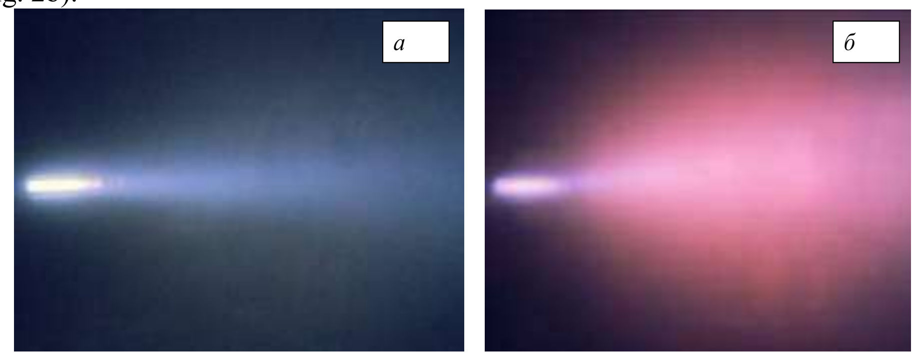

Fig. 2 Beam plasma glow at different beam currents: a - 200 mA, b - 250 mA.

Increasing the accelerating voltage leads to a shift of the glowing region from the electron source along the propagation path of the beam.

Concentration and temperature of the plasma electrons in the presence and absence of luminescence are measured. It is shown that the temperature and density of the plasma in of the glowing region is much higher than similar parameters for the area without glow that gives grounds to assert the presence of beam-plasma discharge generated by an ribbon electron beam in a forevacuum pressure range

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ANALYSIS OF MICROWAVE INTERFERENCE SWITCHES WITH DISTRIBUTED POWER OF SWITCHED WAVE AND PLASMA GAS-DISCHARGE SWICHING[1]

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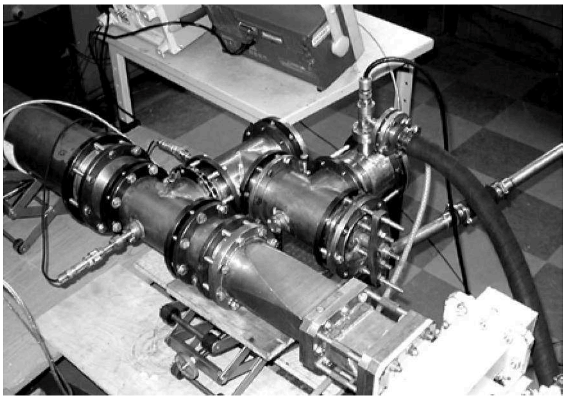
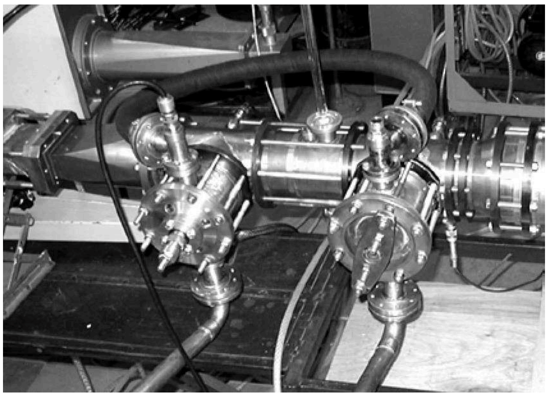
This paper is dedicated to the problem of creation of effective cascade type microwave interference switches [1,2] based on waveguide TE-tees providing switches transition attenuation value of -50dB and more in the “close” switch state, the power losses of -2-3dB in the “open” state ,and the working power comparable with the power of a regularity waveguide. These switches are different combinations of junctions of two or three TE-tees. Each TE-tee has an input and output port and one shorted arm. In addition, the TE-tees contain one or several plasma gas-discharge microwave switches. Different designs of TE-tees combinations provide different distribution of switched wave power among TE-tees and create various power levels of the switched wave. The comparative analysis of the characteristics of such switches made of both matched and unmatched TE-tees from the side of their side arms was carried out using the scattering matrix method. It was shown that the applied matched TE-tees allow decreasing the power level of the switched wave several times, which boosts the operating power and stability of switching, and, alternatively, defined specific combination of unmatched TE-tees may provide effective switching of the wave with decreased power. It was also demonstrated that when the number of TE-tees in the switch is increased to 2 or 3, no noticeable losses during of switching were observed. The results of analysis are compared against the data obtained during the experiments at low and high power level. The authors justified the possibility of effective application of cascade type switches for operation in active microwave pulse compressors acting as passive amplifies of microwave pulse power working by storage the energy of a relatively long input microwave pulse in cavity and its rapid extraction into the load.



a)



b)

Fig. 1. External view of interference switches with the cascade of the three waveguide TE-tees at the side arms of TE-tees (a) and with two waveguide TE-tees connected in a series (b).

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[1] This work was supported by Russian Foundation for Basic Research (Grant № 15-08-01853).

PROLONGATION OF GUIDED DISCHARGE INITIATED BY FEMTOSECOND LASER FILAMENTATION IN AIR FROM 1-MKS SCALE UP TO 1-MS

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Generally, the duration of a guided discharge stimulated by femtosecond laser filamentation is defined by the high voltage source. In most of the published works a Marx generator was used as the HV source for creation of guided discharges. In this case the discharge duration is defined by the product of the Marx "stack" capacitance and the discharge load. In our recent publication [1] a compact Marx generator was used to create ~20-cm long guided discharge of duration about 600 ns due to the mentioned Marx capacitance and 300 Ohm discharge load.

For different applications a guided discharge of much longer duration is required.

We present here experiments with the same Marx generator. To increase the duration of the discharge we employed a second circuit which injects an additional current pulse under much smaller voltage. The discharge current signals and images of the discharge with 100-ns resolution show that guidance has been achieved successfully during 1 ms.

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INCREASE OF UNIFORMITY OF DISTRIBUTION OF DENSITY OF IONIC CURRENT IN AN EXTENDED PLASMA SOURCE WITH THE HEATED AND HOLLOW CATHODE[1]

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In work, research of longitudinal distribution of density of ionic current of the generator of gas plasma with the heated and hollow cathode is conducted. The reasons resulting in not uniformity in this distribution are established. Work on optimization of digit system that allowed increasing considerably uniformity of distribution of density of ionic current along a working zone of a plasmagenerator with the heated and hollow cathode is carried out. By means of the optimized plasmagenerator, nitriding of extended details is carried out and opportunity to receive the uniform nitrated layers on extended details is shown.

[1] This work was supported by RFBR the project 14-08-00997-a

EXPERIMENTAL STUDIES OF HIGH-VOLTAGE SUBNANOSECOND SWITCHES BASED ON OPEN DISCHARGE WITH OPPOSITE ELECTRON BEAMS [1]

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The results of the measurements of the parameters of high-voltage subnanosecond switches based on open discharge with opposite electron beams are presented. Researched switches consist from two parallel plane cathodes with grid anode in the middle [1].

Dependence of compression degree, switching time, jitter, efficiency, frequency and load characteristics on gas type and pressure, switching voltage and geometrical parameters of the switches are presented. The latter are cathode material and area, discharge gap distance and anode grid transparency. The example of dependence of breakdown delay on frequency is shown in the fig. 1. Ranges of voltage, gas pressure and frequency in which experiments were made are 2 – 20 kV, 2-100 Torr, 0.1-100 kHz respectively. In the distinct modes the following parameter's values were obtained: switching time less than 0.2 ns, compression degree more than 100, and switching efficiency more than 0.9.

The estimates of lifetime and maximum average switching power are discussed. Different electrical circuits including researched switches are presented and their working features are analyzed.

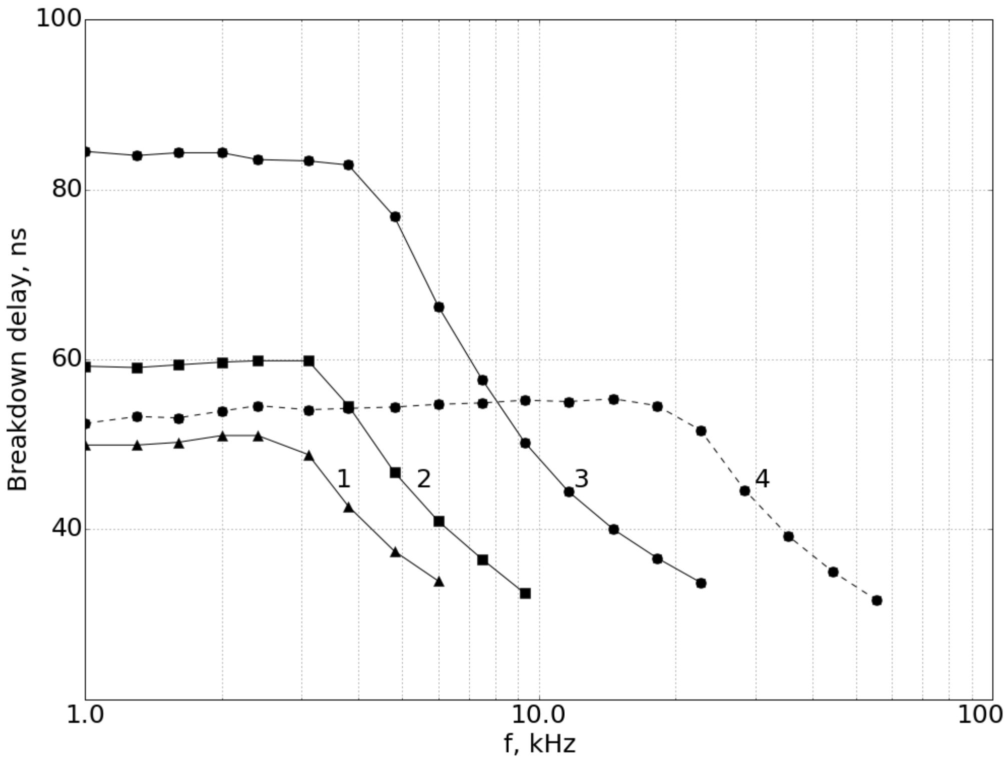

Fig. 1. Dependence of breakdown delay of the switch with 1mm inter-electrode distance on frequency. U = 11 kV; P_{He} = 10 Torr (1), 8 Torr (2), 6 Torr (3,4); P_{H2} = 0 Torr (1-3), 0.2 Torr (4).

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OPERATING FEATURES OF THE PLASMA ELECTRON SOURCE BASED ON THE ARC DISCHARGE IN THE FOREVACUUM PRESSURE RANGE[1]

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The study of operating features of the pulsed plasma electron source based on the arc discharge with the cathode spot in the forevacuum pressure range is presented. It has been established that the working gas pressure in the range of 3–10 Pa affects on both the emission plasma parameters and formation of the electron beam. Increase of the working gas pressure causes an increase of pulse amplitude of the electron beam current at the constant discharge current. Increase of the pressure also leads to a more rapid growth rate of the beam current at the pulse leading edge. We suppose that this influence of pressure on the plasma source features is caused by the reverse ion flow, which presents in the forevacuum pressure due to the ionization of the working gas by the electron beam. The reverse ion flow may affect on the emission plasma generated by the arc discharge because the electron emission area is sufficiently distant from the cathode spot.

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CONSTRICTED ARC PLASMA SOURCE[1]

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Plasma source based on constricted arc discharge, which feature is the ability to adjust the ring constricted channel was developed. Structurally the constricted gap is formed on the individual electrode and the accelerated electrons accelerating radially, which should provide improved generated gas plasma distribution uniformity. Primary plasma is created by a cathode spot, moved on the internal surface of cylindrical hollow cathode and stabilized by magnetic field, similar to the system described in [1]. For the plasma source operation two power supply stabilizing the arc current and potential of electrode with constricted gap was used. Investigations of the main characteristics of the created source in dependence on the operating gas type and it pressure, the values of the stabilizing magnetic field and the discharge current, as well as constriction gap configuration and potential was carried out.

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PLASMA SOURCES AND EQUIPMENT

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MAGNETRON SPUTTERING SYSTEM FOR COATINGS DEPOSITION WITH ACTIVATION OF WORKING GAS MIXTURE BY LOW-ENERGY HIGH-CURRENT ELECTRON BEAM [1]

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The use of electron beam with controlled parameters provides not only effective decomposition of working gas mixtures and dramatic decrease of optimal values of molecular gases pressures and flows, but also ensures a wide range of variation of the ion-to-atom flow density ratio on the surface of the coatings deposited by magnetron sputtering. Conditions of stable generation of high-current pulsed electron beam and the optimum beam parameters for effective decomposition and ionization of working gaseous mixtures in system of oxide, carbide and nitride coating deposition by magnetron sputtering are determined.

The low-energy electron beam (~100 eV) was generated by plasma electron source with grid stabilization as at direct current (4 A) and at pulse-repetitive regimes of self-heated hollow cathode discharge operation (10-100 A, 0,2 ms, 10-1000 Hz) [1,2]. The design of magnetron sputtering system with four flat magnetrons and the planetary multiposition manipulator is presented. Wide (100 cm^2) electron beam enters the system along a system symmetry axis. Joint operational stability of the electron beam source and magnetron sputtering system over the gas pressure range 0,01 - 1 Pa was realized and the maximum pulse ion current density from plasma equal 0,1 A/cm^2 was achieved. It was shown, that plasma activation by electron beam provides excellent adhesion, optimal microstructure and improved properties of superhard nanocomposite (Ti,Al)N-Si3N4 and TiC/-a:C:H coatings deposited by magnetron sputtering [3,4].

Mass spectrometer analysis of the beam plasma composition have shown nearly double growth of N^+ ion density in N2-Ar plasma created by pulse high-current (100 A) electron beam in comparison with a direct current beam plasma.

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HELIUM PERMEATION THROUGH MATERIALS FOR GAS DISCHARGE PLASMAS DEVICES

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The study of the gas permeability trough composite materials is important for creating the gas discharge plasmas devices. It is necessary to determine material type to create sealed devices that has minimized gas permeation during operation. Helium is selected as a tracer gas in tests because of the high value of its diffusion coefficient through the solid body relative to other gases.

The apparatus for the measurement is designed on the basis of a helium leak detector. The method of the helium chamber is implemented with this leak detector in accordance with OST 5.0170-81. The helium mass spectrometer leak detector TI1-14, produced by JSC “Zavod Izmeritel” (Saint Petersburg), provides a minimum detectable flow of helium $7 \cdot 10^{-13}$ $Pa \cdot m^3/s$ [1]. That corresponds to the first class of tightness according PNAEG-7-019-89.

Test object, placed in a vacuum testing chamber, is connected to the leak detector and evacuated from outside and inside with the leak detector vacuum system. Helium is supplied into the chamber with continuous pumping of the opposite side of the object. Quantitative value of the helium flux is measured by leak detector signal after stabilization of the helium diffusion through the test object.

The test sample of a polymer material with a known permeability value for helium was investigated on the measuring instrument. PTFE was selected as a material for the measurement of permeability for helium. The comparison of the calculated data with the experimental values, obtained on the device, confirms the accuracy of the measurement apparatus and method [2].

The polymer samples with metal coatings and vacuum ceramics sample were selected for the measurement: high molecular weight modified plastelastomer with copper coating 100 nm; low-pressure polyethylene HDPE 209-07 with copper coating 100 nm; vacuum ceramics with K400 glue layer.

The samples for the measurement should have a disk shape with the following dimensions: diameter 44 mm; thickness of 1,00 ± 0,05 to 8,00 ± 0,05 mm; surface roughness is not less than Ra = 2.5.

The curves of the time dependence of the specific flux helium through the sample Q_{sp} are shown at the figure 1.

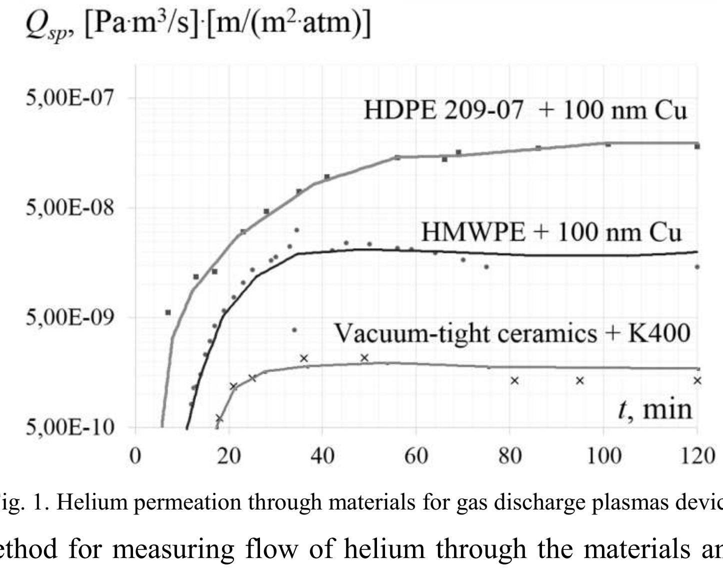

Fig. 1. Helium permeation through materials for gas discharge plasmas devices

Apparatus and method for measuring flow of helium through the materials and coatings, obtained by ion-plasma technologies, are developed and tested. The apparatus for the measurement is designed on the basis of a helium leak detector TI1-14. Research work in the field of diffusion of helium through modern polymer materials with metal coatings are held at this measurement system.

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INVESTIGATION OF THE STABILITY OF THE ELECTRON SOURCE WITH MULTI-APERTURE PLASMA EMITTER GENERATING A LARGE CROSS-SECTION ELECTRON BEAM[1]

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Electrical strength of the high voltage accelerating gap in the electron source with a multi-aperture plasma emitter and large cross-section beam (750 × 150 mm^2) with output into the atmosphere through a thin metal foil is investigated. It is shown that in the presence of plasma emitter mask, dividing the total emission area into a plurality of small cross-section beams, the electrical strength of the high voltage accelerating gap is increased. It is extremely important when using electron source in a frequency pulsed mode at high average power beam. In this case the beam is a superposition of elementary beams formed individual emission structures, the plasma boundary is stabilized by fine-mesh metal grid. In addition, new cathode assemblies of the plasma emitter are created. There cathode assemblies are allowed to reduce the amount of cathode material microdroplets, often leading to electrical breakdown of the accelerating gap. The perpendicular arrangement modernized cathode assemblies relative to electron extraction axis into the accelerating gap also permit to increase the electrical strength of the accelerating gap.

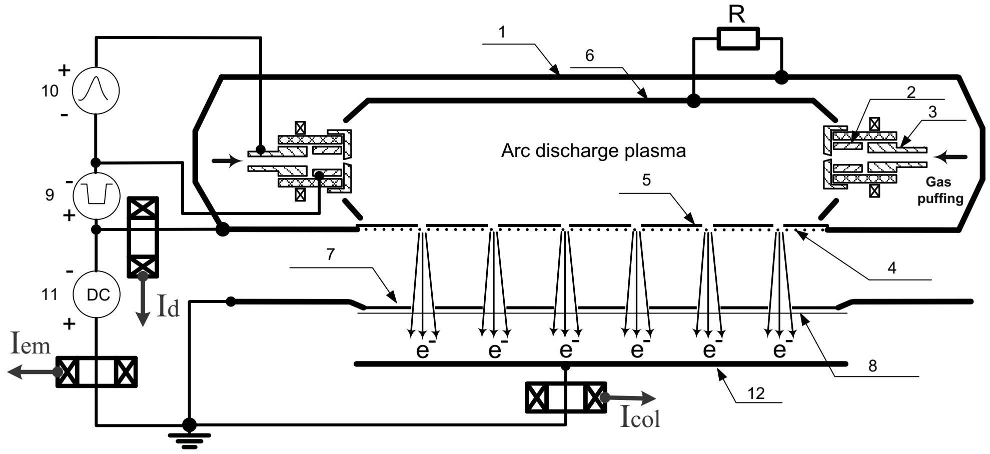

Fig. 1. Scheme electron source with wide-aperture plasma emitter: 1 – hollow anode; 2 – cathode; 3 – igniter; 4 – metallic mesh; 5 – a mask; 6 – screen; 7 – support grid outlet foil windows; 8 – output foil; 9 – discharge power supply; 10 – source power ignition; 11 – high voltage power supply; 12 – the collector.

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[1] The work was supported by the grant of Russian Science Foundation (Projects No 14-29-00091).

ELECTRON SOURCE WITH A MULTI-APERTURED PLASMA EMITTER[1]

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The energy efficiency of the electron source with a multi-apertured plasma emitter and outputting beam into the atmosphere through a thin metal foil is investigated. At this source a plasma boundary is stabilized by fine-wire mesh. The support grid of the outlet foil window is perforated by round holes having a diameter of 15 mm. To prevent loss on the support grid a metal mask with holes of diameter smaller 12 mm is placed on the emission grid. This holes in the mask is located coaxially with the holes in the support grid. Thus, the electron beam is a superposition of elementary beams formed individual emission structures. The plasma boundary of these structures is stabilized by a fine-wire mesh. The output current coefficient from the accelerating gap into the atmosphere reaches 75% from the accelerating gap current. This mechanism of forming and accelerating beam allows to increase the average power of the outputted electron beam into the atmosphere. In our experiments at an accelerating voltage of 200 kV, emission current of 16 A and pulse widths at half maximum of 40 µs into the atmosphere from the accelerating gap was derived about 4 kW average beam power. It is 65% of the beam power into the accelerating gap at 56% geometric transparency of support grid. Further increase in the beam power was limited by power of the high-voltage supply source.

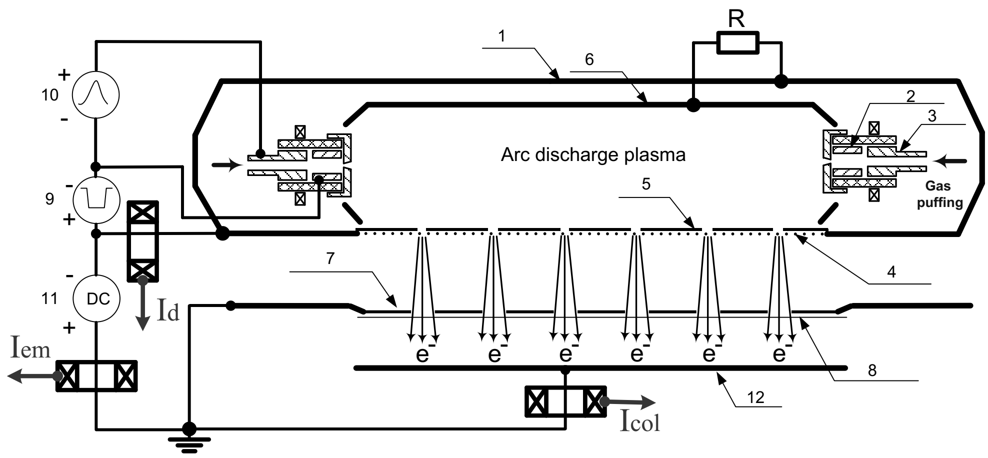

Fig. 1. Scheme electron source with wide-aperture plasma emitter: 1 – hollow anode; 2 – cathode; 3 – igniter; 4 – metallic mesh; 5 – a mask; 6 – screen; 7 – support grid outlet foil windows; 8 – output foil; 9 – discharge power supply; 10 – source power ignition; 11 – high voltage power supply; 12 – the collector.

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[1] The work was supported by the grant of Russian Science Foundation (Projects No 14-29-00091).

MODERNIZATION OF CATHODE ASSEMBLIES OF ELECTRON SOURCES BASED ON LOW PRESSURE ARC DISCHARGE[1]

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The design and main features of several variants of cathode assemblies of plasma electron sources based on low-pressure contracted arc discharge initiated additional discharge in crossed electric and magnetic fields are presented in this paper. In one case, a modification of the initiation system of the arc discharge has reduced the operating pressure into the initiating discharge of electrode system (from ≈10 Pa to ≈0.3 Pa), and change the design of the discharge system of the main pulse arc discharge (t=250 µs). It is extends the range of operating currents of discharge system (up to I_d=300 A), which provides the generation of emission plasma in the plasma cathode. In another case cathode assembly was designed and created, working in a wide range of discharge currents I_d=(5÷100) A, can reduce the number of microdroplets of the cathode material on the electrodes of the discharge system. In addition, when using this cathode assembly the burning of main discharge occurs at a relatively low voltage. Using the cathode assemblies adapted to a particular discharge system extends the capabilities of electron sources with plasma emitter and the scope of their applications in the scientific and technological purposes.

[1] The work was supported by the grant of Russian Science Foundation (Projects No 14-29-00091).

PULSED MODE OF NON-SELF-SUSTAINED ARC DISCHARGE WITH FILAMENT CATHODE AND HOLLOW CATHODE[1]

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In the works [1,2] is shown high potential of a stationary non-self-sustained discharge for plasma generation in large volumes for technological applications. Pulsed mode of the non-self-sustained discharge allow to get pulsed power several times higher than for the stationary mode. As a result a plasma density is also several times higher.

In this work the study of regularities of formation and combustion of the low-pressure pulsed non-self-sustained arc discharge in a plasma source with filament and hollow cathode PINK was implemented. For the discharge burning between the anode (chamber walls) and the hollow cathode was used a pulsed voltage with the amplitude of (20-300)V and with the current up to 600 A for different values of the filament current which provided an electron emission for the main discharge combustion. For voltage-current characteristics determination amplitude values of the voltage and the current measured by oscillograms were used. For getting of plasma parameters of the pulsed non-self-sustained arc discharge with the hollow cathode was used a single cylindrical Langmuir probe.

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[1] This work was supported by Russia research foundation (Grant no. 14-29-00091).

INDUSTRIAL MULTICHANNEL ATMOSPHERIC DISCHARGE PLASMA SOURCES SYSTEM[1]

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One of the main problem by atmospheric plasma (AP) industrial using is the enhancement of total AP system productivity by using AP modules working in parallel. It is not a trivial task when high-voltage open AP reactors (with high level of electromagnetic noise) are using with voltage amplitude up to 100 kV and nanosecond pulse duration. For such a system it is necessary to make special optical control channels communication block (switchboard) operating on the base of touch display (HMI) and communicated by standard protocols with a central control system of a technological line.

The 24 channels communication module developed by authors for using in industrial multichannel AP system have been described in the present paper. There are two types of AP systems can be controlled by this communication module in one system. The first one consist of 12 ADRE-plasma [1-3] modules on the base of "PROTEUS-2" [4] high-voltage generators. The second one AP system consist of 12 atmospheric-water reactors (AWR) pumped by the "POTEUS-5" high-voltage generators. All 24 generators are working as a main part of the wastewater treatment system APHRODITE – 1500 (with productivity up to 1500 ton of treated wastewater per a day).

The symbolic scheme of the communication module has been shown on the Fig. 1.

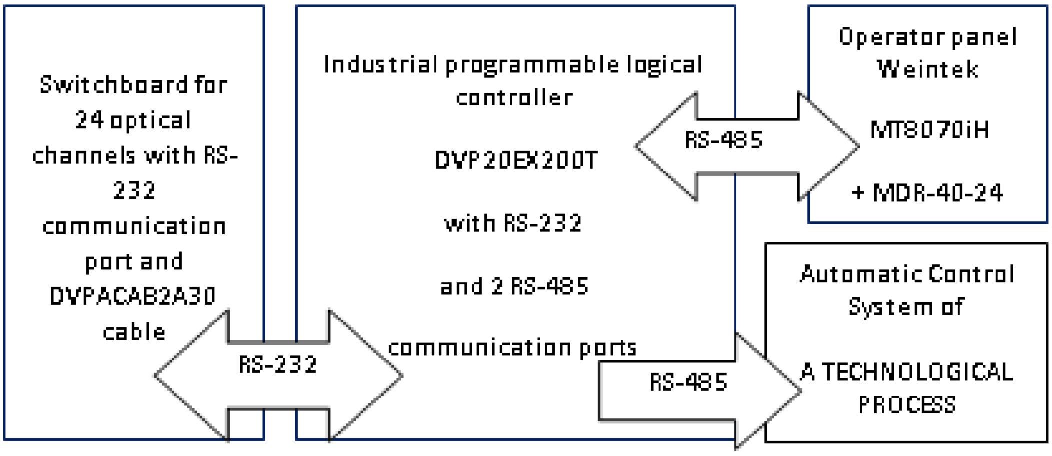

Fig. 1. The symbolic scheme of the communication module for 24 channels AP system control.

The switchboard allows besides 24 generators control to supervise the air or liquids flow through loading (atmospheric or atmospheric - water reactors) to control exhaust ventilation or water flow independently for each channel. It allows lead initial, and service adjustment of generators parameters as well as carry out a power line monitoring, in case of a disorder - stops all generators by one button pushing. The switchboard is compatible to any management information system (RS485 interface, MODBUS protocol). The log of failures are conducting at default for any equipment in a switchboard network and a generation of an alarm sound signal provided for.

The testing work results of the multichannel two type AP system controlled by this communication module in composition of the APHRODITE – 1500 station are describing in the present paper.

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THE MAGNETRON SPUTTERING SYSTEM AS THE SOURCE OF THE Ag NANOPARTICLES FOR APPLICATIONS[1]

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Plasma magnetron sputtering system (MSS) represents special interest for the creation of the sources of clusters, receptions of streams nanoparticles of metals less than 10 nanometers. Using MSS, there is a hope to receive a stream of particles with narrow function of distribution on the size [1]. It is important for researches of properties of separate particles, disperse nanofilms various metals and their chemical compounds (nitrides etc.). Research of process of formation of particles in plasma MSS represents a difficult, complex problem. Particles are formed in plasma conditions, homogeneous and heterogeneous modes of origin clusters, in the fields of electric and magnetic fields, in streams of the rarefied gas etc. The purpose of the given work - to find optimum conditions of process of formation of particles of metals on a silver example in plasma magnetron-sputtering systems, using high-resolution diagnostics methods: appearing through and scanning electronic, atomic-force microscopy. Particles were depositited on materials with various heat conductivity: glass, metals, semiconductors. In the report possible appendices of the received results in the field of gas sensor controls, biosensor controls and biotechnology are considered.

We used planar magnetron sputtering system (MSS). In such sources argon ions sputter a cathode-target surface, atoms of metal leave a cathode surface, dissipate on buffer gas-carrier. If pressure of metal gas above pressure of saturation - in gas germs of metal particles are formed. Formation process clusters is possible near to the cathode, in the limited area plasma area, in area concerning dense plasma. Nuclears of metal particles grow and in the course of drift in buffer gas, in argon. Nanoparticles investigated with the help of high-resolution devices: scanning (JSM-6700F), appearing through (JEM-2010) firms "JEOL" electronic and atomic-force («SMENA» firms NT-MDT) microscopes. Installation is created and electrophysical characteristics plasma sputtering systems are investigated. It is established, that the range of pressure providing stable work magnetron for generation of particles, has limits from 10^{-1} to $3*10^{-2}$ торр. Optimum currents and pressure for magnetron - 2 A and 400V, accordingly. *Fig. 1,2. The surface of the silver nanofilms and nanoparticles*. The particles received at sedimentation on the silicon alloyed by phosphorus (for conductivity) within 1 second is presented. A marker - 10нм. The device - JSM-6700F, Jeol. Particles are separated from each other, they are on considerable distance. We assume, that the size of particles on this mode MPC is close to the size of particles in a stream. The maximum size of particles does not exceed 3-4 nanometers. The most part of particles has the size essentially smaller. In the course of experiences dependence of the size of particles on time of sedimentation on a surface of materials is revealed. It is shown, that sedimentation time can be the factor of management of dispersion nanofilm. It can be analogous, when process of formation of a film of a steam phase goes on the mechanism of vapor - liquid - crystal. This fact is known in thin-film technology. In the given experience other mechanism is probable: cluster - nanoparticle - particle (CNP).

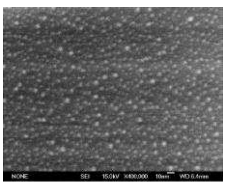

Fig. 1. The surface of the silver nano-films. SEM.

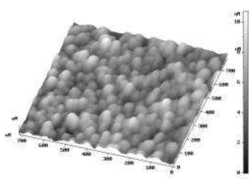

Fig. 2 The silver nanoparticles on the Si. AFM.

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SUBNANOSECOND SWITCHING OF HIGH-VOLTAGE PULSES IN THE "OPEN DISCHARGE"[1]

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Gas-discharge devices based on "open discharge" configuration are useful tools for generating powerful electrical pulses with nano- and subnanosecond rise and fall times and high-energy electron beams. Development and studying of efficient high-voltage sealed-off switches operating at pulse repetition rate of up to tens and hundreds of kilohertz are of current interest due to the possibility of creating high-voltage pulse generators with nano- and subnanosecond rise and fall times for efficient pumping of lasers. Functioning of presented switches is based on the original properties of the "open discharge" which are circumstances of its photoemission nature: large time delay between the moment of voltage applying and the moment when current through the switch peaks (up to tens of nanoseconds), current pulse width can be many times less than the applying voltage rise time (hundreds of times). These factors able to provide circumstances of very fast transition of the device into the highly conducting state, and thus achieving pulse compression to nano- and subnanosecond time range. Review of the results of investigations of such type of devices is presented. Experiments were carried out with chambers operating with opposite electron beams in cylindrical and planar geometry. Physical processes in the "open discharge" that provides mechanism of discharge ignition and sustaining are investigated. Experimental investigations of switching characteristics were carried out. The following values of switches parameters are achieved: switching voltage up to 30 kV; pulse repetition rate up to 100 kHz; switching efficiency up to 95 %; switching current up to 28 kA with maximum current rise rate up to $3.7 \cdot 10^{13}$. The maximum attainable parameters of the devices are discussed.

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IMPROVEMENT OF COMBINATED LASER-PLASMA WELDING

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At technological operation of welding connection of details residual stresses appears in a joint weld. Usage of high-energy sources of energy because of very fast heating in an interaction zone with metals, arises their local linear expansion leading to change of geometry of a joint and emergence of residual stresses[1, 2].

This problem can be solved by preliminary heating of the connected details (or locally - joints) up to the annealing temperature. However it is not always possible and not necessarily leads to positive result. This operation increases technological time and energy consumption.

The combination of high-energy sources leads to increase of characteristics of a technological complex for welding and to expansion of technological capabilities due to combination of processes of welding and annealing. The offered version of the technological scheme is shown in fig. 1:

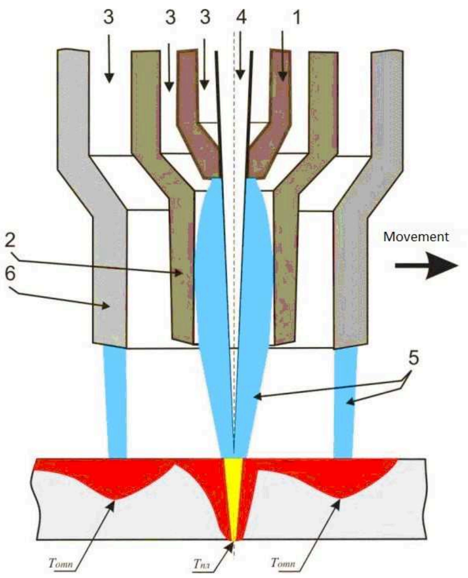

Fig. 1. Scheme of Welding the combined laser-plasma power source.

where 1-Main nozzle of a plasmatron, 2-Concentrating nozzle, 3-Plasma-forming gas, 4-Laser radiation, 5-The plasma combined with a laser radiation, 6-Additional nozzle of a ring stream of plasma.

The approach allowing to reduce residual stresses at laser-plasma welding and to increase coefficient of absorption of laser radiation due to increase metal temperature by plasma is offered. At combination of welding and annealing processes the gradient of temperatures between processes that allows to reduce the speed of cooling of a joint weld that reduces residual stresses decreases. The mathematical model allowing to optimize constructional and technological parameters at laser-plasma welding is offered.

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INVESTIGATION OF PLASMA CATHODE WITH LOW PRESSURE ARC DISCHARGE IN AXIAL MAGNETIC FIELD FOR INTENSE ELECTRON BEAM SOURCE[1]

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In last some years low-energy submillisecond electron beams with the plasma cathode began to be applied actively to surface modification of a metal and ceramic-metal materials, and also to be used for researches in the field of extreme thermal influence on materials.

From the point of view of energy use efficiency for these purposes the electron beam with control quasirectangular energy density profile is ideal. It allows to distribute evenly all energy of a beam on the work surface area. For example, having opportunity to operate a profile of a beam it is possible to put the same energy with maximum efficiency in evenly melted off beam print on materials with various temperature of melting. At the same time today it isn't known technical solutions for sources of intensive electron beams with the plasma cathode which would meet these requirements fully. Therefore development and creation of an electron source with such opportunities is an actual scientific and technical task and it is looks like a perspective direction of investigation.

In the presented work the main efforts were concentrated on development and researches of the plasma cathode based on the gas arc discharge with low pressure which provides discharge current and current of an electron beam in the range up to 500 A. During experiments with an electron source stable operation of the plasma emitter in all range of working gas (Ar) pressure was noted. Discharge current was changed in the range from 20 to 500 A, pulse duration was changed from 20 to 200 microseconds. For three diameters of the used apertures (25, 45 and 65 mm) discharge burning voltage corresponded to the minimum values for the gas discharge for Ar (~ 40 – 45 V).

It was shown that the profile of energy distribution on the electron beam cross-section essentially depends on density distribution of the electron beam in the region of a gas-discharge cell of the plasma cathode. Possibility of increase in efficiency of an investment of electron beam energy at metal surface melting by means of changing of the cathode cavity area in the plasma emitter was experimentally shown.

[1] This work was supported by Russian Science Foundation (project No. 14-29-00091)

IMPROVEMENT OF A BLUMLEIN PULSE FORMING LINE IN BIPOLAR PULSE MODE[1]

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The paper presents the results of studies of a Blumlein pulse forming line with deionised water dielectric (1-1.2 kJ of stored energy, wave impedance 5 Ω) and two spark gas gaps, the main gap at the Marx generator end, and the preliminary gap at the diode one. The experiments were carried using the TEMP- 4M pulsed ion beam accelerator [1] during its operation in bipolar-pulse mode with the first negative (300 - 600 ns, 100 - 150 kV) pulse followed by a second positive (120 ns, 250 - 300 kV) pulse, see Fig. 1.

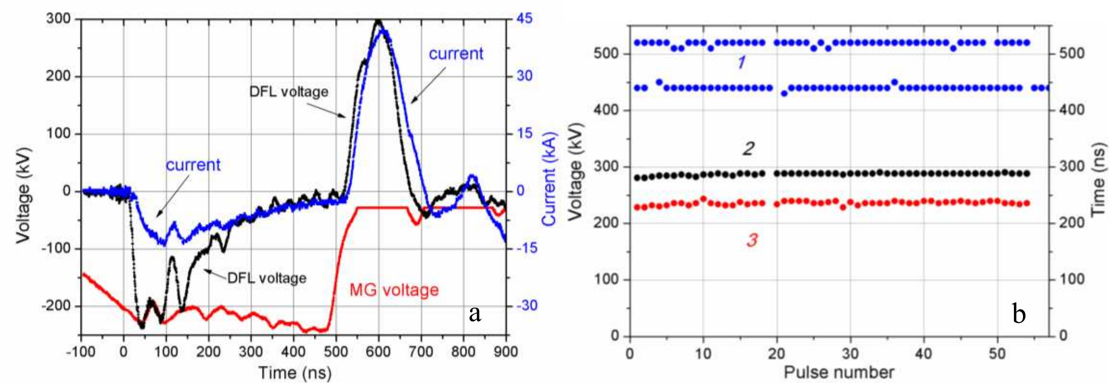

Fig. 1. The waveforms of voltage and current at the output of Blumlein and charging voltage of Blumlein (a). Variation in the duration of the first voltage pulse at different length of the cable (1) and variation in the breakdown voltage of the main gap (2) and the preliminary spark gap (3) operated in externally triggered mode (b)

A characteristic feature of Blumlein operation is an excellent reproducibility of breakdown of the preliminary spark gap, the standard deviation (SD) of the breakdown voltage is less than 2%. At the same time, SD of the breakdown voltage of the main spark gap is 4-5 times higher. To improve the statistical performance of the main spark gap we used the first voltage pulse at the output of Blumlein to trigger the main spark gap [2], see Fig. 2.

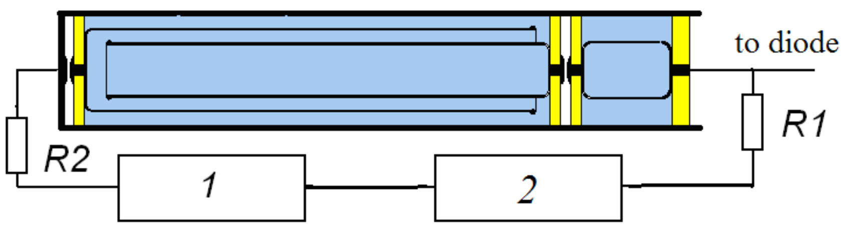

Fig. 2. The schematic of the trigger pulse formation for external triggering of the main spark gap: *R*1 and *R*2 – resistance of a voltage divider and a resistance limiting the current though the discharge gap, respectively; 1 - transformer; 2 – a cable used for the formation of a delay time between formation of a trigger pulse and arrival of this pulse to the trigger electrode of the trigatron spark gap

The study shows that when the main gap is triggered by a voltage pulse of negative polarity (without transformer 1, see Fig. 2) a so called “slow” mode of initiation of triggering breakdown is realized. Changing the polarity of the trigger pulse will make it possible to realize a “fast” mode of triggering mechanism and additionally improve shot-to-shot reproducibility of the breakdown voltage. To change the polarity of the triggering pulse in trigatron we used a transformer with a core made of permalloy tape. The new trigatron – type regime of the main spark gap operation showed a better reproducibility of the first pulse duration, with the time jitter not exceeding 5-7 ns in a set of 50 pulses. When the main spark is triggered by a positive polarity pulse the SD of breakdown voltage was reduced from 8-10% to 1-2% (see Fig. 1).

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TWO-STAGE OPEN DISCHARGE BASED PULSE COMPRESSOR[1]

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One of the most common way to compress high-voltage pulses is magnetic compression due to saturation of the magnetic cores. This method allows to achieve compression ~ two orders using 2-3 stages. However this method has considerable disadvantages: significant power losses due to remagnitization, which leads to core heating, especially at high frequencies; significant permeability deviations even in one batch; large sizes of cores using with submicrosecond pulses; complexity of obtaining pulses with subnanosecond rise time.

That's why finding novel alternative ways of pulse compression is of a great interest. Previously, it was demonstrated that compression ratio of pulses in devices based on open discharge can achieve value up to 100, with efficiency exceeding 90% and pulse repetition rate achieving tens of kHz without decreasing switching characteristics.

Possibility of using open discharge based pulse compressors in the two-stage circuit was studied. Total compression ratio of 250 was obtained, in the second stage minimal pulse rise time of less than 200 ps was measured. Compression ratio tuning was realized due independent pressure variations in devices of each compression stage. Total jitter of two stages was less than 1 ns.

Thus, possibility of stable and efficient compression of 100 ns pulses into subnanosecond region using two-stage compressor with devices based on open discharge was demonstrated. Abilities of creation effective multistage submicrosecond compressor are discussed.

[1] This work was supported by RFBR Grant No. 14-08-31638.

PULSED MAGNETRON DISCHARGE FOR BORON PLASMA AND ION BEAM GENERATION[1]

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Pulsed planar magnetron discharge with boron and lanthanum hexaboride targets was studied. Discharge current pulses with amplitude up to 50 A and duration of 100 μs were applied to the discharge gap together with low-current (0 - 100 mA) DC magnetron discharge. It has been proved that such a DC discharge can be used for boron target heating to a temperature of 300-400 °C, at which conductivity of boron reaches a value sufficient for high-current pulsed discharge mode. In such mode, a self-sputtering[1] of the target is realized, characterized by a boron ion fraction reaching 99%. It was found that for pulsed discharge with boron, and lanthanum hexaboride targets, DC discharge provides stable and reproducible ignition of the discharge, eliminating a delayed current onset[2], and affects on mass-to-charge plasma composition, reducing a fraction of working gas ions and increasing a fraction of the target material ions.

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PLASMA SOURCES AND EQUIPMENT

[1] This work was supported by Russian Foundation for Basic Research under grant # RFBR 13-08-00185a.

SYNTHESIS OF Fe AND Al OXIDE NANOPOWDERS BY SPARK DISCHARGE [1]

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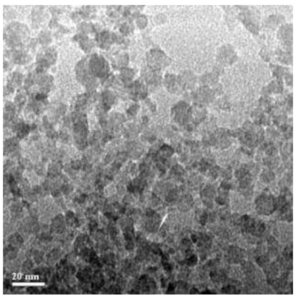
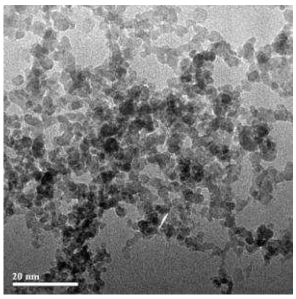
Small nanoparticles of different materials with sizes 1-10 nm have been for a long time the subject of special interest due to their properties which are suitable for a large variety of applications in sensor technology, non-linear optics, nanoelectronics and others [1,2]. Development of technological applications of nanoparticles in the form of nanopowders stimulates development and improvement of methods for their preparation. One of the promising and versatile techniques for gas-phase preparation of nanoparticles with sizes in the range of several nanometers is synthesis of nanoparticles during spark discharge. This method can be used for the production of metal nanoparticles including semiconductors and their chemical compounds.

In the course of this work the spark discharge generator for the synthesis of metal oxide nanopowders has been made and tested. In the developed setup the spark discharge is realized between pairs of iron or aluminum electrodes of the plasma rail gun. Using the rail-type electrode system allowed to realize electrodynamic acceleration of a plasma bridge and to use the emerging pulse for a more intense decrease in the concentration of metal vapor, which are formed in the result of erosion of the electrodes. The power supply to the plasma gun was realized from the current pulse generator with a variable capacitive storage of 0.1-0.4 μF. Charging voltage of the capacitor bank was varied from 10 to 25 kV and the repetition rate of the discharge pulses in the range of 10-100 Hz. The experiments on the synthesis of the nanopowders were carried out in the mixture N_2/ 20% O_2 at 0.11 MPa. The gas system of the setup was of the closed type. The report presents the results of the experiments on the production of nanopowders of Al and Fe oxides. The produced nanopowders were analyzed by BET, XRD and TEM. The dependences of the influence of energy of the capacitive storage, period of oscillations of the discharge circuit and repetition rate of the discharge pulses on the characteristics of nanopowders and productivity of the synthesis are shown. The electron microscopy the nanopowders obtained at different conditions has showed that the nanopowders consisted of spherical primary particles with sizes from 1 to 30 nm (Fig 1) with log-normal particle size distribution (PSD). Increasing of the power of the capacitor storage and the discharge frequency led to the increase of the average size of the primary particles and of the width of the PSD. At the reduction in the duration of the spark discharge the average particle size was reduced and the PSD became more narrow. According to the XRD the produced nanopowders had crystalline structure and the phase composition depended on the conditions of the synthesis.



a)



b)

Fig. 1. TEM images of nanoparticles produced by spark discharge: a) Al_2O_3; (b) Fe oxide.

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[1] This work was supported by RFBR grant № 15-08-06436

THE INVESTIGATION OF METHODS FOR INCREASING THE ELECTRODES LIFETIME AND THE CONTINUOUS WORK TIME OF ELECTRIC ARC AC PLASMA TORCHES.

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The performance reliability of the plasma torch during all the work cycle is one of the main efficiency criterion of AC plasma torches usage in the production process [1]. Electrodes are tend to be the most heat loaded unit of a plasma torch therefore electrodes lifetime defines the continuous work time of the plasma torch.

The increase in the lifetime characteristics of electrodes and the decrease in specific electroerosive wear of the material [2] while using various gases as a working material offers an opportunity in the broad application of plasma torches. They could be used not only in the waste treatment (destruction) industrial-scale plants [3], but also in any plasma chemical processes including the ones that set forward severe requirements in providing temperature conditions and the cycle continuity impact on a feed stock.

The paper presents the experiment results directed towards the increase in the lifetime characteristics of electrode units of the electric-arc AC plasma torches. They were carried out while developing the plasma torches using various gases, including the ones that possess oxidizing properties (air, steam, etc.), as the plasma-forming environment.

Also the paper is devoted to investigate the possibility of the monitoring system implementation of the wear rate of the working part of the end-face electrodes for a high-voltage plasma torch with capacity up to 100 kW in a real-time mode.

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POWER SUPPLY FOR SYMMETRIC AND ASYMMETRIC DUAL MAGNETRON SPUTTERING

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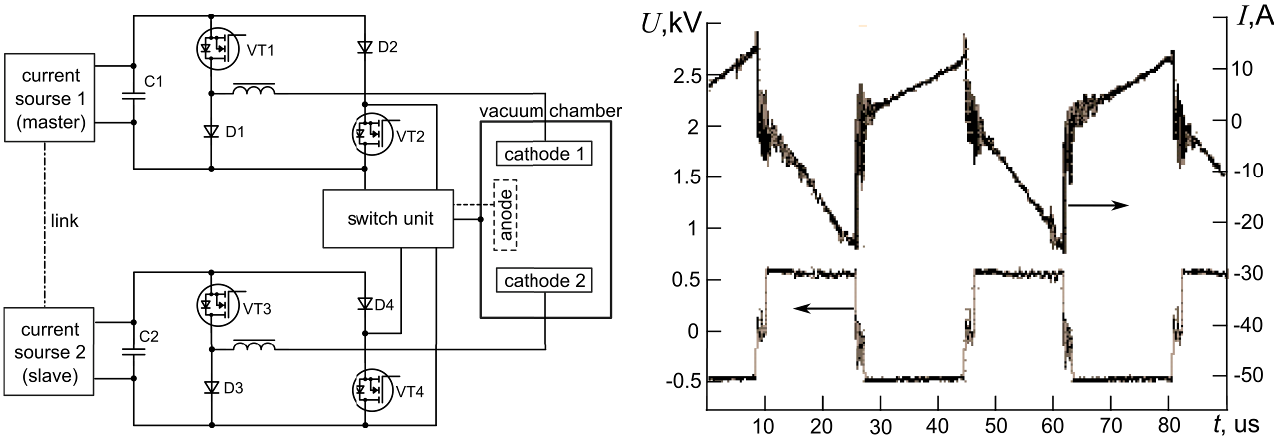
The paper deals with a universal power supply (PS) for mid-frequency dual magnetron sputtering, based on two-transistor forward converter. The power supply consists of two two-transistor forward converters, two current sources and a switch unit.

The circuit shown in Fig.1, can operate with dual and single magnetron sputtering systems (MSS). In addition, an output pulse former allows to operate in symmetric or asymmetric mode. Positive and negative pulses can be controlled independently. Switch unit located at the output end of the former, switches output ends to a required configuration (dual or single). Also switch control method is changed.

Fig 1.b. shows the oscillograms of current and voltage at the output of the dual MSS PS operated in an asymmetric mode. Each target sputtering rate is independently controlled in this mode. Power applied to each target is determined by current, voltage and pulse duration.



(a) (b)

Fig.1.a. The output pulse former, based on two-transistor forward converter, b. The oscillograms of current and voltage at the output of the dual MSS PS.

Output pulses can be formed with a frequency in the range of 1 – 100 kHz. Duty cycle is regulated from 10 to 90%. A peak pulse current value in the output pulse former may be two times higher than the average output current value. This allows obtaining high output power at different duty cycles of positive and negative pulses.

An important feature of this power supply is a fast switching time of polarity, which does not exceed 1 μs. This is due to recovery of energy stored in the output inductance of the power supply.

HIGH-VOLTAGE ELECTRODE OPTIMIZATION TOWARDS UNIFORM SURFACE TREATMENT BY A PULSED VOLUME DISCHARGE[1]

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The present article examines shape optimization and selection of right materials for atmospheric pressure plasma generation system. The purpose of the article is to reach uniform plasma surface treatment maximum of low-voltage electrode about 1 sq dm in area. Low-temperature plasma generation approximately 1 cubic dm in volume requires pulsed volume discharge initiated by corona discharge [1]. Damped harmonic oscillations pulse generator [2] serves as an energy source.

System for measuring the discharge current density distribution is used for evaluating degree of plasma uniformity in low-voltage electrode area [3]. System's low-voltage electrode – the collector – is represented by disc a 100 mm over, with conducting surface divided into 64 equal segments. Each segment's current is registered by high-speed measuring system headed by ARM™-based 32-bit microcontroller. System allowed evaluation of discharge density distribution for both single pulse method and repetitive mode results accumulation method.

Visualization software was created to improve obtained results interpretation. Program provides 2D-image of current density surface distribution in low-voltage electrode area. Based on received data, optimum high-voltage electrode shape was determined.

During the experiment graphite felt (VGN-6 = Russian abbreviation) specified itself as preferred emission surface of high-voltage electrode material. It is a flexible sheet inorganic conductive material. Felt consists of individual thin fibers, which provide significant number of micropoints on the surface. Micropoints in its turn made the corona discharge ignition easier.

Also during the experiment volume discharge in this case reports the ignition to be non-equal around the section, but to be at certain plasma channels or current filaments which carry discharge current flows [4]. Single pulse current density distribution sustains this fact, as it also indicates the absence of current flow in the number of collector's segments. Accumulation 100 pulses results led to the record of current in all segments unexceptionally. The reason probably is that emission centers rolled over the high-voltage electrode surface, which led to the movement of plasma channels locations. Therefore, the implication is that in frequency mode entire low-voltage electrode surface is exposed to the plasma.

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LOW OPERATING PRESSURE DC ION SOURCE [1].

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The paper reports on experimental study of an ion source based on continuous Penning discharge with a cold hollow cathode in crossed electric and magnetic fields. The minimum operating pressure of the source was $3{\cdot}10^{-5}$ Torr for argon and $5{\cdot}10^{-5}$ Torr for hydrogen. The use of hollow cathode effect allowed decreasing the discharge operating voltage down to 350 V at a discharge current of ~100 mA. At a discharge current of 100 mA and accelerating voltage of 2 kV, the ion current was 2.5 mA for argon and 8 mA for hydrogen, and the ion beam current density on the system axis for the gases reached 170 and 450 μA/cm^2, respectively. The current-voltage characteristics of the discharge and collector and the radial ion current density distribution at different accelerating voltages were measured. The influence of pressure on the discharge parameters and their time stability was investigated.

The designed and tested Penning discharge cell will be used as an electron emitter in two-stage magnetron sputtering system subsequently.

[1] This work was supported by the Russian Foundation for Basic Research, project no. 15-08-00058-a.

REDUCTION OF OPERATING PRESSURE OF PLANAR MAGNETRON BY AN ADDITIONAL ELECTRON INJECTION[1].

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The aim of our work is to reduce the lower limit of operating pressure of planar magnetron discharge. To reduce the operating pressure of magnetron discharge below than 0.1 Pa, a two-stage scheme of the magnetron discharge with electron injection from auxiliary discharge with hollow cathode, placed behind the magnetron cathode plane, was used. The auxiliary discharge current is 20-100 mA. Formation of a pressure differential drop between the two discharge stages provides low pressure in the main magnetron discharge, at which a self-sustained mode is difficult or even impossible, and the stable operation of the auxiliary discharge, provides an effective electron injection in the cathode region of the magnetron discharge. Such approach, in contrast to conventional with use of “plasma bridge” and filament ionizers, does not suggest the arrangement of any additional elements or electrodes in the space between the magnetron target and the substrate. It does not expose the substrate to the thermal load and is also is characterized by higher energy efficiency. Moreover, the injected electrons are accelerated in the cathode layer of magnetron discharge, whereby electrons have a sufficient energy to ionize the gas for creation of a dense plasma near the sputtering target.

[1] This work was supported by the Russian Foundation for Basic Research, project no. 15-08-00058-a.

ELEMENTAL COMPOSITION OF VACUUM ARC DISCHARGE PLASMA WITH COMPOUND FILM CATHODE DURING A PULSE[1]

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The paper presents research results on the mass-charge state of the plasma produced in a vacuum arc discharge with a composite cathode which is a flat copper substrate coated with a hydrogen-saturated zirconium film of thickness 10–25 μm. Vacuum arc discharge was operated in a pulse mode with arc current 200 A, pulse duration 250 μm and pulse repetition rate 1 c^{-1}. For analyzing of mass-charge composition we used the method of ion emission diagnostic with time-of-flight mass-spectrometry. It is shown that during the arc current pulse, the fractions of hydrogen and zirconium ions in the plasma decrease synchronously, while that of copper ions increases. The use of the film-coated cathode in a vacuum arc ion source allows generation of multicomponent gas and metal ion beams with a hydrogen ion percentage from several to tens of percent.

[1] This work was supported by Russian Science Foundation under RSF Grant No 14-19-00083.

EXPLOSIVE-EMISSION CATHODE WITH RESISTIVE DECOUPLING IN A HIGH-CURRENT PLASMA-FILLED DIODE[1]

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Resistive decoupling is well-known method stabilizing an operation of explosive-emission cathodes [1, 2]. This method allows one to suppress so-called emission centers-leaders, consistently appearing while operation of wide-area explosive-emission cathodes. Availability of centers-leaders reduces a number of concurrent emission centers and therefore degrades the homogeneity and stability of the cathode operation. To suppress centers-leaders it is needed to limit the current through all emitters since the location of leaders may change from pulse to pulse. Current of each center may be limited by a space charge of electron flux emitted by respective center [3], or by connecting of active resistance in series to the circuit of each emitter. The first method is realized only at low current density (less than 30 A/cm^2), which is not suitable for us. Therefore, the second method was chosen. But the use of resistive decoupling in a plasma-filled diode requires careful isolation of the cathode substrate because the emission can be initiated on a flat surface located under the plasma. Therefore, the emission centers on the substrate may shunt the resistors placed in the emitter circuit what is unacceptable.

The cathode with resistive decoupling was firstly developed and applied for a high-current plasma-filled diode in [4]. This cathode represented a packet of resistors TBO-0.125 glued with epoxy compound. The diameter of emitting part of the cathode was 1.5 cm. The ends of the resistors were cut and polished to expose the carbon core, which served as the emitter. However, carbon erosion products, which may deposit to the treated target, are usually undesirable. Therefore, we have developed two types of cathodes with metal emitters. The first cathode was made from resistors TBO-1 (156 pcs), wire leads of which served as emitters (Fig. 1a). The second cathode emitters represented Ni-Cr wires of 100 μm in diameter (297 pcs) inserted into ceramic tubes with narrow channels (Fig. 1b).

The present paper is devoted to investigations of above mentioned cathodes with resistive decoupling of emitters.

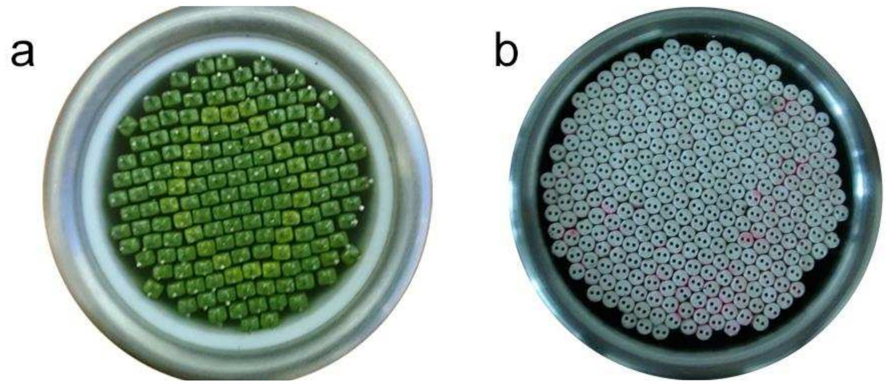

Figure 1. Explosive-emission cathode with resistive decoupling of the emitters: cathode based resistors TBO-1 (a); the cathode made of Ni-Cr wires inserted into ceramic tube (b).

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ELECTROSTATIC PLASMA OPTIC DEVICES: NEW APPLICATIONS[1]

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This is the review of recent results of ongoing research and development of the plasma optic devices based on the cylindrical electrostatic plasma lens configuration. These devices are attractive for application in the state-of-the-art ion-plasma technologies. The electrostatic plasma lens is a well-explored tool for focusing high-current, large area, energetic, heavy ion beams. It provides a convenient, affordable and quick way of carrying out particularly high-dose ion implantation. Here we present some designs of the plasma-optical system and novel attractive possibility for effective practical applications the state-of-the-art plasma technologies.

The one of new application is the high-current wide-aperture non-relativistic electron beams focusing. The plasma optical system used for primary electron beams formation and focusing is formed by the grid-bounded plasma emission surface and open plasma boundary created by a plasma lens discharge in the transport channel.

We describe also the original approach to effective additional filtering of micro droplets in a dense, multi component low temperature plasma flow generated by erosion plasma sources like vacuum arc produced plasma. This approach is based on application of the cylindrical plasma lens configuration (Gabor lens) for introducing in a volume of propagating along axis dense low temperature plasma flow radial convergent energetic electron beam produced by ion-electron secondary emission from electrodes of plasma optical tool for effective additional destroying (evaporation and crushing) of micro droplets.

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HIGH-CURRENT DISCHARGE INITIATION IN A VACUUM DIODE[1]

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Results of oscillographic study of the capillary plasma source are presented. Plasma extends as a result of hydrodynamic expansion with a velocity of ~10^6 cm/s determined by the plasma temperature ~1 eV. Besides this, the ions with the velocity ~10^7 cm/s exceeding the thermal velocity are recorded. This flow of the "fast" ions can be used for compensation of the electron charge in high-current e-beam diodes. Possibility of initiation of a high-current low-resistance discharge with the current ~10^4-10^5 A without of complete filling of the diode gap with plasma is considered. The situation in which plasma fills only a part of the diode gap prior to ignition of high-current discharge is favorable for the realization of the current cutoff with a high rate and e-beam generation.

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DEVELOPMENT OF DIELECTRIC BARRIER DISCHARGING POWER SUPPLY

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Abstract –Dielectric barrier discharging is one of the important ways of obtaining low-temperature plasma. Many researches about dielectric barrier discharging are carried out. In order to study the influence factors of the low-temperature plasma produced by dielectric barrier discharging, a flexible dielectric barrier discharging power supply is needed. In this paper a AC power supply with adjustable output voltage and frequency was introduced. Its output frequency is from 1 kHz to 50 kHz. Its output voltage is standard or approximate standard sine waveform from 0V to 30kV at all range of out frequency. The out power of the AC power supply is 2 kW. The AC power supply can be control at local or remote. The power supply has been used in different condition dielectric barrier discharging research.

INVESTIGATION OF NITROGEN-ARGON PLASMA COMPOSITION PRODUCED BY ELECTRON BEAM OF PLASMA SOURCE WITH SELF-HEATED HOLLOW CATHODE[1]

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Discharge with the self-heated hollow cathode is used in a source of wide (100 cm^2) low-energy (about 100 eV) electron beam which provides additional ionization of the working medium in coating deposition systems with magnetron sputtering [1]. Ionization and dissociation of the molecular gases (e.g., C2H2 or N2) by electron beam accelerates plasma-chemical processes rate in the volume and increases density of the ion flux to the surface that influences the microstructure, growth rate, defective and stress state of the coatings, and ultimately, the coatings properties.

Composition of the ionic component of the plasma generated by a broad low-energy electron beam in the low-current (3 A) continuous and high-current (~ 100 A) repetitively pulsed (200 µs, 200-1000 Hz) discharge modes for nitrogen-argon gas mixture pressure ~ 10^{-3} Torr was studied by mass spectrometry.

In this research, the obtained spectra for electron-beam plasma had no significant traces of self-heated cathode material (Ti) which may be present in the cathode region of the discharge in the form of ions in pulsed discharge mode [2].

It is shown that in a reactive medium with 30% nitrogen and 70% argon, which corresponds to the commonly used medium in installations for superhard nitride coating deposition, the time-averaged ionic composition of the electron beam plasma changes significantly during the transition from continuous to pulsed-periodic mode of operation of the electronic source, even for equal average power in the electron beam. It was found that with pulse generation frequency decreasing and a corresponding increase in the amplitude of the beam current at constant average current (3 A) and electron energy (200 eV) doubling of atomic nitrogen ions content in the total ion current from the beam plasma occurs (Fig. 1).

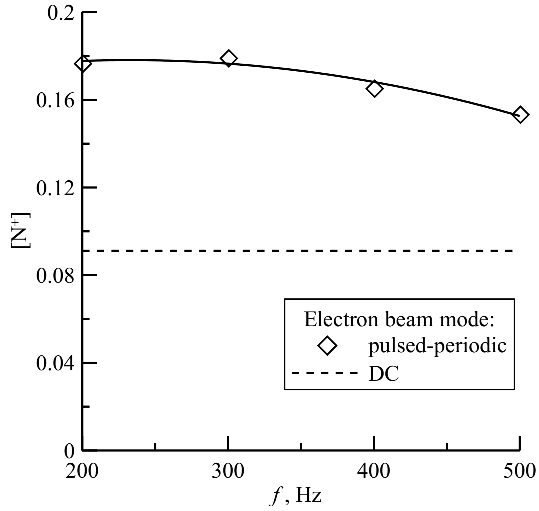

Fig. 1. Time-averaged atomic nitrogen ions content in the total ion flux sampled from beam plasma depending on the electron beam current pulse frequency and in DC-mode (for comparison).

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DIAGNOSTICS OF ANODIC AND ELECTRON BEAM GENERATED PLASMAS OF ELECTRON SOURCE BASED ON A DISCHARGE WITH SELF-HEATED HOLLOW CATHODE [1]

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The spectral composition of the radiation of anodic plasma in electron source based on a discharge with self-heated hollow TiN-cathode (SHHC) and also broad (100 cm^2) low-energy (200 eV) electron beam generated plasma in low-current DC (3 A) and high-current (100 A) pulse-periodic (200-1000 Hz, 200 μs) beam generation regimes was investigated by optical emission spectroscopy.

Measurements were carried out in wide range of wavelengths (200-1200 nm) with use of three automatic spectrographs (UV, visible and IR ranges). It was experimentally shown that in pulse-periodic mode titanium atoms Ti (λ=318,3 nm) and monovalent ions Ti^+ (λ=323,4 nm) lines intensity increases with current pulse amplitude growth at constant average current (Fig. 1). Emission spectra of low-current DC and high-current pulsed electron beam generated plasma in nitrogen and argon gas mixture (Fig. 2) are recieved under conditions of gas pressure ~1 Pa and average beam current ~3 A, which are typical for such processes as nitride coatings deposition and ion-plasma nitriding. In contrast to [1] it was shown that the pulse repetition rate decreasing (with corresponding pulse electron beam current amplitude rise at constant average beam current) leads to significant increasing of monovalent ions N^+ (λ=343,7 nm) part in electron beam generated nitrogen-argon plasma , which can be explained by intensification of processes of argon ions charge exchange to nitrogen molecules and molecular nitrogen ions dissociative recombination with the participation of low-energy plasma electrons as a result of multiple (more than 10 times) ion current density amplitude increasing with corresponding duty factor decreasing.

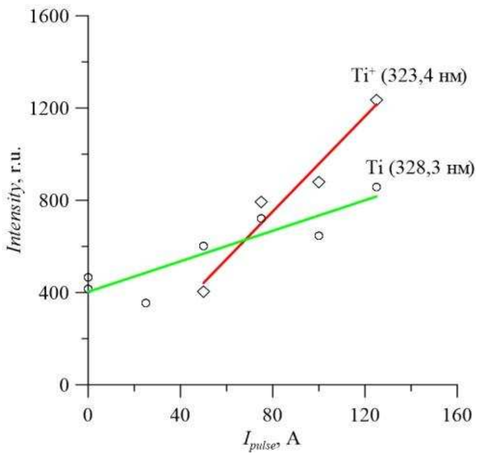

Fig.2. Dependences of Ti and Ti^+ lines intensities on discharge current pulse amplitude.

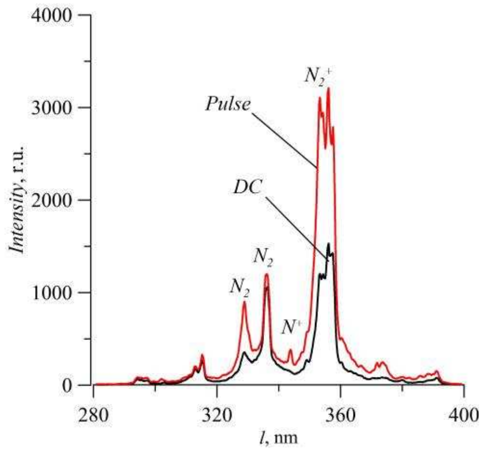

Fig2. Characteristic emission spectra of EBGP at DC and pulse-periodic regimes.

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FORMATION OF THE FOCUCED ELECTROM BEAM BY THE PLASMA SOURCE IN FORE-VACUUM PRESSURE RANGE

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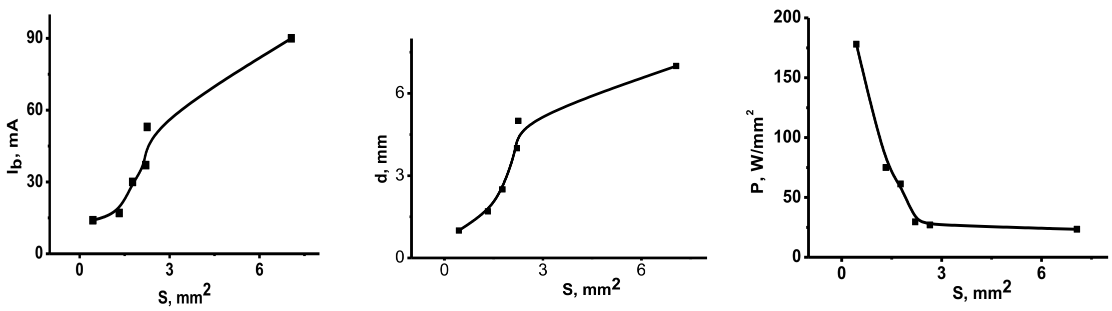
One of the perspective directions of using of an electron beam is layer-by-layer powder sintering for the purposes of creation of 3D-prototyping technology of ceramic products. The most successful tool for creation of an electron beam for declared problem is fore-vacuum electron source with hollow cathode, which could reliably work in a pressure range of 5 - 30 Pa [1]. Successful application of electron beam is determined by, mainly, two parameters: the minimum diameter and power. The said parameters are substantially inconsistent. The purpose of the present work is the search of an optimum parity between two specified parameters.

As the initial parameter of the problem, the area of emission site provided by apertures of small diameter in the source's anode was chosen. The increase in number of apertures in the anode leads to increase in a current of a beam and simultaneously increases its diameter. The anode itself represented the perforated electrode with the thickness of 1 mm with apertures of 0.75 mm diameter. Measurement of diameter of an electronic beam was carried out by means of a double rotating probe [2]. Fig. 1 shows the dependence of the current a), diameter of the focused electron beam b), measured in its focal plane, and power c), delivered to the target, in dependence on the area of the anode emitting surface, i.e. the number of holes in the anode grid.



a) b) c)

Fig. 1. Dependence of a e-beam current a), diameter of the focused electron beam b), measured in its focal plane, and the power density delivered to the target c), depending on the area of an anode emitting surface, at accelerating voltage of 10 kV, discharge current 500 mA, and pressure 9 Pa.

With growth of the emitting surface area, the increase in a current and diameter of an electron beam is observed, thus the power density to the target decreases. At minimum experimentally obtained electron beam diameter of (~1 mm), the power density is sufficient for sintering of ceramic powders.

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JITTER OF THE LTD SPARK GAP SWITCHES[1]

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In modern pulsed power, the LTD technology is considered as rather promising for different applications. At a same time, the possibilities of this technology would extend depending on whether the LTD cavities may operate at a jitter below ~0.5 ns. In our tests of separate LTD switches designed for the cavities with oil insulation, it was found that in the preferable trigger conditions their overall jitter is ~2.2 ns. It was found also that this overall jitter includes not only the occasional but also the systematic part. In the report we investigate the reasons of this systematic part without which the jitter of the LTD cavity with more than 25 bricks would reduce to less than ~0.5 ns.

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POWERFUL NANOSECOND VUV VOLUMETRIC GAS DISCHARGE

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Powerful nanosecond VUV generator with attendant acoustic radiation was constructed for studying of properties of optic pumping of laser mediums, dynamic of transformation of absorption spectra of crystals, and also features of passing of acoustic pulses in a crystal lattice.

The device represents the uniform coaxial design consisting of a trigatronny optical source, the powerful generator of high-voltage nanosecond pulses (GIN) and the generator incendiary of the volumetric gas discharge. Optical source works in regime of the volumetric gas discharge, which is formed when on a volume plasma interval is switched the high-voltage pulse of GIN. Parameters of GIN: 200 kV; 30 J; 1 ns; 0,1-0,5 Hz.

The high-voltage picosecond generator (150, 300 kV; 5 kA; 100 ps; 0,1-12,5 Hz) is developed and used for formation of the volumetric plasma interval [1]. This device was made on the circuit of resonant Tesla generator, but the capacity of the subnanosecond contour was divided and its equal components wormed the structure of the two-step Marx generator. In turn the external facing of the second step of the Marx generator carries out function of compounded line and has a special coaxial design. Steps (capacity) of Marx generator are charged by pulse method. It is raises the electric durability of isolating elements of a design and gas spark intervals. It has allowed to reduce the dimensions of the picosecond generator. Thus losses of energy on the skin-layer, parasitic inductance and capacity of a design, dynamic resistance of gas spark intervals have been essentially reduced.

Controllers of the power high-voltage generator and the picosecond generator forming the volumetric plasma interval have the information channel of communication and their work is initiated by special computer program.

Thus the high intensity volumetric nanosecond VUV discharge was achieved at switched of powerful high-voltage pulse of GIN on the generated plasma interval at gas pressure of 1–5 atm. The spectral maximum of the wide-bend VUV plasma radiation is observed at ~ 30 nm. According to the Wien law $(T = b/\lambda_{max})$ the temperature of plasma conforms to ~ 10^5 K. The minimum duration of VUV and acoustic pulses of 1 ns and pulse edge of 0,1 ns are reached on the gas mix Xe-Ar, N-Ar. The yield of the attendant nanosecond acoustic pulse reached of 40-50%. Earlier with use of this GIN the same parameters were reached when the volumetric gas discharge was formed by a powerful nanosecond electron beam [2].

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THE METHODS OF DECREASE OPERATING PRESSURE OF FAST NEUTRALS SOURCE[1]

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Recently the fast neutrals sources are increasingly used in various technological processes such as surface cleaning, etching and assisted deposition [1]. The use of fast neutrals sources instead of ion sources allows significantly increase the quality of surface processing due to the absence of surface charging, charge-related beam divergence and charge-induced damage [2].

The various designs of fast neutrals source are known. Among them the source described in [3] can be distinguished. The source consists of three electrodes: anode, laminar cathode and hollow additional cathode. During the source operation, ions are generated in the gas discharge plasma located between cathodes. The ions are accelerated in the near-cathode potential well and neutralized at the cathode plates.

The main feature of this source is overlapping areas of ions acceleration and ions neutralization. Through this total absence of fast ions in output beam is guaranteed since not-neutralized ions cannot leave near-cathode potential well with energy higher than few tens of eV. Moreover, the source uses direct current power supply and does not need water cooling what significantly simplify its operation.

However this fast neutrals source has a significant disadvantage since its operation pressure is bounded below by 1…2 Pa. At the same time for many technological processes it is necessary to have process operating pressure as low as possible to increase processes quality. Therefore it is necessary to find methods to decrease minimal operating pressure of the fast neutrals source.

In the work progress a few methods of decrease operation pressure were developed. Each of them requires some modification in the source design and provides certain decrease of the source operating pressure. In addition it is possible to use combination of methods for further decrease of pressure.

First method is to create a pressure difference between gas discharge area and vacuum chamber. Since operation of the source determined by pressure in the gas discharge area while for technological process significant is the vacuum chamber pressure.

Creation of pressure difference is possible due to the main and hollow additional cathodes form a quasiclosed volume. To obtain the sufficient pressure difference the main cathode should have high resistance to the flow of gas. To provide in the cathode was made in form of thick plate with many small diameter openings and thus has high transparency and gas flow resistance at the same time.

Second method is using crossed electrical and magnetic fields similar to what used in magnetron sputtering system. The curvature of electron trajectory by magnetic field and thus increase of length of electron paths in the plasma allows maintain gas discharge at the pressure down to the 0.1 Pa.

Though crossed electric and magnetic fields cause uneven concentration of plasma if can be fixed if the source of magnetic field is far enough from main cathode. In this case the concentration of the gas discharge plasma will be uneven afar from cathode but in the near-cathode area the concentration equalized.

Third method is using an auxiliary gas discharge to support the main discharge. For this the quasiclosed volume of the source is divided into two parts by a partition with very small holes in it. In smaller part of the source volume the sufficiently high pressure is maintained, in this part the auxiliary discharge takes place and the gas ionization is occurred. Then ionized gas gets in the larger part of the volume and thus decreases the minimal pressure of the main discharge maintaining.

Using all three methods at the same time allow significantly decrease the minimal operating pressure of the fast neutrals source. Thereby the source sphere of application expands as well as quality of technological processes increases.

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THE STABILITY OF THE VOLUME DISCHARGE WITH A HIGH SPECIFIC ENERGY IN THE CHEMICAL NON-CHAIN HF-LASER[1]

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In this paper we present the results of experimental studies of chemical HF laser non-chain reaction. The possibility of a complete laser efficiency of 5%, using conventional circuitry of the pump C-C with charging voltage 21 kV is shown. Conditions of formation of in homogeneities in the discharge plasma are studied. Possibility of stable volume discharge for specific energy in the range of 150-350 J/l is demonstrated. It is shown experimentally that the input specific energy of 350 J/l, with a specific energy of the active medium in a mixture of SF_6/H_2 - 14/1, at a total pressure of 0.27 atm is 21 J/l. Fig. 1 shows the dependence of the energy generation and laser efficiency as a function of Ne pressure in the gas mixture.

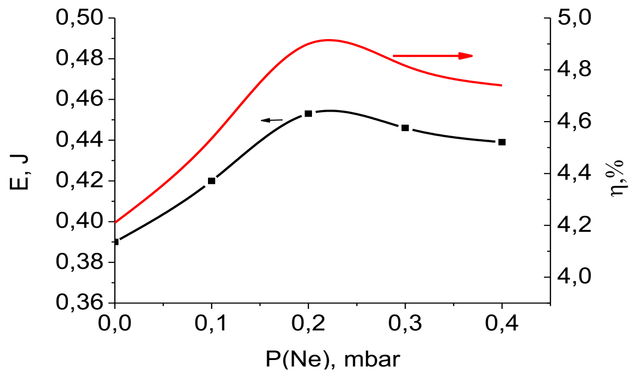

Fig. 1. Dependence of the output radiation energy and laser efficiency as a function of Ne pressure in the gas mixture.

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INVESTIGATION OF METAL PUFF Z PINCH BASED ON MULTICHANNEL VACUUM ARCS[1]

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The performance of a metal double puff Z-pinch system has been studied experimentally. In this type of system, the outer and inner cylindrical shells were produced by ten plasma guns. Each gun initiates a vacuum arc operating between aluminum electrodes. The net current of the guns was 80 kA. The arc-produced plasma shells were compressed by using a 450-kA, 450-ns driver, and as a result, a plasma column 0.2 cm in diameter was formed. The power of the Al K-line radiation emitted by the plasma for 7 ns was 800 MW/cm.

[1] This work was supported in part by the Russian Foundation for Basic Researches under Grants # 14-02-00382-a.

PLASMA PARAMETERS OF NON-SELF-SUSTAINED GLOW DISCHARGE WITH HOLLOW CATHODE UNDER SEPARATE SUBSTRATE BIAS VOLTAGE[1]

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In the non-self-sustained glow discharge with the hollow cathode a plasma density is reached up to 10^{18} m^{-3} with a high homogeneity [1,2]. It allows to carry out efficient processes of materials surface treatment in particular processes of nitriding. In the work [3] nitriding of steels in the plasma of such discharge was carried out. Samples were connected to potential of hollow cathode. For independent control of energy of ions bombarding sample surface it can be used separate bias power supply. In this case a reference electrode is the anode of discharge. However under large difference between the hollow cathode potential and the substrate potential the uniformity of the plasma density distribution in hollow cathode can deteriorate especially for volumetric details.

In this work the study of influence of bias power supply parameters on plasma parameters distribution in the hollow cathode volume. The scheme of an experimental installation is shown on the figure 1. For ignition of the non-self-sustained glow discharge and the substrate supply were used two power supplies with output voltage of up to 300 V, output pulsed current up to 500 A, pulse frequency of up to 1 kHz and possibility of duty factor changing from 1 to 100%. For getting of plasma parameters of the pulsed non-self-sustained glow discharge with the hollow cathode was used a single cylindrical Langmuir probe.

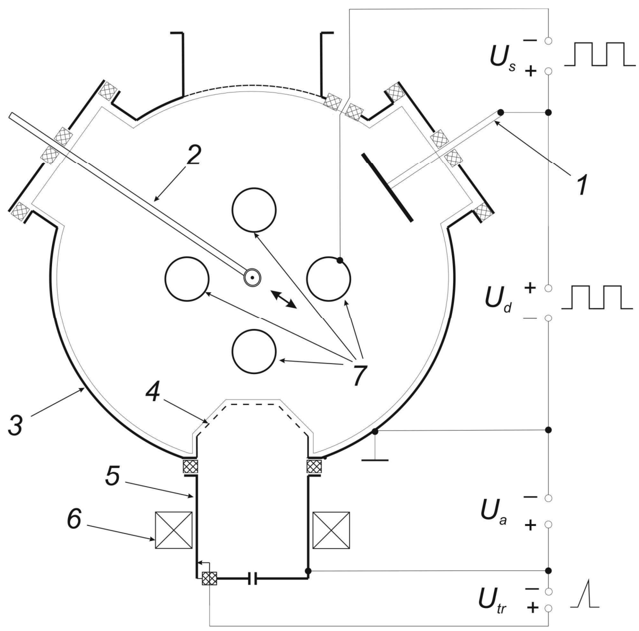

Fig. 1. The scheme of experimental installation. 1- the main discharge anode, 2 – the single cylindrical Langmuir probe, 3 – the vacuum chamber (the main discharge cathode), 4 – the anode of the arc discharge, 5 – the source of arc discharge with the cold hollow cathode, 6 – the magnetic field coil, 7 – samples.

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[1] This work was supported by Russia research foundation (Grant no. 14-29-00091).

INFLUENCE OF THE INITIATING ELECTRODE POLARITY ON THE ION CURRENT OF PLASMA BUNCH GENERATED BY VACUUM SURFACE FLASHOVER[1]

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It is well-known that there are two types of surface flashover: cathode-initiated and anode-initiated flashover. Cathode-initiated flashover is related with generation and propagation of avalanches secondary electrons, whereas anode-initiated flashover is considered as quasibulk and characterized by greater damage of the surface and higher breakdown voltage [1]. Cathode-initiated flashover is studied better than anode-initiated one [2,3]. However, influence of the polarity of the initiating electrode on the parameters generated by the plasma beam are still not understood.

In this work we studied influence of polarity of central electrode in coaxial discharge geometry on the ion current of plasma bunch generated by vacuum surface flashover at 80 kV. Marx generator was used as a source of voltage. Parameters of the generator are as follows: erected Marx capacitance is 2 nF, energy stored in the output stage is 6 J. Voltage pulse was applied to the central electrode of the coaxial discharge cell with PTFE sample. Diameter of the central electrode is 7 mm, inner diameter of the outer electrode is 30 mm. Ion current of the plasma bunch was registered by a Faraday cup located at a distance of 27 cm from the discharge. Electrons were separated from ions by magnetic field of 0.07 T. Mass consumption was measured by weighing of the sample before the experiment and after 2000 bits.

It has been found that the formation time of the discharge at positive polarity of central electrode is 40 ns, which is longer than for negative polarity (30 ns). Dielectric mass consumption is 1 μg/pulse at positive polarity of central electrode and 0.35 μg/pulse at negative. However, current density for positive polarity is lower (2.2 mA/cm2) than that for negative polarity (3.2 mA/cm2). It was observed that positive polarity discharge causes strong carbonation of the surface.

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INVESTIGATION OF INFLUENCE OF FILAMENT CURRENT ON PLASMA PARAMETERS OF "PINK" PLASMAGENERATOR[1]

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"PINK" is a source of nitrogen and argon plasma which can be used for nitriding and plasma assisted coating deposition [1, 2]. Power supply of the heated cathode is carried out by alternating current to reduce the probability of a cathodic spot initiation on a surface of the filament cathode. During the work it was revealed a significant influence of the heating current on the magnitude of discharge current, which is caused by unstable emission from the cathode surface [3].

In this work influence of parameters of heating current on plasma parameters was investigated.

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VACUUM ARC POWER SUPPLY WITH WIDE RANGE OF WORKING CURRENTS[1]

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The vacuum arc discharge is widely used in various technological processes of surface modification as a source of gas or metal plasma. As usual, for ensuring the demanded parameters of various technological processes it is necessary to provide burning of the vacuum arc discharge in the wide range of currents. The top limit of this range for the particular arc plasma source in the sputtering system is usually limited only to its design and the maximum current provided by the power supply. But as for the small values the arc current (close to the threshold current), it is sometimes very difficult to achieve a stable ignition and arc burning. A series of experiments showed that the lower limit of the vacuum arc burning under specific conditions depends on the used power supply circuitry. This paper describes the methods to raise the stability of a vacuum arc ignition and burning while operating at the lowest possible currents for the particular discharge system by the power supply circuitry.

Various designs of plasma sources (with the conical cathode, with the extended rectangular cathode, with the hollow cathode), and also various materials of the cathode are considered (Ti, Al, Zr, Cu and composite TiAl, TiCu, TiCr).

The purpose of this work is to determine the appropriate circuit design and to create the power supply system which allows on the one hand to achieve the discharge currents close to the threshold, on the other hand to provide high values of the discharge current.

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NUMERICAL SIMULATION OF TURBULENT GAS FLOW CIRCULATION INSIDE VORTEX CAMERA OF ELECTRIC PLASMOTRON

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Gas flow circulation in electric plasmotron is used for stabilization of plasma arc position and for cooling of the device walls. Main characteristics of such flow are values of tangential velocity and temperature inside vortex camera and caused pressure gradient. Besides in this case provision of the necessary flow parameters depends on gas mass flow rate, size and configuration of the vortex camera etc.

The article represents the results of numerical simulation of quasi-stationary turbulent flow of viscous compressible gas inside the vortex camera containing four tangential nozzles. RANS method, energy equation, ideal gas equation, equations of two-layer Realizable k-ε turbulence model with wall functions were used. Numerical simulation was carried out using STAR-CCM+ software. Scalar fields of pressure and temperature, vector fields of velocity inside the vortex camera and hydraulic resistance of the device were obtained.

RECEIVING OF TOOL MATERIALS WITH THE SURFACE MODIFIED BY THE SYNTHESIZED COMBINATIONS ON THE EXAMPLE OF THE ZIRCONIUM MICROALLOYING OF THE NITRATED HIGH-SPEED STEEL

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For carrying out of the experiments as a substrate material the HSS steel plates which are previously nitrated in two-stage vacuum and arc discharge [1] on depth about 50 microns were used. On the samples by means of the magnetron sputtering it was applied a Zr film 150 - 250 nanometers thick. Then the samples were subjected to influence of a series of impulses of a wide-aperture low-energy high-current electron beam to initiate the chemical reactions between the metal film and nitrogen in the substrate, residing both free and as a part of connections. Processing was carried out in the RITM-SP unit [2].

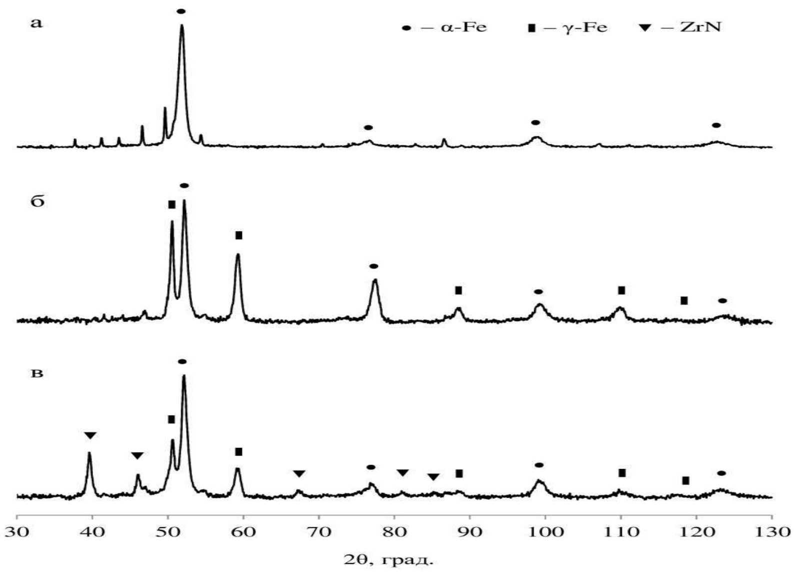

Fig. 1 a) diffraction pattern (CoKα) from a surface of the nitrated high speed cutting steel P6M5 б) the same after the influence of wide-aperture low-energy high-current electron beam, в) the same after zirconium microalloying.

It is enough the thermal impact on the nitrated steel of a beam of electrons with energy of 4.5 J/cm2 to cause dissociation of iron nitrides especially of ε-phase. On a surface a virtually continuous layer of residual austenite enveloping the partly melted carbides is formed. After deposition on a sample of a thin Zr film, as a result of initiation of chemical reaction of the self-propagating high-temperature synthesis (SHS) of refractory ZrN, evaporation from a surface decreases significantly. Process of SHS takes place when heating all surface of the sample in the thermal explosion mode. Formation of ZrN is confirmed by the X-ray diffraction analysis data presented in figure 1.

The received experimental results testify to possibility of receiving the tool materials with the surface modified by the synthesized connections. Thus the problem of increase of thermal stability of the nonequilibrium structural and phase states allowing to receive unique physical and strength properties can be solved.

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INDUSTRIAL TESTING AND ANALYSIS OF ACTIVATED CARBONS DERIVED FROM PLASMA ARC

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Currently carbon adsorbent (activated carbon) is used in many processes of chemical technology. In addition, the purification of exhaust gases and waste water is mainly based on activated carbon adsorption [1]. Therefore, to study the nature of coal and solve a number of applications, are important characteristics of their adsorption capacity. In this case, the basic process of obtaining the target product is thermal degradation [2].

As a new method of thermal activation of coals as compared with the existing technology, possibly using low temperature plasma [3]. Quality coal sorbents are generally determined by the nature of the porous structure is directly dependent on the following factors: the actual density of coal ρd, apparent density ρk coal, coal bulk density ρn [4].

One of the main consumers of activated carbon are water treatment plants and water treatment systems, usually located at the power station, power plants, etc. The problem is complicated wastewater that this water is, in fact, are inhomogeneous complex system, consisting of many different substances in different states [5].

The results of studies on the structure and properties of coal, the last arc-plasma treatment to produce a sorbent, and explore the possibility of industrial application of these sorbents for wastewater treatment plant.

Using plasma arc significantly intensify heat treatment processes coal increase the yield of synthesis (sorbent) and thereby reduce production costs and considerably improve environmental performance.

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INVESTIGATION OF PROPERTIES OF COAL-WATER SLURRIES PRODUCED BY ELECTRIC DISCHARGE METHODS

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Abstract: The purpose of research is to obtain a coal-water slurry, corresponding to modern requirements, with minimum energy consumption. The paper presents the characteristics of coal-water slurries prepared by electric discharge methods. The raw material is coal from different fields (Tugnuisky, Aduun-Chulunsky, etc.). By scanning electron microscopy obtained micrograph of the surface and the chemical composition of the coal particles in the slurry. Photomicrographs showed that the electric discharge treatment resulted in a significant dispersion of the coal particles. Elemental analysis showed a significant reduction of oxides of sulfur and nitrogen. Slurries viscosity was determined by Brookfield rotational viscometer and is close to the standard of GB / T18856.4.

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PLASMA TREATMENT OF HEAT-RESISTANT MATERIALS

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The aim of the research is the development heat-resistant materials such as fireclay refractories treated low-temperature plasma. Obtaining protective coatings on heat-resistant materials is progressive way of thermostrengthening that enhances problem solving effective use of such materials.

Meaning of heat-resistant materials in the industry is constantly growing. The quality of these materials depends largely on the level of development of industry and first of all metallurgy, power engineering, chemical, gas and glass industry. Heat-resistant materials may serve different temperature conditions and a variety of environments. Some refractory materials in contact with different kinds of melt (glass, slag, molten metals, etc.) and take both physical and chemical corrosion. Therefore, the basic requirements for such materials is their high density, strength and certain chemical composition. Other heat-resistant materials are used only in a gaseous medium, in less severe environments. Still others are designed for service in conditions of repeated alternate heating and cooling should therefore have a high thermal resistance.

Among the existing methods of applying protective coatings, in large part, due to its advantages, took plasma treatment. There are some papers about using of plasma coatings for materials protection [1-4]. Plasma-chemical processes take place within fractions of a second to form on the surface of glass-ceramic compound under the influence of the plasma on the fireclay refractories.

The objective of this study was to develop on the surface of the refractory fireclay high density nonporous protective coating by low-temperature plasma treatment. The surface of the product had been treated until a thin layer was appeared. Testing was performed reflow parameters under different operating conditions of plasmatron. Treatment quality determined both visually and adhesion strength of the molten layer with a basis weight, porosity and thermal stability.

Experiments were performed on plasma unit manufactured at a power 60 - 80 kW and a speed of 0, 13 - 0,19 m / s. Results modes of fusion are shown in table 1.

Table 1. Effect of treatment parameters on surface quality

Material	Treatment parameters		Adhesion, MPa	Porosity, %
	Power, kW	Treatment speed, m/s		
Fireclay	60	0,13	2,20	1,60
	80	0,13	2,80	1,20
	80	0,17	3,20	0,80
	80	0,19	2,80	1,10

At treatment of products with a power of 80 kW, the optimal speed is V = 0,17 m / s.

Thus, it was found that the production of heat-resistant protective coatings on refractory fireclay using low-temperature plasma - thermostrengthening progressive way that enhances problem solving effective use of refractory materials. The resulting coating has high adhesion strength (R = 3.2 MPa), with no visible cracks and porosity is 0.8%. The resulting coating is enriched with mullite and has high thermal stability and chemical resistance to aggressive conditions.

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OPERATION MODES OF PLASMA ANTENNA: THEORY AND SIMULATION [1]

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A using of the plasma technologies in the antennas is one of the most actual problems in radio engineering and plasma physics. The developments of Plasma Silicon Antenna (PSiAN) [1] and the studies of the explosive plasma antennas [2] are well known. But today the plasma antennas with discharge plasma in the dielectric tubes [3-8] are the most perspective, because they have some advantages such as the low radar cross section, a fast switching and a fast electronic antenna reconfiguration (a fast frequency tuning and etc.).

Nowadays the researches of the plasma antenna noises and the nonlinear distortions of a signal are key trends [9]. A selection of transmission and receiving modes with the minimal distortions is very important. The operation modes of a plasma asymmetrical dipole antenna have been researched in this paper. We used theoretical methods and a numerical simulation in our work.

A dispersion equation of a surface electromagnetic wave on a plasma cylinder was solved for a cylinder radius r_0=0.5 cm and the plasma density values n_e=10^{10}-10^{12} cm^{-3}. The solutions of the dispersion equation showed that a plasma density value affects the propagation mode of the surface wave with frequency f_0=1.7 GHz. We found three propagation modes of the surface wave on the plasma cylinder: nonradiating, nonlinear and linear. Only a potential surface wave exists along the plasma cylinder into a nonradiating mode. In the nonlinear mode a velocity of surface wave is much less than velocity of light *c* on the frequency f_0. In the linear mode the velocity of surface wave is near velocity of light *c* on the same frequency.

The models of the plasma asymmetric dipole antenna had been done in KARAT code [10]. In this models we have studied a radiation and propagation of Gaussian form pulse with duration τ_p=15 ns and carrier frequency f_0=1.7 GHz by the plasma asymmetrical dipole antenna with length l=4 cm and radius r=0.5 cm. We have considered two models of a low collisional plasma (ν_e<f_p): Drude model and PIC (Particle-In-Cell) model. The electric field component distributions and the radiation patterns have been obtained in Drude model of the plasma antenna. These characteristics have varied when we have changed a plasma density (plasma frequency). This fact has shown that the operation modes of plasma antenna exist and correspond to the surface wave propagation modes [11]. PIC model have confirmed the operation modes of the plasma antenna. The spectral and time characteristics of a signal have obtained in the different operation modes. These characteristics have shown nonlinear signal distortions in the nonoptimal modes (nonradiating and nonlinear). The nonlinear distortions are the high frequency harmonics, plasma oscillations and other low frequency and high frequency noises.

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OPTIMIZATION THE PLASMADYNAMIC SYNTHES OF ε-FE_2O_3

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Iron oxides are one of the most common compounds which are widespread in nature. In the case of iron oxide Fe_2O_3, α-Fe_2O_3 (hematite) and γ-Fe_2O_3 (maghemite) are the most frequently found minerals and have been widely studied. They have also been used for many applications in industry. As for, ε-Fe_2O_3 are rare phases, and their research have been some the difficulty in obtaining pure phases [1].

However, currently materials that effectively restrain electromagnetic interference in the region of millimeter waves almost do not exist. Thus, finding a suitable material has received much attention. Insulating magnetic materials absorb EM waves owing to ferromagnetic resonance. Particularly, a magnetic material with a large coercive field is expected to show a high-frequency resonance. In recent years, a single phase of ε-Fe_2O_3 nanomagnet has been isolated [2].

This article describes a novel method for obtaining ε-Fe_2O_3 iron oxide powder by using coaxial magneto-plasma accelerator. The air atmosphere pressure P_0 = (1–2) atm. in the chamber-reactor by using oxygen. Dispersity, chemical and phase composition of the powdered material are determined by the original components composition, process energetics, plasma speed and expansion velocity, cooling and hardening of the synthesized material [3].

Series of experiments which show that an increase in the oxygen reactor chamber affects the phase composition of the product and its percentage. This allows to optimize the conditions for the experiments. The maximum number of epsilon phase at 80% oxygen. The synthesized product was analyzed by X-ray diffraction.

Thus, the main result of the paper is a demonstration of the capabilities plasma dynamic synthesis of iron oxide ε-Fe_2O_3. Also, ε-Fe_2O_3 is metastable phase, but our method allows stabilize it.

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NITRIDING OF COMMERCIALLY PURE TITANIUM IN A LOW-PRESSURE GAS DISCHARGE PLASMA USING PLASMA GENERATOR «PINK»: STRUCTURE, PROPERTIES[1]

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The analysis of the structure and properties of commercially pure titanium VT1-0 subjected to nitriding in a low-pressure gas discharge plasma using plasma generator «PINK» have been carried out. Multiple (more than four times) reduction in the friction coefficient, wear resistance enhancement (more than 8 times), and microhardness (more than 3 times) have been revealed. The analysis of the mechanisms of hardening of the surface layer have been carried out. It is shown that the increase in strength and tribological characteristics of the material due to the saturation of the crystal lattice of the titanium with atoms of nitrogen, the formation of subgrain structure, the generation of particles of titanium nitride Ti2N. According to these results it can be assumed that the nitriding of front surface of titanium sample is carried out on intercrystalline (diffusion along intraphase boundaries) and intragranular (diffusion along dislocation nucleus and interstices) mechanisms; nitriding of the back surface of titanium sample is carried out mainly on intercrystalline mechanisms.

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PROCESSING-TEXTURE RELATIONS FOR RF-MAGNETRON PLASMA DEPOSITED HYDROXYAPATITE COATINGS

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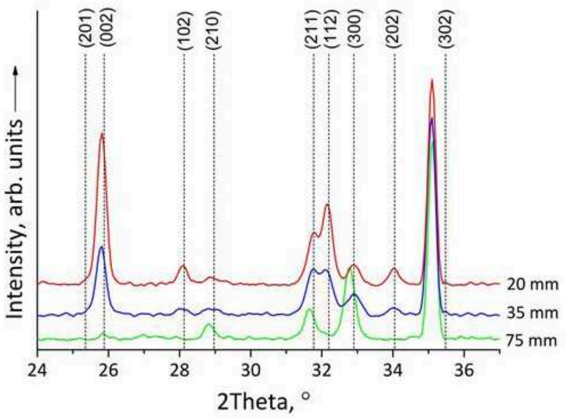
This study reports on the investigation of the properties of hydroxyapatite (HA) coatings deposited by means of RF-magnetron sputtering [1]. An objective of the work is to investigate the relationship between the deposition parameters and film characteristics, in order to develop strategies to obtain calcium phosphate (CaP) coatings with uniform and tailored properties. HA is known as a material which is widely applied in biomedicine due to its chemical and structural similarity to bone minerals [2]. It allows to increase the biocompatibility of medical devices used in surgery. In our contribution the HA coatings were deposited on titanium substrates [2]. The sputter target was prepared from mechano-chemically synthesised HA ($Ca_{10}(PO_4)_6(OH)_2$) precursor-powder, and powered with a RF-generator ((13.56 MHz, COMDEL). During the deposition the substrate holder was rotated. This rotation was coupled with a rocking displacement of the center of the substrate holder. The distance between the magnetron and the substrate holder was fixed at 40 mm. The samples were mounted radially from the center of the substrate holder. All other experimental conditions, such as pressure (0.4 Pa), RF-power (500 W), substrate bias (grounded), were kept constant. The deposited coatings were studied by ellipsometry, XPS, XRD and SEM.
XRD and SEM revealed that the films were crystalline and had a columnar structure. A clear variation of texture was noticed as a function on the sample location on the substrate holder (see Figure 1). This dependence was not connected to the film thickness. The microstructure, i.e. the columnar structure, was not affected by the sample position.



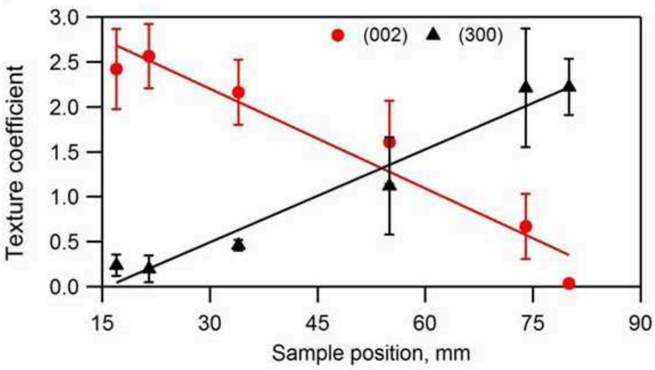


Fig. 1. The XRD patterns of the HA coatings deposited at different sample position on the substrate holder (left) and texture coefficient variations of (002) and (300) planes as a function of sample position relative to the center of substrate holder (right).

The observed trends can be connected to the substrate movement relative to the target race track, or the position of the most intense plasma. A longer residence time under the racetrack results in a change of the out-of-plane orientation from preferential (002) to (300) and in an increase of the Ca/P molar ratio.
The performed study suggests that the process conditions and sputtering geometry have significant impact on growth mechanism of HA films . Further study is needed to to determine if the variation of residence time under the racetrack opens a potential route to engineer the HA coatings with a tailored crystallographic orientation.

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CHARACTERIZATION OF CONDUCTIVE SURFACE ALLOYS FORMED WITH AN E-BEAM CLADDING

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It is well-known that deposition of coatings and irradiation of materials by concentrated energy fluxes in particularly by low-energy high-current electron beams (LEHCEB) of microsecond duration are effective methods of surface modification [1]. Formation of surface alloys by a thin film deposition followed by a LEHCEB mixing with the substrate combines all advantages of these methods.

The paper is devoted to the formation of silver-brass surface alloy with a LEHCEB. Formation of the surface alloy was carried out with the electron-beam machine "RITM-SP" [2-3]. Formation of the silver-brass surface alloy is the result of several iterations of thin silver film deposition onto brass substrate and its subsequent mixing by a LEHCEB irradiation. The number of iterations is specified to provide the required thickness of the coating and its properties. The benefit of the above described technique is that the surface alloying is performed in a single vacuum cycle.

The surface alloy was formed on brass samples of flat and complex surface shape containing square cavities of size of 13×11×8 mm. The surface morphology and topography were observed by scanning electron microscopy (SEM) and optical profilometry. Chemical composition of the surface layer and in-depth elements distribution were investigated by energy dispersive X-ray (EDX) microanalysis. Comparative scratch adhesion test was carried out for samples with silver-brass surface alloy, silver coatings deposited by magnetron sputtering and electroplated silver coating. The electrical properties were investigated by measuring the attenuation coefficient of the microwave signal (the ratio of power of the microwave signal passed through the sample to the power of the input microwave signal). The measurements were carried out on the brass samples with two types of coating: 6-µm-thick silver-brass surface alloy and 6-µm-thick electroplated silver coating. The measurement of attenuation coefficient of the microwave signal was carried out using a vector network analyzer R4M-18 at a frequency corresponding to the X-band microwave 8.223-8.367 GHz.

The tests showed that the surface of the formed surface alloy is smooth without defects such as pores and cracks. Chemical composition of the surface layer of samples with the formed silver-brass surface alloy of 6 µm thick is 100 at% silver.

Investigation of the depth distribution of elements showed that the surface alloy consists of two layers. The first layer has a thickness of 64 ± 9% of the total thickness of the surface alloy and composed of pure silver. The second layer is a transition layer of thickness of 36 ± 9% of the total thickness of the surface alloy. The concentration of silver in this layer drops from 100 at% to 0 whereas the concentration of Cu and Zn increases from 0 to 61 and 39 at%, respectively.

The comparative scratch adhesion testing showed a significant difference between the adhesion of coatings obtained by standard methods and silver-brass surface alloy. Adhesion of the silver-brass surface alloy is significantly higher in the considered load interval (from 0.01 N to 30 N), because the surface alloy remains on the surface sample and is not delaminated, as evidenced by the data of OM, SEM and chemical analysis. The fracture of electroplated silver coating occurs in the middle of the scratch at the load on indenter of 14.6 N. The magnetron coating was destroyed near the end of a scratch, at the load on indenter of 24.15 N.

Measurements of the attenuation coefficient of the microwave signal showed that the attenuation coefficient for samples with electroplated silver coating is of 42%, and for samples with a surface alloy of 41.5%.

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THE INFLUENCE OF THE CENTRAL ELECTRODE MATERIAL ON THE SYNTHESIS PRODUCT IN W-C SYSTEM[1]

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At present platinum-based catalysts is widely used in fuel cells. However, these catalysts have some disadvantages such as high cost and limited long-term stability. Therefore less expensive alternatives are being searched for, substituting for platinum and not influencing catalytic activity adversely. Nanosized tungsten carbide is recognized as promising alternative [1-3].

One of the possible synthesis method of tungsten carbide nanoparticles is plasma dynamic synthesis in an electrodischarge plasma jet generated by a high-current coaxial magnetoplasma accelerator (CMPA) [4]. The device is experimental and needs further investigation. This paper introduces synthesis product depending on the central electrode material: tungsten and graphite. The X-ray diffraction (XRD) determination shows that the synthesized product is composed of WC1-x, g-C, WC, W2C and pure W in both experiments. In both cases, range of particle distribution size is from 10 nm to 200 nm, determined by transmission electron microscopy. The investigations indicated that application of graphite central electrode of CMPA provides with growth of the WC1-x concentration due to increasing of discharge power and plasma temperature as compared with tungsten electrode.

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MAGNETRON DISCHARGE SPUTTERING FOR FABRICATION OF NANOGRADIENT OPTICAL COATINGS[1]

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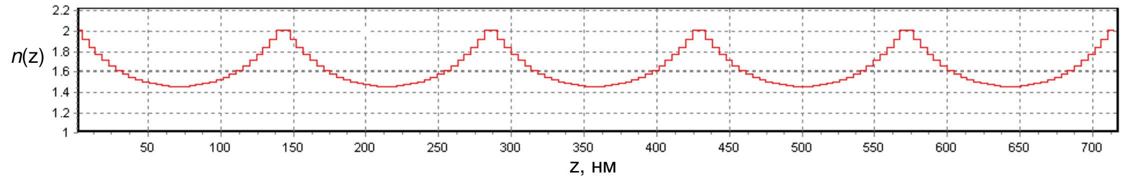
Fabrication of optical coatings with gradient of refraction index $\mathrm{grad}_z\, n(z)$ along light direction **z** is of great importance for modern optics. Different CVD and PVD methods including magnetron sputtering may be used [1]. Our work is devoted to the new field of magnetron technology that is deposition of coatings with nanogradient profiles of $n(z)$. For this, a computer-controlled sputtering set-up, containing two magnetrons with metal targets, has been built. Sputtered target materials from the both magnetrons are deposited onto substrates and the deposit composition determines n. The programmable movement of the substrates over the magnetrons allows obtaining the desired composition variation of coating material along **z**. The pulse mid-frequency mode of magnetron discharge provides stable deposition process in reactive gas medium (usually, Ar + O_2 is used). An oxygen activator is used for better oxygenation of the deposited material. Fig. 1 depicts, as an example, five-period nanogradient profile of $n(z)$, which was to be formed by sputtering of Si and Ta in Ar+O_2 medium, and its transmission spectra. One can see the excellent agreement of calculated and experimental spectra (the lower plots) and strong dispersion (the kind of photon band gap) in the visible range and almost non-dispersive plateau (the good antireflection property) in the near IR field.



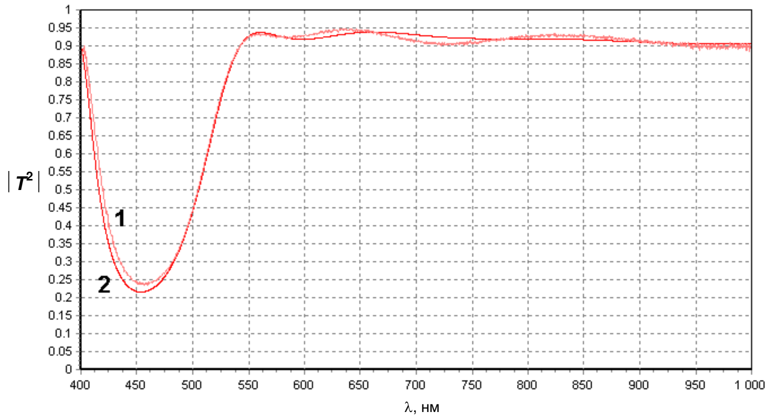


Fig. 1. Nanogradient five-period profile of $n(z)$ for coating from SiO_2+Ta_2O_5 mixture (the upper plot) and calculated (1) and experimental (2) transmission spectra of the coating (the lower plots). The substrate is from quartz glass

The obtained results confirm the high potential of pulse magnetron sputtering of metal targets in reactive medium for fabrication of nanogradient optical coatings with excellent properties including gradient optical metamaterials [2] for high-performance solar cells and devices based on transformation optics.

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BORIDING OF CARBON STEELS BY THE ELECTRON BEAM TREATMENT IN VACUUM [1]

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Conditions of formation, structure and properties of boride iron layers on carbonaceous steels 3 and 45 were investigated at electron beam borating. New process to make layers of iron borides (Fe_2B, FeB) using electron beam is reported. The microstructure and microhardness of boride layers are investigated and are compared to layer properties obtained at solid phase borating. Formed layers were heterogeneous structure combining solid and weak components and resulting to fragility reduction of boride layer.

We attempt to form the layers based on borides Fe_2B and FeB in the synthesis of their stoichiometric mixtures with Fe_2O_3, B and C on the surface of steel 45. To do this, take a mixture of the initial components in a ratio of Fe_2O_3: 3B: 3C (Fe_2B) and Fe_2O_3: 2B: 3C (FeB), thoroughly ground in an agate mortar, mixed with an organic binder and the reaction surface of the sample steel 45. Electron beam processing was carried out in a vacuum at most 2×10^{-3} Pa at power electron beam W = 250-450 W for 1-3 min.

Application of the protective layer of amorphous boron oxide contributes towards equilibrium boride layer (Figure 1). The eutectic observed in all layers with the microhardness 650-800 MPa. Rounded and elongated inclusions were ordered arrangement in the layer in the layers of their microhardness were Fe_2B + B_2O_3 (1650 and 1850 MPa), FeB + B_2O_3 (1800 and 2350 MPa), respectively.

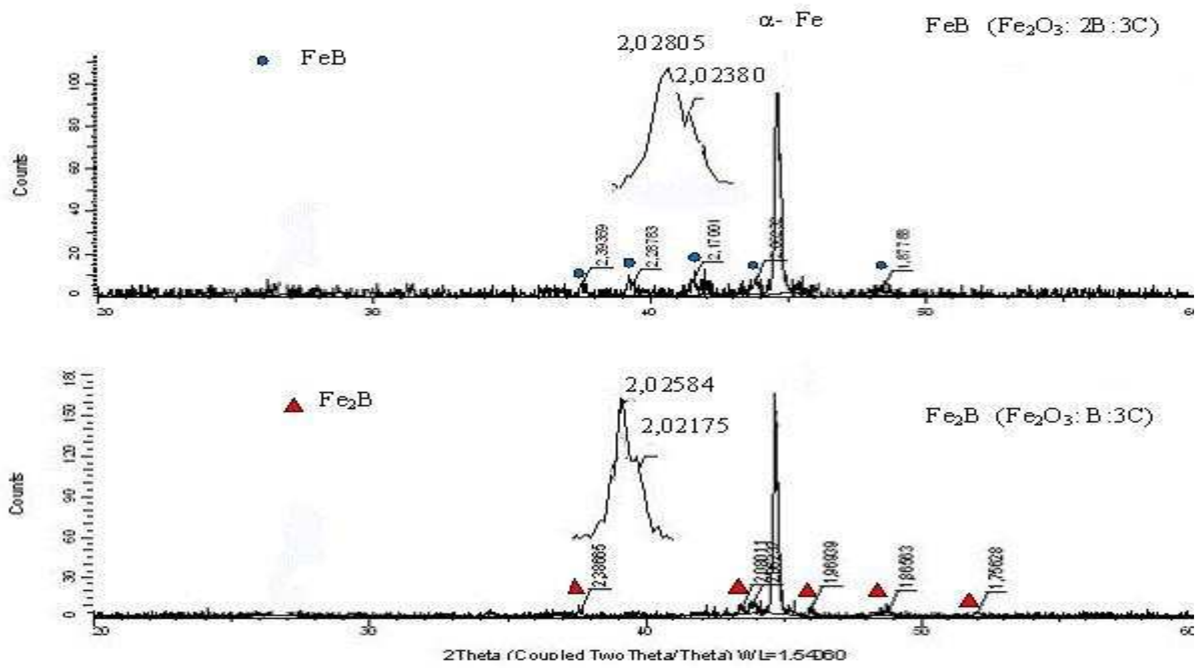

Fig. 1. X-ray phase analysis of produced boride layers

Dendrites are inclusions of ferrites with parameters cells, a = 0.2821 nm). In the original steel 45 ferrite has a cubic volume-centered cell with a = 0.2869 nm. The use of high-resolution diffractometer D2 Phaser Bruker (Cu $K_{\alpha 1}$) enabled to detect the x-ray lines reflexes plane (110) ferrite owned metal base. Also, found reflection from 20 % intensity, which, in our opinion, is the ferrite, which is formed during crystallization narrow melted near-surface zone.

For FeB: by reflex [110] cubic unit cell parameters: α-Fe (metal matrix) *a*=0,2868 nm, α-Fe (dendritic crystal), *a*=0.2821 nm.

For Fe_2B: by reflex [110] cubic unit cell parameters: α-Fe (metal matrix) *a*=0,2865 nm, α-Fe (dendritic crystal), *a*=0.2859 nm.

[1] This work was supported by The Russian Foundation for Basic Research, grants No. 14-08-31412_mol_a and The RAS Presidium program "Arctic" project № 84.

THE GAS-DISCHARGE DEVICE BASED ON THE VACUUM ARC DISCHARGE AND MAGNETRON DISCHARGE FOR THE NANOSTRUCTURED COMPOSITE TiN-Cu LAYERS SYNTHESIS[1]

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In this paper, we propose a hybrid technology of receiving composite layers. The main feature of this technology is in coordinated acting of vacuum arc discharge and magnetron discharge. Such combination gives us the following advantages: the possibility to apply coatings on details of various geometric forms, to produce high speeds of deposition, low temperature of the substrate and the possibility of introducing impurity component. The industrial VU-1B installation has been modernized for the process of deposition realization. The modernization was made by placing the planar magnetron into the vacuum chamber. On the base of abnormal glow discharge of the direct current this planar magnetron is working and is widely applied for producing thin nitride and carbide films. The magnetron is installed vertically on the sidewall of the vacuum chamber.

The TiN-Cu layers deposition was carried out by simultaneously copper target's reactive magnetron sputtering and the titanic target's arc evaporation. The parameters used in this experiment are presented in Table 1. To avoid focusing influence of a substrate material on a structure of the composite layer TiN-Cu a plates of fusing quartz (amorphous SiO_2) by thickness of 1 mm have been used. The TiN-Cu layers are set while both devices are simultaneously working.

Table 1

Parameters of composite TiN-Cu layer formation

Number	Current of the arc discharges, A	Current of the magnetron discharges, A	Voltage of the magnetron discharges (Cu), V	Pressure in a chamber, Tor
a	80			$2x10^{-3}$
b	90	0.8	35	$2x10^{-3}$
c	60	0.6	40	$9x10^{-2}$
d	60	0.6	40	$9x10^{-2}$

Figure 1 show X-ray diffraction (XRD) of the pattern with copper intensity. According to X-ray analysis, in a composite layer there are reflexes of TiN. Besides, on X-ray pattern a pure Cu peak are put. On the X-ray pattern it is possible to observe the copper intensity which varies from 10 %.

Figure 2 show the microstructure of surface layer of the pattern with copper reflections (pattern d). At research of a microstructure of a layer surface, the presence of Ti drops is not revealed. Layers have a homogeneous globular structure. Possibly, copper is on grain borders. It is necessary to expect, that within TiN grains have the columns structure. Thus, the structure and phase structure of a layer of composite TiN-Cu assumes creation of the composite material combining firm nitride of the titan and plastic copper.

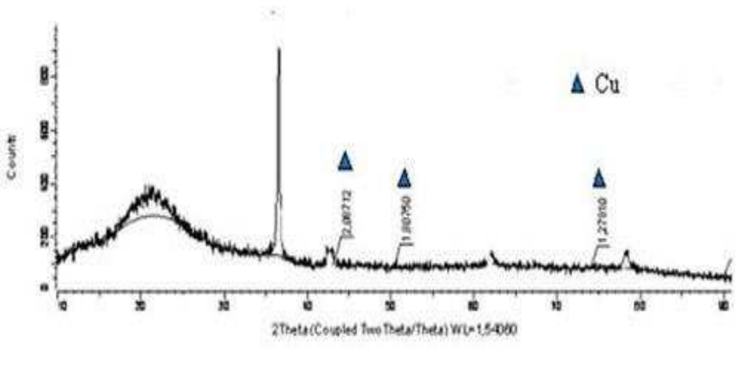

Fig. 1. XRD patterns of TiN-Cu film: d) 60 A (280 mm)

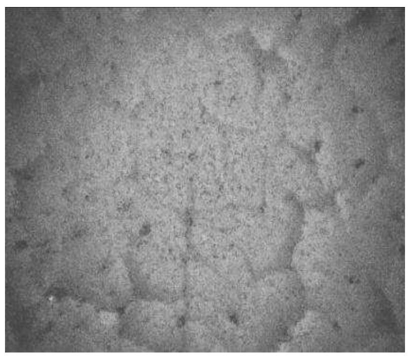

Fig. 2. Microstructure of TiN-Cu layer

[1] This work was supported by the RAS Presidium program "Arctic" project № 84.

SYNTHESIS OF TRANSITION METAL BORIDES LAYERS UNDER PULSED ELECTRON-BEAMS TREATMENT IN A VACUUM FOR SURFACE HARDENING OF INSTRUMENTAL STEELS[1]

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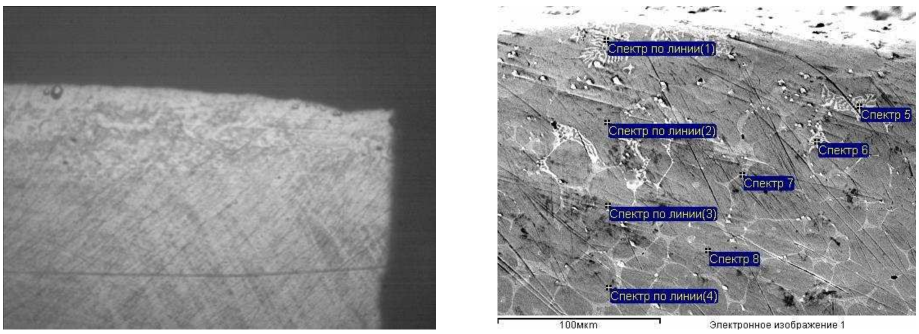
The saturation of the surface layers of metals and alloys boron is conducted with the purpose of increase of their surface hardness, wear resistance, etc. Multicomponent layers containing in its composition borides of refractory metals, as a rule, formed by the methods of chemical-thermal processing in the interaction borating component with refractory or by saturation boron refractory impurities metal or alloy [1].

In this work, we studied the features of vanadium and iron borides formation on the surface of instrumental steels U8A and R18 under the influence of intense electron beams in continuous and pulse modes.

Vanadium boride layers VB_2 (and forth, and borides of iron Fe_2B and FeB) at the same time synthesized and formed on the surface of cutting plates size 12×12×5 mm with roughness Rz = 4.41 ÷ 4.02 microns of instrumental steels U8A and R18. Samples were prepared by applying the reactionary daubs on the pre-prepared (well-fat) surface of the steel. In the composition of the daubs consisted of 1:1 by volume stoichiometric mixture oxide, boron containing and carbon component and organic binder - solution 1:10 glue BF-6 in acetone. As initial substances used amorphous boron, charcoal (birch) and oxides V_2O_3, Fe_2O_3. Processing of samples was conducted within 2-5 minutes with the power of electron beam 150-300 watts. The pressure in the vacuum chamber did not exceed 2×10^{-3} Pa [2, 3].

X-ray diffraction revealed that in the boride layer on steel U8A observed prevalence of carbide phases (cementite). This can be explained only by the deviation from stoichiometry by evaporation of the intermediate boron oxide. Application of the protective layer of amorphous oxide B_2O_3 (1:1 by volume reactionary daub: daub based B_2O_3) allowed to form a more uniform boride layers. It was found that the weight of the crystalline phases in the samples is 92.3%, and the amorphous phases - 7,7%, while the crystallite size ranges from 15 to 70 nm.

Figure 1 shows a general view (fig.1.a) and the structure of the boride layer VB2 on the surface of cutter plate steel U8A (fig.1.b). Layer thickness reaches up to 500 microns.



a b

Fig.1. General view (etched layer) (a) and structure (b) layer VB_2 on steel U8A

Microhardness testing showed uneven distribution of its thickness in the cross-section. Separate very rare inclusions have microhardness HV≈ 24000 MPa and are located in the surface layers. Next we will see two areas: in the first area microhardness reaches 2500 MPa, and in second - 1500 MPa. The metal base is microhardness 200 MPa.

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[1] This work was supported by the RAS Presidium program "Arctic" project № 84.

MICRO ARC OXIDATION AND ITS APPLICATION FOR DEPOSITION OF CALCIUM PHOSPHATE-BASED COATINGS ON Ti-Nb ALLOY[1]

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One of the shortcomings of commonly-used Ti-based alloys is high hardness, expressed as high elasticity modulus (typically > 100 GPa). For a given Ti-based alloy, it is desirable to reduce its elasticity modulus to one of healthy bone (4–30 GPa) while maintaining its high strength and good plasticity. One way of solving this problem is the use of titanium-niobium alloys (for example, Ti-40mas.%Nb). However there are conflicting data about biocompatible properties of these alloys. One of the methods of improving implant adaptation in human body is formation of calcium phosphate (CaP) coatings. The coatings effect positively on living organism and they stimulate the regenerative processes of bone tissue. Micro arc oxidation is a relatively convenient and effective method for deposition of bioactive CaP coatings on the surface of Ti and its alloys. This technique allows to introduce various desired elements into micro arc coating composition and to produce various functional coatings with a porous and gradient structure [1].

In this work the influence of oxidation voltage (150-400 V) and process duration (5-15 min) on the morphology, topography, chemistry and wettability of CaP coatings on low-modulus Ti-40mas.%Nb alloy was investigated. The scanning electron microscopy results showed that the main components of the coating structure are "spherolytes" with pores. Such structure starts to form at oxidation voltage of 200 V (fig. 1). The further increase in the voltage to 300 V leads to a structural element growth. The "spherolyte" and pore sizes depend on the value of micro-plasma discharges in electrolyte. Thickness and surface roughness of CaP coatings on Ti-40mas.%Nb alloy grow linearly with increasing of the oxidation voltage and process duration from 40 to 140 μm and from 2.5 to 8 μm, respectively.

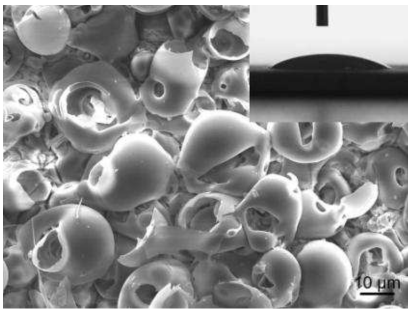

Fig. 1. SEM micrograph of CaP coating with image of water drop on surface produced at oxidation voltage of 200 V.

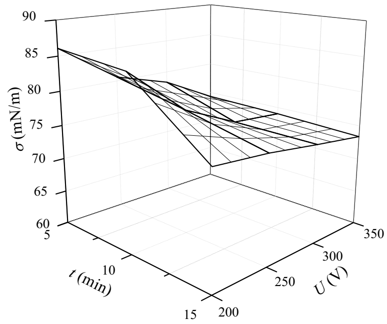

Fig. 2. 3D-plot of the free surface energy of CaP coatings against the oxidation voltage and duration.

X-ray diffraction analysis showed that CaP coatings after deposition have quasi amorphous state. To identify the structural phases the crystallization annealing at the temperature of 800°C was carried out. After this a large amount of calcium-containing phases was found in the coatings [2]. The wettability tests of the CaP coatings showed that the increase of the oxidation voltage and process duration leads to linear decrease of contact angles with liquids from 50 to 8º and linear decrease of the free surface energy to 73 mN/m (fig.2). It indicates a high hydrophilicity. Decrease of the surface energy in the coatings depends on surface roughness growth. There is a certain roughness value of 4 μm above that the water wetting is absolute.

Thus, the optimal micro arc oxidation parameters such as electrical voltage of 200 V and the process duration of 10 min allow to form CaP coatings with specific properties and high hydrophilicity.

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COMPOSITE THIN FILMS MADE BY ATMOSPHERIC PRESSURE PLASMA CVD FOR BACTERICIDAL APPLICATIONS[1]

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In the last couple of years a broad range of atmospheric pressure plasma sources were developed, following intensified attempts to create functional surface coatings at ambient conditions. The so called atmospheric pressure plasma enhanced chemical vapor deposition (APCVD) is a useful tool to apply such coatings on several substrate materials (even plastics) due to the low gas temperatures. We will report on our investigations concerning silicon oxide thin films deposited with a jet plasma arrangement [1]. By choosing appropriate deposition parameters it is possible to vary the overall surface properties in a broad range. Typical applications can be found in the field of controlling the wetting ability, transmission improvements of float glass or transparent plastics, for photovoltaic applications or corrosion protection of light metals like magnesium.

A next step is the creation of functional composite layers by implementation of additional components into the growing silicon oxide matrix structures. One part of our contribution places emphasis on the possibility to create wear resistant, antimicrobial thin layers by using silver containing solutions as additional precursor substance [2]. In this way it is possible to apply such coatings successfully on textile fibers, textile wound dressing materials [3] as well as bone substitute materials like titanium alloys for medical applications. Furthermore, a therapeutic range with good bactericidal but non-cytotoxic properties could be determined.

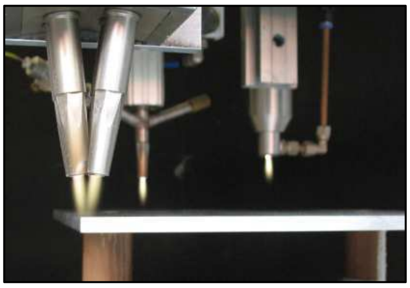

Fig. 1. Different atmospheric plasma jet systems usable for APCVD of composite coatings

The next attempts to create bactericidal coatings were performed on wood and WPC (wood polymer compounds) substrates. The silicon oxide composite coatings were also realized using silver as a bactericidal agent. Besides surface analytical results (SEM, wear resistance tests) first results will be presented concerning bactericidal properties as well as leaching tests.

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MORPHOLOGY OF CERAMIC PARTICLES PRODUCTED BY PLASMA-CHEMICAL SYNTHESIS[1]

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The use of fine powders of metal oxides in the preparation of ceramic composite materials enables to synthesize products for various purposes with unique mechanical properties, create metal-substituting construction materials and protective coatings, as well as filters, membranes, and thermoinsulating and catalyst structures with a specified pore size. One of the most promising technologies for producing ceramic powders with controlled parameters is plasma-chemical synthesis, including the thermochemical decomposition of liquid-drop reagents (precursors) in a flow of high-temperature gaseous heat carrier. This technology is known as "spray pyrolysis". Depending on the chemical composition of the precursor, a wide range of metal oxide powders can be obtained: Al_2O_3 from an aluminum nitrate $Al(NO_3)_3$ solution, zirconium oxide ZrO_2 from a zirconium nitrate $Zr(NO_3)_3$ (or zirconium chloride $ZrOCl_2$) solution, as well as mixed oxides, such as $ZrO_2 + MgO$, $ZrO_2 + Y_2O_3$, $ZrO_2 + CaO$, $ZrO_2 + Y_2O_3 + Al_2O_3$, etc.

Electron microscopic studies of powder particles prepared by the plasma-chemical method revealed that their morphology may vary, featuring solid spherical single-crystal formations, hollow spheres and their fragments, films, and porous or foamed particles. The internal structure of ceramic particles is the most important parameter that determines the quality of the product. While the production of construction ceramics requires fine spherical solid particles, the manufacture of heat-shielding materials and catalysts preferably uses porous and hollow particles.

Clearly, the particle morphology is defined by both the precursor characteristics (dispersion of drops, solution concentration) and thermochemical process parameters (speed of drops, time of their residence in the reactor, temperature regime, aerodynamic pattern of the two-phase flow in the reactor, thermophysical properties of the reagents, etc.). To ensure a controllable mode of operation of the plasma-chemical reactor in order to produce particles with desired characteristics, it is necessary to develop mathematical models of the processes occurring in it. The development of such a mathematical apparatus involves multivariate analysis of the problem of calculating the parameters of a multicomponent two-phase chemically reacting medium with a detailed description of heat and mass transfer in the individual spray drops and between the drops and the gaseous heat carrier. However, the available studies are based on mathematical models involving a number of serious simplifications in describing the processes within the solution drops, an approach that significantly reduces the possibility of predicting the characteristics of the synthesized powders of metal oxides, in particular, their morphology(internal structure)..

In this report, we developed a mathematical model of heat and diffusion processes in a drop of slightly concentrated solution of a metal salt as it is heated in a plasma-chemical reactor. This model is designed to predict the morphology of the particles of ceramic powders depending on the characteristics of the solution and gaseous heat carrier.

Analysis of the results of numerical calculations within the framework of this model showed that the only dimensionless parameter that determines the structure (morphology) of the particle formed is the ratio of the characteristic times of diffusion t_1 and evaporation t_2: $K = t_1/t_2$. At $K < K_{cr}$, diffusion is faster than evaporation, and therefore, solid particles are formed; at $K > K_{cr}$, hollow spherical particles are formed.

In the case of the formation of hollow particles, the process of salt crystallization occurs in two stages: the primary precipitation to form a layer of thickness h_1 followed by the deposition of the remaining salt onto the inner surface of the particles to form a layer of thickness h_2. The ratio between h_1 and h_2 is determined by the value of K.

In producing ceramic powders with a given morphology, the main parameters of the controlled plasma-chemical synthesis are the initial concentration of the precursor salt (salt solubility), temperature difference between the gaseous heat carrier and the precursor, as well as the difference between the critical supersaturation concentration C_{cr} and equilibrium saturation concentration C_0.

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PLASMA ACTUATORS CHARACTERISTICS FOR BOUNDARY LAYER CONTROL

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The presented experimental study is related to laminar flow control method based on an attenuation of the cross-flow-type instability in three-dimensional boundary layer on a swept wing due to electrogasdynamic force impact on boundary layer flow in the vicinity of the wing leading edge [1].

Experimental study of a set of the electrogasdynamic actuators using near surface dielectric barrier discharge (DBD) and intended for boundary layer control on lengthy aerodynamic surfaces in relatively thin layers is executed [2].

The average electric power consumed by DBD-actuators is measured with the help of some simplified method. The dependences of the power consumption on some geometric parameters of DBD-actuators are founded. The specific power consumed per one meter length of the external electrodes is determined.

The volume force and energy efficiency of actuators both at normal and reduced static air pressure are evaluated on the base of integral momentum method with the use of measured flow velocity profiles induced by actuators.

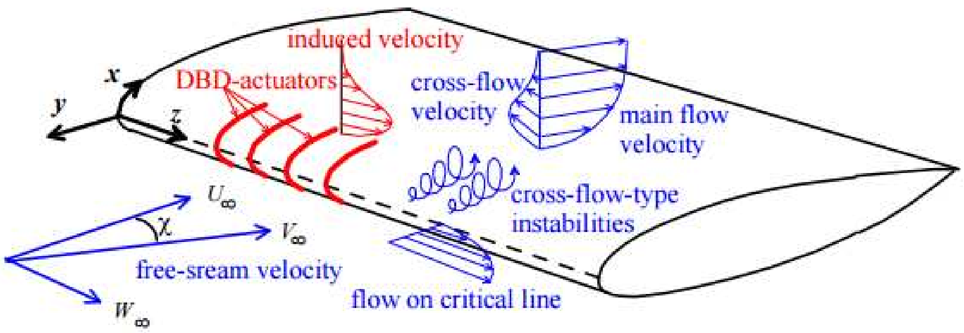

Fig.1. The concept of the electrogasdynamic method of laminar flow control on a swept wing

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THE USE OF PULSED POWER SOURCE FOR DISINFECTION OF WATER DIAPHRAGM ELECTRIC DISCHARGE

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The article presents the characteristics of molecules of hydrogen peroxide, copper and silver ions from the energy input to the diaphragm discharge pulse, the frequency of the pulse discharge voltage, which allow you to create an automatic control system output of antibacterial agents. Describes the current-voltage characteristics of the reactor water disinfection new design when powered from the pulse voltage authoring. The results of microbiological investigations of the process disinfection water by low-temperature plasma formed by the diaphragm pulse electric discharge.

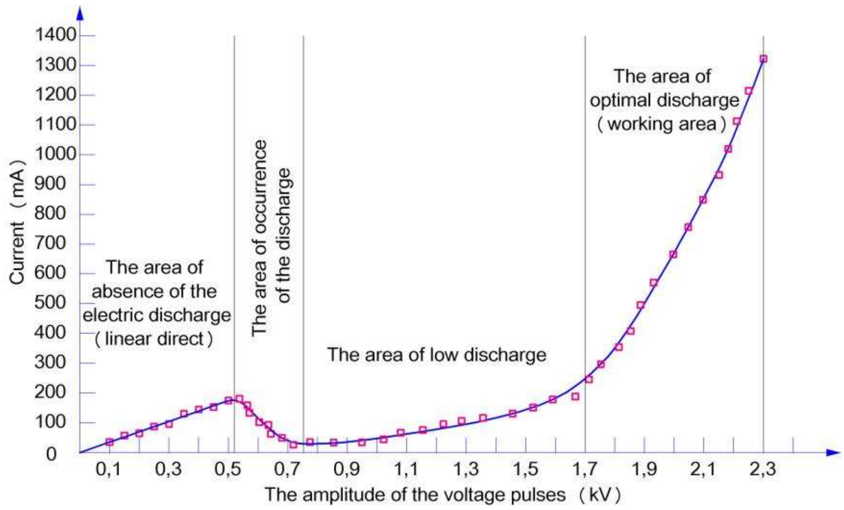

Fig. 1. The volt-ampere characteristic of the diaphragm of the electric discharge

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IMPROVEMENT OF SURFACE FLASHOVER STRENGTH IN VACUUM OF PMMA BY SURFACE MODIFICATION USING LOW-TEMPERATURE PLASMAS[1]

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Polymethylmethacrylate (PMMA) is widely used as insulators in vacuum. However, surface flashovers always occur over vacuum insulators of electrical equipments, which may damage both insulators and equipments. It is necessary to improve surface flashover performance of the PMMA in vacuum.

In this paper, surface modifications of PMMA are performed by low-temperature plasmas sustained by both dielectric barreier discharge (DBD) and atmospheric pressure plasma jet (APPJ) for improving the PMMA surface flashover performance in vacuum.

In the case of DBD modification, the experiments are conducted by using working gases of Ar and CF_4 (10:1). Results show that the plasma can etch the PMMA surface and introduce fluoride groups to the surface, and then increases the hydrophobic property of the PMMA. Furthermore, the plasma modification can significantly improve the surface flashover voltage of PMMA. For samples with different contact angle ranges (70°-80°, 80°-90° and 90°-100°), the stable flashover voltage are increased by 19.0%, 69.8% and 34.5% at 1.5 mm air gap.

In the case of APPJ modification, the experiments are conducted by using working gases of Ar. Results show that polar groups such as OH and O enhance the hydrophilic property of the PMMA surface. The water contact angle decreases from 68° to a minimum value of 16°after the treatment. Moreover, all the surface flashover voltage in vacuum for the PMMA samples treated by APPJ are high than that for the untreated PMMA samples. When the water contact angle is 15°-20 °, the increase of the surface flashover voltages at different gaps are 70.7%, 41.7%, and 20.7%, respectively.

The increase of the surface roughness and the introduction of the fluoride groups can improve the surface property, and decrease the secondary electron emission yield. Therefore, the surface resistance increases, making the surface flashover voltage be enhanced in vacuum.

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APPLICATION OF THE HOLLOW CATHODE EFFECT FOR LOCAL ION NITRIDING OF THE MACHINE PARTS

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It is known that during the operation machine parts undergo the local loads, for example the contact surface of the gear teeth, the shaft bearings [1,2]. In such cases, there is no need the the hardening of all surface of part, and it is sufficient only to process the work surface. It has been experimentally proved in the works of Kreindel Yu.E, Lemeshev N.M., Slosman A.I., Budilov V.V., Agzamov R.D. and others that the application of Hollow cathode effect (HCE) for ion nitriding in a glow discharge can significantly intensify the process of diffusion compared to treatment without HCE [3,4,5]. Therefore, in this paper we propose a method of local ion nitriding, the essence of which is the creation of HCE only in areas of intense wear of workpiece surface.

In this paper we study the effect of local ion nitriding in glow discharge with HCE on the structure, microhardness, wear resistance of the diffusion layer of steel 38KhMYuA. A probe measurements of glow discharge plasma in the cathode cavity was performed and the charged particles density distribution was obtained.

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IMPROVING THE OPERATING PROPERTIES OF PARTS OF TITANIUM ALLOYS BY SURFACE HARDENING IN HIGH DENSITY PLASMA OF GLOW DISCHARGE

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Titanium alloys are used in the aviation industry to make critical products such as helicopter rotor head, shafts, gears, compressor parts of turbine engine, wheels and low-pressure and high-pressure compressor vanes. However, there are negative properties that limit using of titanium alloys as a structural material: low surface hardness and low wear resistance [1]. The ion nitriding process is an effective method of titanium alloys surface hardening. However, it takes a long time, so high density plasma is used to intensify the process. The hollow cathode effect (HCE) is an efficient way to increase plasma density[2]. The aim of presented work is to study the influence of the ion nitriding using HCE on the microstructure, phase composition, surface layer hardness of VT-6 titanium alloy.

Microhardness test of nitrided samples showed that surface microhardness increased to 2.5 times in case of use of the HCE, and to 2 times without HCE. Found that microhardness growth occurs due to titanium nitrides and alloying elements nitrides formation on the samples surface. Microscopic examination of nitrided samples of VT-6 showed presence of nitride layer and diffusion zone. Found that ion nitriding using HCE leads to thicker nitrided case comparing to nitriding without HCE occurrence. So, nitride layer and diffusion zone thicknesses of samples nitride with HCE was 20…25 μm and 60…80 μm respectively, according to 17 μm and 19 μm for case without HCE. X-ray diffraction analysis of nitride samples showed decreasing of α-phase and increasing of β-phase amounts due to approaching the temperature of $\alpha \rightarrow \beta$ polymorph transformation. Level of this transition in case of using HCE was higher comparing to conventional ion nitriding. Process had led to titanium nitrides formation of various stoichiometry (TiN, Ti_2N). From analysis of obtained data revealed the ion nitriding with HCE leads to mechanical characteristics improvement. Therefore, it is an effective way to better the operational properties of parts of VT-6 titanium alloy.

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PHASE COMPOSITION, STRUCTURE AND PROPERTIES OF CEMENT STONE AFTER MODIFYING FULLERENES[1]

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Carbon nanomaterials are perspective additives for modifying cement composites. In this work the influence of carbon nano-modifier (CNM) formed in plasma chemical reactor on phase composition, structure and properties of cement stone was investigated. Method of dispersion of nanoparticles has been used, which consists in sonication mixing water with carbon nano-modifier and super plasticizers (SP).

Change in phase composition, structure and properties of modifying cement stone were investigated. The effects of the CNM on the early hydration process of cement were studied using X-ray diffraction analysis and scanning electron microscopy analysis. The CNM were found to accelerate the hydration reaction of the C_3S in the cement. In particular, the CNM appeared to act as nucleating sites for the hydration products, with the CNM becoming rapidly coated with C-S-H. With the introduction of CNM is reduced porosity of cement stone, which leads to high strength characteristics of modified cement.

Experience of application CNM in technology of cement composites and concrete shows that the effect of their influence on cement system varies depending on a kind used nanomaterials. It is connected by that at various ways and conditions of reception carbon nano particle their form and the sizes, the maintenance in the received mix of fullerenes and carbon nanotubes change. Considering, that introduction CNM leads to considerable effect of improvement of the basic properties of cement and concrete, carbon nanomaterials, received plasma-chemical method, research of possibility of use is of interest for updating of a cement stone.

Synthesis of initial carbon nano-modifier carried out on a plasma chemical reactor or Arc discharge apparatus. The basis of the system is based on the erosion of graphite electrodes in the arc discharge plasma. The discharge is initiated at a pressure of 10^5 Pa, by passing through the electrodes and current frequency 44 or 66 kHz. Erosion of rods occurs in close sealed volume filled with helium.

Carbon condensate containing fullerenes of 10-12%, the benzene was allocated fullerenes. CNM contains parts by weight: 0.8 - C_{60}; 0.15 - C_{70}; the rest - higher fullerenes and oxides $C_{60}O$ and $C_{70}O$.

Changing the properties with the introduction of CNM associated with changes in the phase composition and structure of modified cement stone.

According to X-ray diffraction analysis, the original Portland cement includes traditional phase characteristic of OPC: calcium silicates and Ca_3SiO_5 Ca_2SiO_4, calcium aluminates $Ca_2Ca_2(FeAl_{0,9}Mg_{0,1})O_5$ and $Ca_3Al_2O_6$ and calcium sulfate $CaSO_42H_2O$. In hydrated cement decreased intensity of peaks attributable to the original cement phases, appear peaks attributable to $Ca(OH)_2$ and hydrated calcium sulfoaluminate in low-sulfate form $Ca_3Al_2O_6(SO_4)14H_2O$ (d=0,4729 nm) with expressive intensity of peak. Introduction of CNM into the cement causes a change of distance from d=0.4682 nm to d=0.4833 nm.

Contents of aluminates $Ca_2(FeAl_{0,9}Mg_{0,1})O_5$ and $Ca_3Al_2O_6$ in hardened specimens is reduced, which is testified to intensive hydration of these phases, especially in the presence of CNM. For example, for phase $Ca_3Al_2O_6$ (PDF 00-006-0495 ICCD) a decrease in intensity of the reflection is d_{100}= 0.2700 nm. Furthermore, the introduction of CNM into hydrated cement leads to change in samples of distance from d=0.2561 nm to d=0.2604 nm for this plane. This variation can be explained in terms of the degree of crystalline of hydrated cement samples. So in the control sample cement content of the amorphous phase reaches 46%, and the addition of fullerenes leads to an increase in crystalline up to 63%, which indicates an increase the degree of hydration of PCs in the initial period of hardening.

Introduction of CNM changes not only phase composition of hydrated cement but also the microstructure of cement stone. Introduction of CNM reduces porosity of cement stone due to formation of gelatinous hydration products filling interporous space. It should be noted that an increase in hardening time from 3 to 7 days leads to a substantial reduction in porosity of the hydrated stone and reducing crystallite size. All of this favorable effect on the changes in physical and mechanical properties of modified cement stone.

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IMPROVING THE QUALITY OF ASPHALT COATING WITH FULLERENES[1]

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This work deals with the possibility of modifying the binder by adding carbon nanomodifier (CNM) to bitumen to improve the quality of asphalt. Synthesis of initial carbon nano-modifier carried out on a plasma chemical reactor or Arc discharge apparatus. The basis of the system is based on the erosion of graphite electrodes in the arc discharge plasma. The discharge is initiated at a pressure of 10^5 Pa, by passing through the electrodes and current frequency 44 or 66 kHz. Erosion of rods occurs in close sealed volume filled with helium.

Carbon condensate containing fullerenes of 10-12%, the benzene was allocated fullerenes. CNM contains parts by weight: 0.8 - C_{60}; 0.15 - C_{70}; the rest - higher fullerenes and oxides $C_{60}O$ and $C_{70}O$.

Addition of 0.05% - 0.5% of nanomodifier significantly changes the properties of bitumen. Asphalt with this astringent has increased strength, heat resistance and shear resistance.

For managing the process of bitumen structure formation with specific parameters (distribution of different fractions of bitumen according to thickness of its adsorption layer) a variety of modifiers is being used, both organic and mineral compounds. These compounds are working in different ways: first, formation of the polymer “grid”, which is responsible for increasing the interval of flexibility, or second, enlargement of quantity of active centers on mineral part surface, which can take part in chemical reacting with bitumen (chemisorptions). The first method is provided by adding different organic compounds, such as rubber, polymeric additives, their combinations, etc. The second technique is implemented by other agents, such as phosphoric acid or hydrochloric acid. Different nano additives like nanotubes, fullerenes, astralenes and nanodiamonds compose a separate group of agents which performance is poorly investigated

Table 1. Properties of the original bitumen and the bitumen modified by CNM

Name index bitumen	Initial bitumen BND 90/130	Bitumen + 0.05 % mas CNM	Bitumen +0.1 % mas CNM	Bitumen +0.25 % mas CNM	Bitumen+0.5 % mas CNM
Penetrationat 25°C, 0.1mm	95	90	81	78	62
Temperature of softening, °C	46	45	43	42	40

Table 2. Physical and mechanical parameters of organic compounds on the basis of bitumen, modified with CNM, identified by the StSt 12801-98 methods.

Sample	Average density, g/cm^3	Breaking point at compressing specimens, MPa			Water resistance index	Water saturation in volume, %
		$R_{50°C}$	$R_{20°C}$	$R_{0°C}$		
-	2.37	0.91	2.53	4.31	0.94	3.22
Mechanical mixing by 140ºC, 0.05% CNM	2.38	1.05	2.5	4.13	0.95	2.98
Mechanical mixing by 140ºC, 0.1% CNM	2.39	1.53	2.75	4.37	0.98	2.31
Spreading CNM in toluene, 0.1% CNM	2.37	1.21	2.53	4.55	0.97	2.29
Requirements of the StSt 9128-97		Least 0.9 MPa	Least 2.2MPa	Not more 10MPa	Least 0.9	1.5%-4.0%

[1] This work was supported by the RAS Presidium program "Arctic", project № 84.

APPLICATION OF ATMOSPHERIC PLASMA WITH RUNAWAY ELECTRONS FOR INDUSTRIAL WASTEWATER TREATMENT[1]

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The CONAP technology developed by authors at the "Laser Technologies & Systems", LLC (Tomsk) for removing heavy metal ions, organics and bacteria from industrial wastewater with residual concentrations less than MPC (maximal permitted concentration) for fishing water areas (most strong criteria for wastewater treatment) is described in the present paper. Atmospheric gas discharges plasma (AP) including ADRE (Atmospheric Discharge with Runaway Electrons [1-3]) is using in developed CONAP technology, as well as generation of metallic (as a rule - iron, or aluminum) nanoparticles with absorption on its surface of pollutant converted by AP and coagulation of this nanoparticles to micrometer size for subsequent filtration on standard sand filters.

The industrial water treatment station APHRODITE - 1000 (for productivity up to 1000 tons of wastewater per a day) pilot sample developed and tested for industrial approving in China also described in the paper as well as its testing results. The picture of this water treatment station with 8 AP channels working in parallel is shown on the Fig. 1. The functional scheme of the station includes as a main parts the power supply units of "PROTEUS-2" [4] and "PROTEUS-5" types and Atmospheric-Water Reactors (AWR) developed by the "Laser Technologies & Systems, LLC (Tomsk). There are two main types of AWR using in the CONAP technology: ADRE-plasma reactors for organics and bacteria removing, as well as repetitive pulsed AP inside air bubbles in water with iron (aluminum) metallized ore pellets. The coagulation chamber of special design, pressed sand filter and the membrane type filter-press are using for coagulation, water filtration and producing nontoxic solid waste (could be applied in several industries as useful component).

Some testing results for simulated and real wastewaters shows the treatment effectiveness of Cr^{6+}, Cu^{2+}, Ni^{2+}, Zn^{2+}, and other heavy metal ions as well as COD (organics) levels decreasing on a level of 99.9% what is much higher than the effectiveness of conventional chemical reagent technologies. That makes possible a use of such a station for wastewater treatment in metallurgy, textile, mining, chemical and some other industries with high heavy metal ions and organic pollutant concentrations.

Fig. 1. The picture of APHRODITE-1000 wastewater treatment station at the Laser Research Institute of Shandong Academy of Sciences, Jining, China

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TEMPERATURE MEASUREMENT OF THERMAL PEAKS IN PURE METALS AND Al-Mg-Li-Zn ALLOY UNDER ARGON ION IRRADIATION (E = 5–20 keV)

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The experimental technique for the determination of the parameters of energy release in dense cascades of atomic displacements is proposed. It is based on the measurement and analysis of the spectral density of the surface emission of condensed media irradiated with accelerated ions, under the assumption of the presence of a thermal constituent of emission defined by the presence of thermalized cascade regions.

The spectral density of emittance of the metal targets under bombardment with Ar^+ ions (E = 5-20 keV) were measured using an OC-12 diffraction spectrograph and were approximated by two Planck functions of thermal radiation. These functions are consistent with: (1) thermal spike regions and (2) volume of targets cumulatively heated during irradiation.

Irradiation was performed with argon ions using an ILM-1 ion beam implanter equipped with a PULSAR-1M ion source based on a low-pressure glow discharge with a hollow cold cathode [1]. A quartz optical fiber, the receiving end of which was set at a distance of 1 cm from the edge of the sample and was directed onto the sample surface at an angle of 60°.

As a result, the *temperatures* of nanoscale regions of thermalized cascades of atomic displacements (thermal spikes) were experimentally determined in tungsten (99.96 W), zirconium (99.98 Zr), iron (99.99 Fe), and aluminum of technical purity (99.5 Al), and commercial 1424 aluminum alloy of the Al-Mg-Li-Zn system.

The estimates of the temperature of thermalized cascade regions being in the range 3600-6200 K are in a good agreement with the results of calculations made using molecular dynamics and Monte Carlo (TRIM) methods [3]. The data obtained for pure iron are in a good agreement with those of a work devoted to ion sputtering [2].

Rapid heating of cascade regions during the period of time of $\sim 10^{-12}$ s to the experimentally determined temperatures indicates that they are the regions of explosive energy release. This proves that the emission mechanism, which was predicted by the theory, of post-cascade shock waves that are able to rearrange metastable media is valid.

The pressure estimated based on the measured data in the regions of thermalized cascades is 4-10 GPa and more, which is an experimental confirmation of the probable emission of post-cascade solitary waves with the stresses at their fronts exceeding the yield strength of the material (including aluminum and its alloys). Such waves may be responsible for the rearrangement of condensed matters under ion bombardment.

According to our data, the rate of energy release (about 10^{16}-10^{17} W/cm^3) in a dense cascade is comparable to the rate of energy release during nuclear explosion.

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PLASMA EBG STRUCTURES AT HIGH MICROWAVE POWER [1]

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The glow discharge plasmas have a great potential for application as a control element in microwave devices designed on the basis of electromagnetic band gap (EBG) structures (or otherwise, electromagnetic crystals) [1]. The 1D EBG structure formed in a waveguide solely by plasma columns of low-pressure glow discharges is reported in [2]. The possibility to control microwave propagation through triangle 2D EBG structure by these low-pressure plasma columns is experimentally demonstrated in [3]. Low-pressure plasma inhomogeneities allow the permanent control of crystal transmission at microwave power less than the one leading to microwave breakdown of the gas in discharge tubes. In this report, we address plasma control of microwave propagation through the 1D and 2D triangle EBG at high power (50 kW).

Three pulsed discharges in argon (or helium) at atmospheric pressure are used as the plasma inhomogeneities forming a one-dimensional electromagnetic crystal in waveguide of 24×10 mm^2 (Fig. 1(a)). In the experiment, the pulse discharge duration is about 250 μs. Maximal concentration of about 2×10^{17} cm^{-3}

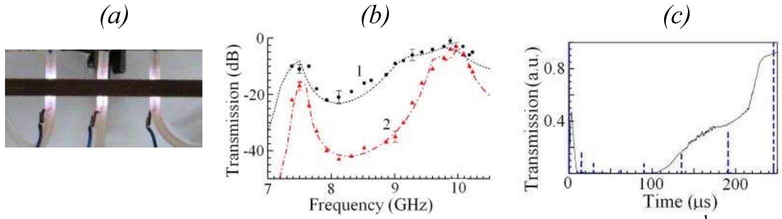

Fig. 1. (*a*) Image of waveguide section with discharges, (*b*) transmission spectra at 3rd (1) and 17th (2) microseconds and (*c*) transmission of high power (50 kW) pulses at frequency of 9.15 GHz.

is reached at 15-20 microseconds. The transmission spectra of one-dimensional electromagnetic plasma crystal at 3rd and 17th microseconds are shown in Fig. 1(*b*). The amplitudes of short (~200 ns) and powerful (50 kW) microwave pulses at frequency of 9.15 GHz are strongly suppressed when they fall in the time range of the existing of plasma structure (Fig. 1(*c*)).

The propagation of powerful microwave pulses through the triangle metallic 2D EBG structure with

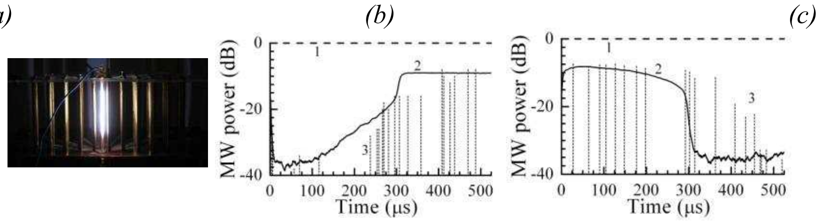

Fig. 2. (*a*) Image of 2D EBG metallic structure with a discharge column and its transmissions of high power pulses at frequency of 9.15 GHz in a direction of 45^o in the cases of defect compensator (*b*) and additional defect (*c*).

plasma as control element is investigated, as well (Fig. 2(*a*)). The pulsed discharge in argon at atmospheric pressure in a gap of 50 mm is used. Maximal concentration is about 6×10^{16} cm^{-3}. If plasma column is used as a compensator of defect in the front row of EBG structure, the transmission of powerful microwave pulses in direction of 45^o quickly ceases (during time of a few tenth of nanoseconds), and this suppression continues for about 200 μs (Fig. 2(*b*)). If plasma column is used as an additional defect, the transmission quickly arises and maintains over the time of about 350 μs.

The obtained results are important for the development of electrically controlled microwave devices capable of working in a complex automatic system under PC control.

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THE EFFECT OF ELECTRON COMPONENT IN ION BEAM ON THE STRUCTURE OF HYDROGENATED AMORPHOUS CARBON FILMS DEPOSITED ON THE END-HALL ION SOURCE

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Amorphous carbon (a-C) and hydrogenated amorphous carbon (a-C:H) films attract vast attention[1-2] due to the exceptional mechanical, chemical and tribological properties. The developments of low-friction and wear-resistant thin a-C:H coatings would allow new possibilities in many applications such as friction loss reduction and highly reliable mechanical components in machines.

Hydrogenated amorphous carbon thin films were synthesized by end-Hall (EH) ion beam deposition using methane precursor gas. The effect of the fraction of ions and electron components in the ion beam on the microstructure, surface morphology, mechanical and optical properties was investigated as any results of the similar researches are missing from the literature. The fraction of sp^3 hybridized carbon atoms was determined by means of X-ray photoelectron spectroscopy. The behavior of sp^2 hybridized carbon atoms network was explained by the results of Raman spectroscopy according to the method proposed by Robertson and Ferrari[3]. The surface topography of the films were studied using atomic force microscopy. The nanoindentation technics were used to determine the hardness and Young's modulus the at the depth of indentation in the range 10-150 nm. The transmission and reflection spectra of the films in the range of 190 nm – 3300 nm and the values of the optical gap were measured. The thickness of the films was determined by means of scratching method.

The hydrogenated amorphous carbon films were deposited on silicon and glass substrates with titanium interlayer and without. Titanium interlayer was deposited directly before the deposition of the carbon film using the magnetron sputtering system. In the deposition processing, the discharge voltage was tuned in the range of 35–200V while the ion discharge current was 2A for all experiments. The synthesis time was varied from 5 min to 60 min to study and identify stages of the film growth. The ion beam current varied in the range from -160mA to 20mA by changing the emission current and flow rate of the methane. A measurement of the energy of the electron component of the beam current registered wide dispersion of the electrons and the average value of the electron energy about 30 eV. The distribution of electrons on energy in the ion beam is showed in figure 1. Such high value exceeding values of the binding energy means the electrons play one of crucial roles in the formation of the structure of the hydrogenated amorphous carbon on a par with the influence of the ion energy and the ion flow quantity. Thus, the high intensity of the electron component may lead to graphitization of the carbon film.

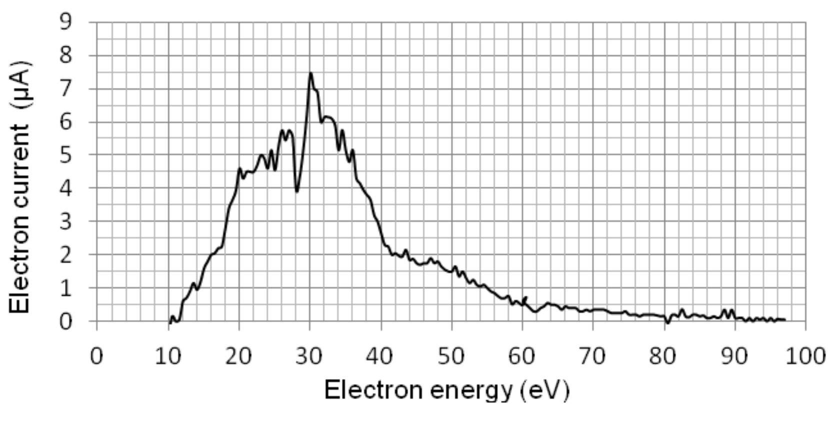

Fig. 1. The distribution of electrons on energy in the ion beam.

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OPERATING EXPERIENCE OF PSEUDOSPARK SWITCH IN PULSE POWER APPLICATIONS

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The results of using of pseudospark switch (PSS) type TDI1-200k/25H developed by Institute of High Current Electronics SB RAS in cooperation with Research Institute "PLASMA" [1] are presented. PSS was applied in pulse power system for electric-discharge blasting of rocks and concrete. The pulse power system has pulse current generator with capacity of 560 µF, stored energy – up to 63 kJ, operating voltage – up to15 kV, amplitude of current pulse – up to 200 kA with duration more than 200 µsec [2]. The data of short-circuit experiment of the pulse current generator and experiments of the electric-discharge blasting of concrete at a charging voltage 12 kV are presented. PSS was operated in ringing single pulse mode with exceeding more than two maximum permissible parameters: current pulse amplitude; current pulse duration and maximal pulse energy. Internal electrode erosion of PSS is shown and possible reasons of asymmetric current feed are discussed [3].

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MODELLING OF UNDERGROUND BED GEOMECHANICAL CHARACTERISTIC FOR ELECTROPHYSICAL CONVERSION OF OIL SHALE

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Oil shale energy extraction is urgent issue of modern science and technique [1]. Due to electrical discharge phenomena is possible to create a new efficient technology for underground conversion of oil shale to shale gas and oil [2]. This method based on joule heat in rock volume. During the laboratory experiments problem is appeared, when significant part of shale fragment is heated, further heating is impossible due to specimen cracking. It leads to failure of current flows and heat exchange. Evident, in underground conditions these processes will not exist. Cement, clay and glass fiber/epoxy resin armature are used for modelling of geomechanical underground conditions. Experiments show that, in case of reinforcing jacket application, is possible to convert full rock fragment. Also, thermal field extend radially from the center of dendritic structure and has elliptic cross section shape. It takes place as a result of oil shale anisotropy due to laminar structure. Therefore, heat propagation is faster along of layers then across.

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THE INFLUENCE OF STRUCTURE OF THE DIFFERENT MODES OF DEPOSITION ON STRUCTURE RF-MAGNETRON CALCIUM PHOSPHATE COATING[1]

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Calcium phosphate (CaP) coating is widely used in medical application because its biocompatibility and osteoconductive properties. CaP coatings on the base of hydroxyapatite (HA) are widely used in biomedicine. The influence of the different sputtering process parameters, such as discharge power level, process gas pressure, electron bias, have been carefully investigated [1, 2]. Morphology of implant surface, element and phase composition and structure of coating are often the determining factors in the “success” of the implant. Therefore, the effect of the mode of deposition on structure of the rf-magnetron CaP coating has been studied in the paper.

The XRD analysis of diffraction pattern of titanium substrate with CaP coating showed only reflections from the titanium substrate. Hydrothermal treatment does not lead to crystallization of coating. Reflections from TiO2 (rutile) appeared after isothermal annealing of coating in the air at 700°C. Weak peaks at the 2Θ angle range of 31-34° are also appears. There are the most intensive peaks featuring HA phase – Ca5(PO4)3OH at this 2 Θ range. The research of the coatings with grazing angle X-Ray diffraction confirmed the formation of the Ca5(PO4)3OH phase in coating. Fig.1 presents Raman spectra of CaP coatings obtained at the following modes of deposition: standard mode (, electric bias on the substrate was of -50 V and +50 V, addition of 18% vol. oxygen (O2) in the chamber working gas. Symmetric vibration bands PO43- (ν1) at the range of the Raman shift of 920-980 cm-1 are the most intensive bands in apatite specter. Location of the line at the range of 945-950 cm-1 confirms presence of disordered phosphate lattice of apatite or formation of amorphous structure of the obtained CaP coating. Addition of 18 vol. % O2 in the chamber working gas resulted in appearance of additional low intensive band (shown by arrow on the fig.). It can be explained by forming of tricalcium phosphate (TCP) or other non-stoichiometric calcium phosphate in coating.

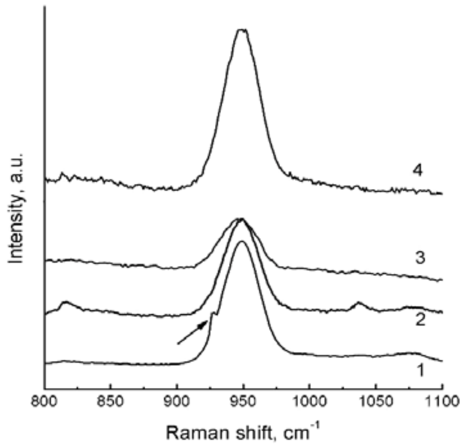

Fig. 1: Raman spectra of CaP coatings obtained at the following modes of deposition: addition of 18% vol. O_2 in the working gas atmosphere (1), standard mode (2), electric bias on the substrate of -50 V (3) and +50 V (4)

Amorphous CaP coatings were obtained at different deposition modes. Crystallized structure was obtained by annealing. Addition of oxygen in the working gas atmosphere resulted in appearance of weak band of TCP or non-stoichiometric CaP on the Raman spectra.

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THE APPLICATION OF ASSISTING GAS PLASMA GENERATOR FOR LOW-TEMPERATURE MAGNETRON SPUTTERING OF Ti-C-Mo-S ANTI-FRICTION COATINGS ON TITANIUM ALLOYS[1]

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The positive effect of assisting influence of high-density gas plasma formed by an independent plasma generator PINK on mechanical and tribological characteristics of Ti-C-Mo-S magnetron coating on titanium alloys at lower to 350°C temperature of coating regardless of alloy structural condition was revealed bymethods of calotest, nanoindentation, scratch testing and frictional material tests. The coating formed by means of a combined magnetron plasma method reduces titanium alloys friction coefficient in multiple times (Fig.) and increases wear resistance by two orders of magnitude. At the same time the mechanical properties of ultrafine-grained titanium alloys obtained by nanostructuring do not deteriorate (Table).

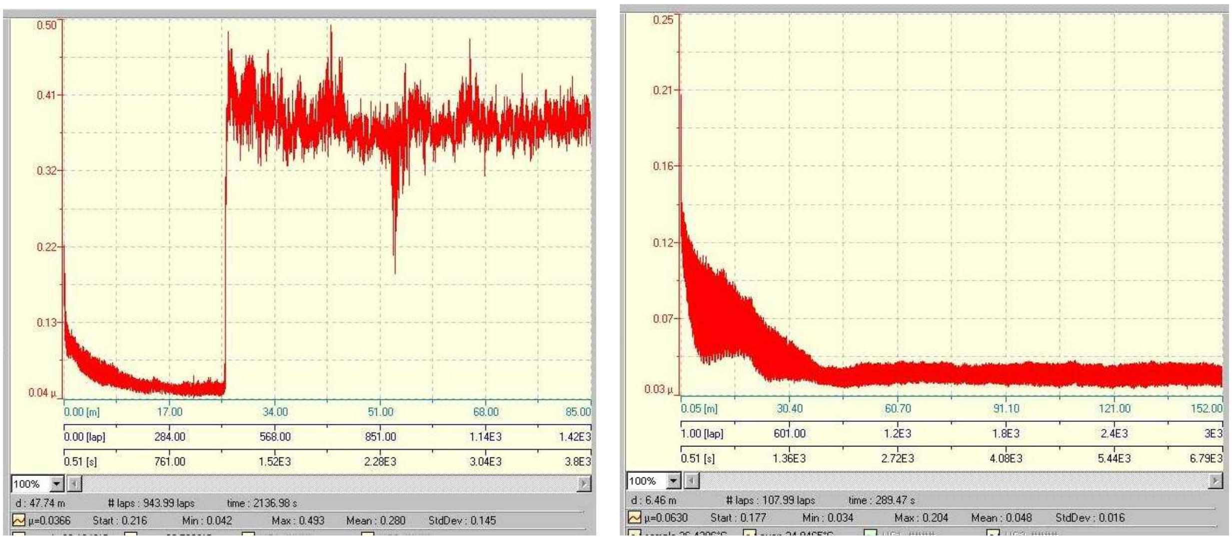

Fig. Friction coefficient μ of the ultrafine alloy VT6 coating by conventional magnetron sputtering techniques (a) and by the combined magnetron-plasma method with an assistant gas- plasma generator PINK (b)

Table. Influence of magnetron plasma coating Ti-C-Mo-S in the tensile strength (σ_B) and elongation to fracture (δ) alloy VT6 in coarse and ultrafine states.

Status of alloy	Baseline values of strength and plasticity		Indicators of strength and ductility after magnetron plasma coating	
	σ_B, MPa	δ, %	σ_B, MPa	δ, %
Coarse-grained	900±10	10,5±0,5	920±10	9,5±0,4
Ultrafine	1040±10	10,5±0,5	1070±10	13,0±0,3

[1] This work performed under the state Ministry of Education task (task №2014 / 223 Project Code: 727)

THE EFFECT OF DOPING ON THE ELECTRICAL PROPERTIES OF POLYCRYSTALLINE DIAMOND FILMS DEPOSITED FROM ABNORMAL GLOW DISCHARGE[1]

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Unique chemical, mechanical, electrical and thermal, optical and photoelectrical properties of diamond contribute to its wide application in high–frequency, high–temperature electronics and semiconductor manufacturing of a special purpose [1, 2]. Due to the limited possibility of using diamond single crystals and epitaxial diamond films, because of their high cost in the most appropriate instruments are the polycrystalline diamond films (PDF), which are obtained by developed methods of the chemical vapor deposition (CVD) [1]. PDF are successfully used for the production of stable radiation-resistant detectors of UV and ionizing radiation, as well as for laser and photodiode structures [1]. Depending on the characteristics of polycrystalline structure of PDF, the content of alloying impurity atoms and defects, electrical characteristics, as well as the mechanism of the transport and type of the charge carriers vary widely [1]. Among the various PDF deposition methods, there are microwave plasma, hot filament, arc–jet and glow discharge CVD to be marked out. Glow discharge CVD is considered to be an effective diamond film deposition method because of its simplicity and high growth rate [2]. The aim of this work is to study the effect of boron doping impurity atoms on the electrical characteristics on the dominant transport mechanism, on the energy spectrum of localized states of defects in polycrystalline diamond films deposited from abnormal glow discharge plasma.

The energetic and kinetic characteristics of surface dark and photoconductivity of PDF and their temperature, field and spectral dependences were investigated. Dominant carrier transport mechanisms, their type and the energetic spectrum of localized defect states were established. Doping of the polycrystalline diamond films of boron impurity atoms in the deposition of an abnormal glow discharge allows to form on the Si substrate with the semiconductive layers of p–type conductivity, which is not inferior to the properties of PDF obtained by alternative methods. Lower weakly conductive layers PGF isolate the upper conductive layers from the influence of the substrate. Vacuum annealing of the films to 720 K stabilizes electrical properties. Doping reduces the degree of disorder of the material films growth defects compared with undoped films, which affects the electrical and photoelectrical properties and conduction mechanism. Activation component of p–type conductivity is realized through the exchange of charge carriers between the valence band and the shallow acceptor levels with an activation energy 0.013–0.022 eV. In the doped films is enhanced role of hopping conduction mechanism between localized states of defects with a density of $(1–6)\cdot 10^{20}$ $eV^{-1}\cdot cm^{-3}$ near the Fermi level, which is located near the valence band of the material. Electrical characteristics, mechanism of charge transport of deposited PDF were caused by defects of different nature, the energetic levels of which are continuously distributed on energy in the band gap.

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GENERATION OF MICROWAVE OSCILLATIONS IN THE DEVICES BASED ON THE PHOTOELECTRONIC OPEN DISCHARGE[1]

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A variety of electron beam generators and switching devices based on the photoelectronic open discharge (POD) have been created earlier [1,2]. Their main advantage is the transition from a non-conducting stage to conducting one in a time less than 1 ns and an electron beam current rise rate of up to 50kA/ns. In addition, these devices can operate at frequencies of tens of kHz without reducing the switching characteristics. Already achieved electron beam current density exceeds 1 kA/cm^2 from surface of the cathode. Further increases in the electron beam current density and rise rate are limited by current oscillations [3]. The frequency of these oscillations depends on various parameters (voltage, switching power, etc.) and can be in range from hundreds of MHz to several GHz.

From the viewpoint of a fast switching of the energy this phenomena is undesirable, so it was suggested to limit the maximum intensity of the electron beam due to making cathodes of piezoceramics with high secondary electron emission (barium titanate). Device was fabricated in a planar geometry with opposite electron beams. Significant increases in the current density and the current rise rate were obtained while the current oscillations were absent. Nevertheless, this device design features also lead to the generation of high-frequency oscillations, but with a different mechanism. The device represents two ceramic cathode plates, one side of each is closed on a common grid-anode by discharge, and other is connected to the charging circuit. To charge both halves of the device simultaneously, the cathodes are connected by copper foil with minimal possible contour which provides electrical strength of the structure. This resulted in excitation of RF oscillations in the discharge circuit at the resonant frequency of the circuit. These oscillations did not affect the switching rate, because they exist after the passing of the beam current, and changing other conditions of the pumping mainly affect the intensity of the oscillations without affecting their frequency. Q of the circuit was high and the duration of the existence of oscillations was limited to the parameters of charging and measuring circuits, where their energy dissipates.

Thus, devices based on the POD are able to generate the high frequency oscillations by two different ways: due to electron beam current oscillations in the discharge plasma and due to the high Q factor of the oscillatory circuit formed by the high capacity ceramic electrodes and the foil joining them. In the first case it is possible fine tuning of frequency and burst duration RF/microwave oscillation in a wide range by changing the supply voltage and the storage capacitance. In the second case, the frequency is given by structural capacity and inductance of the device and doesn't dependent on external factors. Moreover, this type of oscillations does not affect the frequency, switching and other characteristics of the device. In particular, packets of RF oscillation with frequency greater than 100 kHz can be achieved.

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THE STRUCTURE OF GROWTH AND PROPERTIES OF NANOCRYSTALLINE GRADIENT COATINGS TI-AL-SI-CU-N PRODUCED BY ION-ASSISTED MAGNETRON SPUTTERING

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At present, the common approach when creating functional materials and coatings is the use of multi-element compositions, allowing forming a nonequilibrium heterophase structure modification and properties which may correspond to a range of environmental changes. With regard to the synthesis of a wear-resistant coatings in the capacity of compositions can be selected that which form the nanocomposite structure with significantly different tensile properties (fracture toughness) forming phases, with their high adhesion strength and adhesion to the substrate. The possibility to control and obtain optimum values of the selected characteristics is realized in the synthesis of coatings with gradient in the growth direction of the elemental composition and structure. In this regard, according to the above requirements for the synthesis of these materials system of elements Ti-Al-Si-Cu-N is a promising and nanocrystalline coatings on the basis of that system are obtained at changes of the copper concentration in the range up to 13 at. % in coating thickness.

Attestation of structure, elemental and phase composition in the coating thickness was carried out by transmission and scanning electron microscopy, electron microprobe and X-ray analysis. It has been established that a coating is a single-phase solid solution with the B1 structure in the coating thickness average crystal size of constant ~ 6 nm regardless of the elemental composition. Shows the effect of the growth of the copper concentration of the alloying elements and the elements forming the nitride phase. Not monotonic behavior at amplitude of a few percent of the period of crystal lattice of the nitride phase depending on the concentration of copper was detected. The bending-torsion of the crystal lattice in the individual nanocrystals at different distances from the surface of the coating was studied. The increasing of the magnitude this structural characteristics to the surface of the coating with achievement of the values order 400 deg. / µm in the surface layer was revealed.

Shows by the nanoindentation technique using a variation of hardness in a coating thickness at 50% reduction of its size in the surface layers with a high concentration of copper. The critical loads and structural features of the fracture and delamination of coatings on substrates with different hardness in the scratch test were determined. The preferential localization of fracture and delamination of the coatings on a solid alloy due to the different nature of the stress-strain state in the cross section of a scratch track was established. The changes of the coefficient of friction and wear rate, depending on the thickness of the layer extracted for inhomogeneous wear along the track were shown for various conditions of the tribological tests. The results obtained are analyzed using the concepts of the secondary ion sputtering of elements from the surface of the growing coating, on the solubility of alloying elements in the nitride phase, on the impact of soft metallic phase at the hardness and strength and gradient structure – at adhesion characteristics.

SURFACE HARDENING OF STAINLESS STEEL BY RUNAWAY ELECTRONS PREIONIZED DIFFUSE DISCHARGE IN AIR ATMOSPHERE [1]

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In the present study, runaway electrons preionized diffuse discharge (REP DD) was employed for surface treatment of stainless steel in air atmosphere. This type of discharge was realized in non-uniform electric field by applying of high voltage pulse of 2 ns full width at half maximum to cathode with small curvature radius. As a plane anode, stainless steel foil of 200 μm thickness was used. In a REP DD, the anode experiences complex action of several factors:

1) dense nanosecond discharge plasma with a specific power up to 100 MW/cm^3 in a pulse mode [1];
2) a shock wave which was recorded with a calorimeter [2];
3) UV, VUV radiation, as well as X-rays from the discharge plasma [3];
4) a supershort avalanche electron beam (SAEB) with a wide energy range [2].

High voltage pulsed generator RADAN-220 provided negative voltage pulses with amplitude up to 250 kV and pulse front of 0.5 ns was used for REP DD formation. The distance between high voltage tube cathode and plane anode was 18 mm. Microhardness was measured by Berkovich diamond indenter on the system of NanoTest 600 by Oliver-Pharr method.

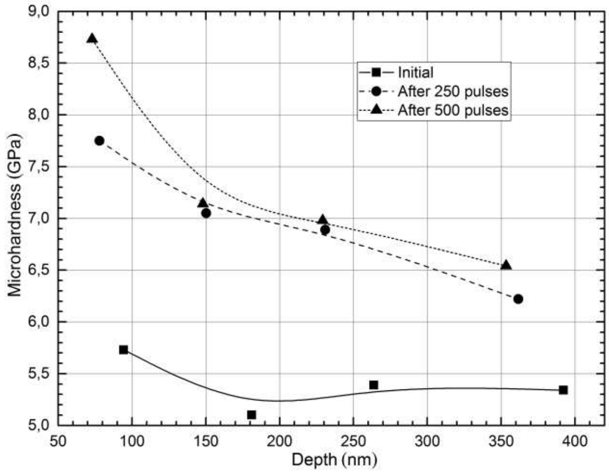

Fig. 1. Dependences of surface microhardness versus its depth for initial stainless steel samples, and samples treated by REP DD.

It has been found that samples modified by REP DD have microhardness almost 2 times higher than untreated ones, and increase with increasing of number of pulses (see fig. 1). The optical technique based on the relative radiation intensity of rotation structure of electronic-vibrational molecular transitions was used for measurement of gas temperature *Tg*. Values of *Tg* was found to be of ~ 380 K at condition under study [4], that is not sufficient for modification due to melting of metal surface layers. Electron beam also could not induce it because of its short time duration and low energy. Most likely microhardness was increased due to change in surface layers chemical composition by mixing the oxide and substrate layers after shock waves. The Auger spectroscopy shown that discharge-treated samples covered with oxide layer and its thickness increased with increasing the number of shot pulses.

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SIMULATION OF THE POLYMERIZATION ON SILICON IN CF_4/H_2 PLASMA[1]

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The processing of thin films by fluorine atoms in plasma-chemical reactors is widely used in microelectronic device production. The active particles are formed in the RF-discharge zone by the dissociation of gas molecules containing such atoms. Usually they are pure gases CF_4, SF_6 or binary gas mixtures with O_2, H_2 and etc. Due to the complex multichannel nature of fluorine formation the probable mechanisms of gas-phase chemical reactions in glow discharge are insufficient investigated. Surface phenomena at the RF-electrodes and wafer surface are even less understood. The defining set of chemical reactions in plasma is usually chosen using the experimental results. The concentrations of active particles strongly depend on the choice of chemical kinetic model and the electron density distribution in RF-discharge. To provide a good optimization of the etching process is quite essential to compare the probable kinetic models of fluorine formation in such chemical systems. Some results obtained for chemical kinetic model of silicon etching in CF_4/O_2 glow discharge plasma have shown that to obtain adequate results it is necessary to use a detail plasma-chemical kinetics with precise description of heat and mass transfer [1].

In the paper one of probable mechanisms of gas-phase chemical reactions in CF_4/H_2 mixture and their influence on the etching process are studied. The calculations were carried with using 2D mathematical model of plasma-chemical etching reactor [2] in which a special attention gives to the multicomponent chemical kinetics of gas-phase reactions. In CF_4/H_2 mixture the basic set of chemical reactions corresponding to reactions in pure CF_4 was derived. Further the chemical reaction set was added by possible reactions of CF_4 with H_2. Consequently the chemical kinetic model contains 28 gas-phase reactions of dissociation and recombination processes, which include F, CF_2, CF_3, CF_4, C_2F_6, F_2, H, H_2, HF, CHF_3, CH_2F_2. The chemical kinetics of heterogeneous reactions was presented by processes of adsorption of CF_2, CF_3 at wafer surface.

The CF_4/H_2 system is characterized by lower fluorine concentration and higher coverage of silicon surface by CF_2, CF_3 compared to the CF_4/O_2 system. . The main part of fluorine atoms obtained from the dissociation of tetrafluoromethane are consumed in the reactions with hydrogen atoms to form an abundant component HF. As a result the fluorine concentration monotonous decreases along the flow direction whereas the concentration HF rises and reaches a maximum at the outlet of reactor. The most substantial components after CF_4 are HF and CF_2 which reach a maxima at 50 % addition of H_2. With increase of H_2 percentage in the feed gas mixture the fraction of silicon wafer occupied by radicals CF_2 rapidly rises and at 40 % H2 comes to 99 %. The fraction of silicon wafer covered by CF_3 not exceeds 1.5 % in all range of parameters. The fluorine component is weakly consumed in the etching reaction owing to the passivation of silicon surface by the adsorbed radicals CF_2, CF_3. Moreover the fluorine concentration decreases in general. The adsorption of CF_2 on the surface results in to the reduction of etching rate when the fluorine concentration is nonzero. The etching process is completely stop at 35 % H_2. The main channel of reduction of silicon etching in CF_4/H_2 connects with two processes - the fluorine depletion and the surface passivation by radicals CF_2. Thus the hydrogen addition up to 30 – 40 % allows to completely stop the etching process and it is an effective factor to control the processing regime.

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IONIC ENLIGHTENMENT OF NONLINEAR OPTICAL CRYSTALS TYPE KTP

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The possibility of strengthening the reflection waveguide layers in the optical spectrum under ion irradiation high-resistivity crystals (potassium titanyl phosphate $KTiOPO_4$ - KTP) coated with a transparent film MgF_2 was investigated. The Hall ion source was used for irradiation. Ion current was equals 10-15 mA at a voltage of 10 kV.

It was found that removal rate of the antireflective coating in the shadow of the crystal is much greater than the etching rate under the beam. The effect is explained by the formation of ion clusters in the area of recombination on the shady side of the crystal [1]. A model of the interaction of the ion flow with the crystal is presented on figure 1.

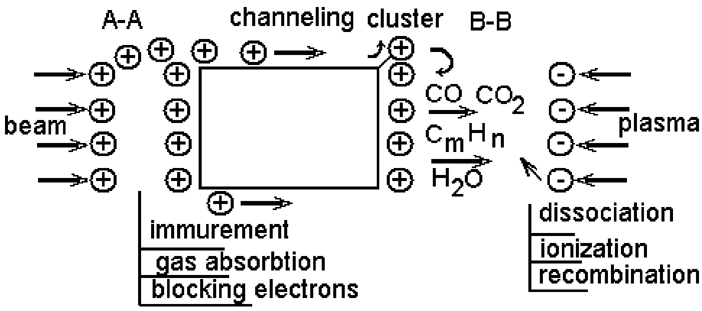

Fig. 1. Model of the interaction of the ion flux to the crystal

The dynamics of the process is as follows.

In during ion irradiation around the crystal is formed an electric double layer. Main processes for the irradiated side of the crystal (A-A) - is immurement and absorption of gas, blocking by ions electrons from the plasma, electrostatic charge of the surface.

On the sidewalls of the crystal, ions moved at a small angle (5 degrees) to the surface in the directions of the minimum axes of the crystal (channeling), creating the effect of grouping into clusters.

Behind the crystal is formed zone of high electric field intensity on the faces of the crystal. This enhances electrostatic scattering of ion flow, reduces the local current density in the ion beam and generates an extended trajectory of the electron drift behind the crystal.

The drift electrons removed part of the charge from the shadow surface of the crystal due to bias currents and recharge. As a consequence, behind of the crystal are formed region ionization, dissociation and recombination of particles. Under the influence of these processes, the surface charge on the shady side of the crystal decreases. Ionic clusters under the action of the local electric field of faces of the crystal are flock to the shady side of the crystal and bombard it. Ionization and recombination processes are stimulated by desorption of gas from the crystal. Before the crystal region of free drift of the particles is not formed. Charge of the surface distorts the trajectory of the primary ions, causing their channeling along the axes of symmetry of the crystal.

As a result, the etching rate was implemented at a ratio of 2 nm/ min under beam and 20 nm/ min on the shadow side of the crystal. After ion irradiation reflection spectrum of the crystal expands in the optical wavelength (crystal is enlightened).

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GROWING OF ALUMINIUM NITRIDE FILMS BY PLASMA-ENHANCED ATOMIC LAYER DEPOSITION AT LOW TEMPERATURES[1]

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Aluminium nitride (AlN) combines a number of physical and chemical properties, useful for practical application. Aluminium nitride thin films are used in fabrication of field-emission cathodes, buffer layers for growth of high-quality materials, dielectric and passivation layers in semiconductor devices as well as in manufacturing of gas sensors, UV LEDs and photodetectors.

One of the most promising techniques of thin (less than 100 nanometers) film growth is atomic-layer deposition (ALD). This method enables growth of homogeneous thin films with controlled repeatable thickness and controlled chemical composition. Using of plasma for enhancing of reactivity of one of the process chemical agents (precursors) (plasma-enhanced atomic layer deposition – PEALD) helps to drastically reduce growth temperature and shorten cycle time. Furthermore, in respect to the aluminium nitride thin films deposition, PEALD makes it possible to use as a nitrogen source not only ammonia plasma, which is toxic and explosive gas, but also plasma of mixture of gaseous nitrogen and hydrogen.

Generally, atomic-layer deposition methods are used for growth of amorphous films. The goal of our research was to determine possibility of growth of aluminium nitride crystalline films using this technique at low substrate temperatures, which is particularly significant for development of passivation coatings for microscale and nanoscale electronic devices.

AlN thin films we deposited using TFS-200 system manufactured by Beneq (Finland), equipped with inductively coupled plasma source. Operating frequency of the high-frequency generator was 13.56 MHz. Thin films were grown on the monocrystalline silicon substrates (111) at the process temperatures 80 to 280°C. Film thickness increased linearly in proportion to the number of deposition cycles. Each PEALD cycle included four steps: 1) treatment of the substrate surface (growing film) with the first chemical agent (trimethylaluminium); 2) blowing of the reactor with nitrogen; 3) exposure of the growing film surface to the second chemical agent – plasma, generated by HF generator in the mixture of the gaseous nitrogen and hydrogen; 4) blowing of the reactor with nitrogen. Optimum output power of the of the HF generator (W) for chosen growth conditions was 200 W. Decrease of the W value required additional time of exposition to the plasma, which resulted in increase of the whole time of the PEALD cycle. During the deposition process stability of the plasma characteristics (reflected power and potential displacement) decreased with the increase of W, and this worsened the repeatability of the microstructure of AlN thin films.

Obtained series of samples of the aluminium nitride thin films were examined using X-ray diffractometer Rigaku. Results showed that in the self-limiting growth mode, which is the basic condition of the atomic layer deposition process, film growth rate was not more than 0.12 nm/cycle. Films, grown in this mode and having thickness 50-52 nm, are nanocrystalline. This was evidenced by well-defined reflexes seen on the X-ray diffraction pattern. It is important to note that crystalline grains in the aluminium nitride thin films grown at 280°Ccorrespond par excellence to the hexagonal polytype. While thin films grown at 250°C were formed by crystalline grains with cubic structure.

As can be seen from the above, it was found that crystalline aluminium nitride thin films can be grown by plasma-enhanced atomic layer deposition in the self-limiting growth mode at temperatures less than 300°C.

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INFLUENCE OF THE SURFACE TREATMENT COMPRESSION PLASMA FLOWS ON THE ADHESIVE PROPERTIES OF THE FILM-SUBSTRATE SYSTEM[1]

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Radiation treatment of the material, based on the use of low-energy high-current ion and electron beams, compression plasma flows, has become an effective tool for modifying the properties and improve the performance of construction materials. This treatment allows to increase: microhardness, wear resistance, modified surface relief produce coatings with different properties. An important task is to increase the adhesion properties of the coating material to a substrate material for radiation processing the film-substrate systems.

The work is devoted to experimental Investigations of the influence the surface treatment compression plasma flows (CPF) on the adhesive properties of the film-substrate system.

We studied 50x50 –mm steel 3 samples with a thickness of 3 mm. Pre-treatment samples were compression plasma flows generated in gas-discharge magnetoplasma compressor compact geometry (MPC-CG) at different processing modes. In the experiments the initial voltage on the capacitor bank was 3.5-4 kV, the discharge time of ~ 100 μs. Velocity of the plasma formations compression flow in the MPC-CG is (1-4) × 104 m/s. The temperature and the electron density of the plasma compression flow rate was 1-3 eV, respectively, and $(4\text{-}7)\cdot 10^{17}$ cm^{-3}. Nitrogen was used as a plasma forming gas. The pressure of the plasma forming gas was 400-500 Pa during the discharge. The energy density absorbed by the target surface was altered by varying the distance between the sample and the cut of the cathode from 6 to 14 cm. According to calorimetric measurements, the energy density in the reported experiments varied in the range W = 10–35 J/cm2.

Processing CPF resulted to the modification of the surface topography of the samples. The surface is highly developed and has become a large-scale wave-like relief: increased roughness with Ra = 1 micron to 12 microns. After processing CPF on magnetron sputtering method samples deposited copper film with a thickness of 1-20 microns.

Research has shown that pretreatment of the steel samples 3 and treatment regimens significantly affect the adhesion of the film material with the substrate material.

1 This work was supported in part by the Ministry of Education and Science of the Russian Federation (contract no. 1030 (2014105-GZ) for support of research at the South Ural State University).

REGULARITIES OF STRUCTURE AND PHASE COMPOSITION FORMATION OF SURFACE LAYER OF SILUMIN SUBJECTED TO ELECTRON-BEAM TREATMENT[1]

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The treatment of silumin surface by high-intensity electron beam at a different pulse duration, energy of the accelerated electrons and the energy density of the electron beam was carried out. The studies of the structure and phase composition of the surface layer of silumin at initial condition and after electron-beam modification was performed. The possibility of dispersing of silumin structure due to ultra-high-speed heating and cooling which realized in the surface layer of the material, and of the formation of the modified layer with increased (1.5-fold relative to the initial) microhardness was demonstrated.

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SICNAL FROM PLASMA ANTENNA IN DIFFERENT OPERATION MODES[1]

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The most important problems of a study of the plasma antennas in the discharge tubes is a selection of transmission and receiving modes with the minimal distortions and noises [1,2]. Three operation modes (nonradiating, nonlinear and linear) of a plasma antenna had been found in [3] by numerical simulation These operation modes affect the radiated signal of the plasma antenna [4]. Thus the studies of radiated signal from plasma antenna are necessary.

In our work we have been researched the radiated signal of a plasma asymmetric dipole antenna (PAD) in the different operation modes. The models of PAD with l=4 cm and radius r=0.5 cm had been created in KARAT code [5]. We have considered Particle-In-Cell (PIC) model of a low collisional plasma ($v_e<f_p$). This model of plasma allows studying an interaction an electromagnetic wave with the plasma particles. In the model we have studied a radiation of a Gaussian form pulse with duration τ_p=15 ns and carrier frequency f_0=1.7 GHz. The spectral and time characteristics of the pulse have been gotten in the plasma and a near antenna field.

The spectra of the signal, the spectrum changes over time, a signal-to-noise ratio, an autocorrelation function (ACF) have been studied in the different operation modes. The mentioned studies have been done by the programs in MATLAB. A program of correlation analysis have been written based on the data processing techniques created, tested and patented by Malakhov D. V., Skvortsova N. N. and etc. in GPI RAS [6].

The results of our researches show that an amplitude value of a frequency component f_0 is very small and less than amplitude of the low frequency noises in the nonradiating operation mode. A spectrum contains frequency component $2f_0$ with small amplitude value in the nonlinear mode. In the linear mode the spectrum of radiating signal has the biggest amplitude of the frequency component f_0 which is bigger than this amplitude in other modes. But the spectrum has small high frequency noises from f_0 to f_p.

The ACF of the signal add to the understanding about the operation modes of the plasma antenna. The ACF's results show a radiating signal falling-off in the nonradiating mode. In the nonlinear mode the ACF's results show high value of the low frequency noises and energy loses. We have achieved stable signal radiation in the linear mode.

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EFFECT OF VACUUM CONDITIONS AND PLASMA CONCENTRATION ON THE CHEMICAL COMPOSITION AND THE ADHESION OF THE VACUUM-PLASMA COATINGS

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The characteristics of the chemical composition of titanium nitride (TiN) and silicon (Si) coatings, deposited with using a new equipment (vacuum-plasma processing installation with magnetron sputtering system, electric arc evaporators and efficient high-concentration gas discharge plasma generator). It is shown that the deposition of these coatings due to the high purity of vacuum conditions and the high-quality surface cleaning in gas-discharge plasma is performed substantially without plasma contamination with oxygen and carbon as the interface coating-substrate and coatings themselves. It was found that the interface of obtained coating is the mixed of the substrate and coatings components layer and it has length of 60 nm or more. These factors clearly affected on the increased adhesion coating of titanium nitride obtained with the new equipment over the brass coatings, deposited by industrial technology through the transition layer of titanium oxide. It is concluded that the using of presented vacuum-plasma equipment advantages allows developing of effective processes of the materials and products surface properties modification by method of vacuum-plasma immersion doping.

PHASE FORMATION IN THE TITANIUM-YTTRIUM SYSTEM FORMED BY CONCENTRATED ENERGY FLUXES[1]

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Combined method including irradiation of plasma produced in the electric explosion of a conductive material (titanium foil with a small amount of yttrium powder), and subsequent processing of high-intensity pulsed electron beam carried out alloying of commercially pure titanium surface in a technical vacuum. Phase diagrams, detected possibility of formation in a surface layer of the multi-phase structure have been plotted. The studies of elemental and phase composition of the modified surface layer have been carried out. Formation of a multiphase multilayer submicro- and nanocrystalline structure on the basis of α-yttrium, α-titanium, titanium and yttrium oxides and carbides, with high mechanical strength have been revealed.

[1] This work was supported by the grant of Russian Science Foundation (Projects No 14-29-00091).

FEATURES OF FORMATION OF STRUCTURAL-PHASE STATES ON THE SURFACE OF TITANIUM ALLOY VT1-0 AFTER ELECTRON-ION-PLASMA TREATMENT

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Currently, one of the most promising approaches to creation of wear-resistant coatings is a method of formation of composite materials with titanium diboride. Such a composite material has a high load-bearing capacity combined with high physical and mechanical properties (high hardness, low values of the thermal expansion coefficient, low sensitivity to heat shock) and is not subject to plastic deformation which contributes to accumulation of defects in a crystalline lattice and the subsequent damage during a tribological contact. Such a surface is possible to create using pulsed melting with simultaneous saturation of the material surface layers with doping elements followed by crystallization and formation of strengthening phases, carried out by plasma formed during an electric explosion of a conductive material (electroexplosive doping), is one of the promising methods for modification of the structure and properties of metals and alloys.

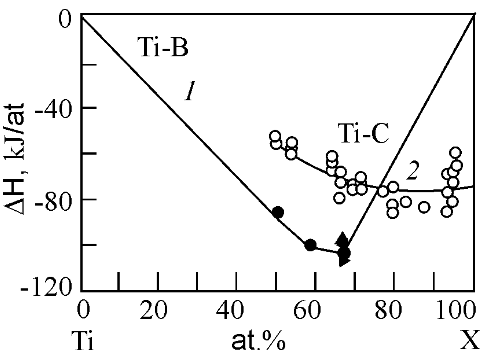

Fig. 1. The enthalpy of compound formation in systems Ti-B (curve 1) [1] and Ti-C (curve 2) [2] at 298 K

This paper presents the results of the study on the combined treatment effect, which includes electroexplosive doping and the subsequent exposure to a high-intensity pulsed electron beam, on the structural-and-phase state of the surface layer of the alloy based on titanium VT1-0.

Doping of the surface layer of the alloy based on titanium VT1-0 was carried out by exposure to plasma formed during an electric explosion of a graphitized carbon fiber, on the surface of which in the area of the explosion a sample of the powder of titanium diboride TiB_2 was placed. Additionally, pulsed melting of the modified layer was carried out with a high-intensity electron beam on the installation “Solo”, under the mode: electron energy 18 keV, energy density of the electron beam (45-60) J/cm^2, duration and the number of exposure pulses 100 ms, 10 pulses; 200 ms, 20 pulses, the pulse repetition rate 0.3 s^{-1}. Structural studies were carried out using methods of scanning and electron diffraction microscopy, X-ray analyses; physical-and-mechanical properties of the surface layer were studied by measuring the microhardness, the wear resistance, and the friction coefficient.

According to the literature data on the enthalpy, formation of compounds in systems Ti-B [1] and Ti-C [2] is significant and it indicates a high stability of compounds TiB_2 and TiC_X (Fig. 1).

It has been established that the main mechanisms responsible for an increase in the mechanical and tribological properties of the material are solid-solution (saturation of the crystalline titanium lattice with atoms of carbon and boron); dispersion (allocation of nanoscale particles of carbide, boride, and carbide-boride phases); grain boundary (formation of a grain structure with submicron dimensions).

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PRODUCING ULTRA COMPOSITION TiN-Cu USING MAGNETO-PLASMA ACCELERATOR EROSION TYPE COMBINED ACCELERATOR CHANNEL

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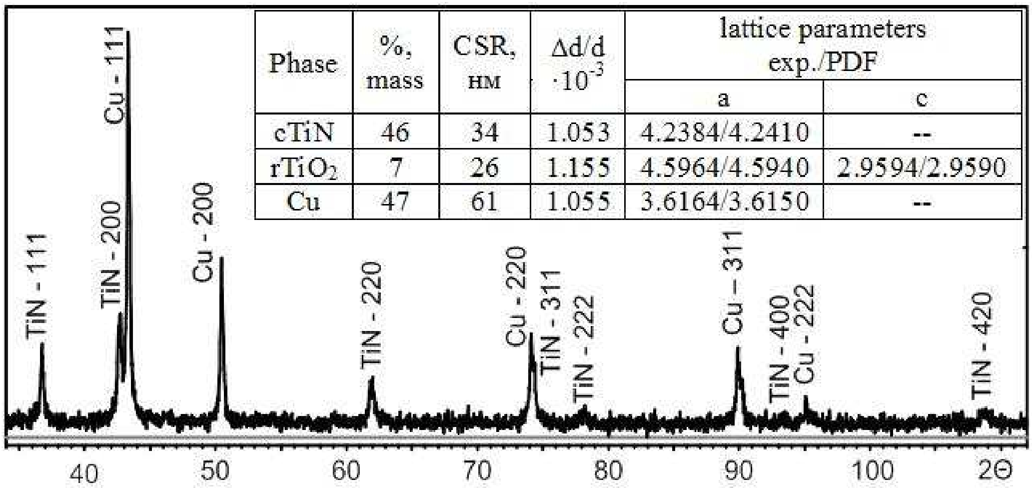
In [1] have demonstrated a significant increase in the physical and mechanical characteristics of the material based on titanium nitride by the introduction of copper supplements in the amount of 10-12%. The microhardness of the coatings of this type is close to 40 GPa. A method of obtaining ultrafine composition TiN-Cu using a coaxial magneto-plasma accelerator (CMPA) [2]. Experiments were carried out for values of input energy 22 kJ and 80 kJ. In the accelerating channel contains four copper wire with a diameter of 2.0 mm. Fig. 1 shows the XRD-pattern of powder materials obtained in experiments with energy parameters W= 80 kJ, as well as basic data full-profile X-ray analysis: the ratio of crystalline phases in weight percent, the average size of coherent scattering regions (CSR); the value of internal microdistortions Δd/d, and lattice parameters.



Phase	%, mass	CSR, нм	Δd/d ·10^{-3}	lattice parameters exp./PDF	
				a	c
cTiN	46	34	1.053	4.2384/4.2410	--
rTiO_2	7	26	1.155	4.5964/4.5940	2.9594/2.9590
Cu	47	61	1.055	3.6164/3.6150	--

Fig. 1. X-ray diffraction data and X-ray analysis

X-ray analysis shows that the primary crystal phase of the obtained product is a dynamic synthesis cubic titanium nitride, titanium dioxide with a rutile structure and copper crystalline. The copper content can be controlled in a wide range by the energy supplied to the accelerator (approximately 4% at 22 kJ of energy and approximately 48% at an energy of 80 kJ).

As seen from the micro-electronic analysis (fig. 2) product includes three phases: titanium nitride, copper and titanium dioxide with a rutile structure, uniquely corresponding three-phase system cTiN, cCu and rTiO_2. Cluster consists of particles ranging in size from 70 nm to 100 nm.

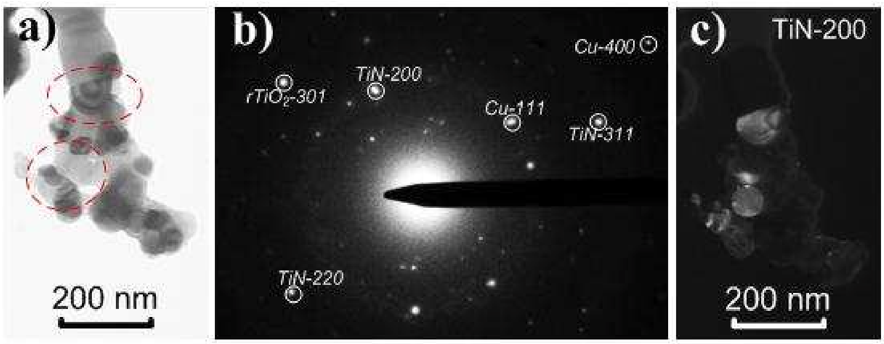


Fig. 2. These TEM-investigations composite powder material of TiN-Cu: a) light-field image b) electron diffraction, c) dark-field image in the reflex TiN-200.

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INFLUENCE DISPERSION THE RAW POWDER ON THE PROPERTIES OF SPS-CERAMICS

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In previous studies [1, 2] it is shown that there is a fundamental possibility of a full cycle of the ceramic with submicrostructure by consolidating product plasmodynamic synthesis. Dispersed and phase characteristics of the base product [3-5] have a significant impact on the physical and mechanical properties of the sintered ceramics. Dispersing the product was necessary to prevent the formation during sintering of focal defects.

SPS-consolidation of powder samples before and after activation was conducted under the same parameters of SPS: V_T = 850°C/min, T = 1300°C, P = 80 MPa without holding at a constant temperature.

Increased bulk density and the effect produced by them is very clearly visible when comparing the curves punches move during the time of sintering. Moving the movable punch experiment unactivated powder was 3.5 mm, while the activation of the powder allowed to reach a displacement of 1.75 mm under otherwise equal conditions.

As seen in Figure 1, the use of the product activation on a planetary mill allowed to exclude focal defects and achieve a strict uniform structure.

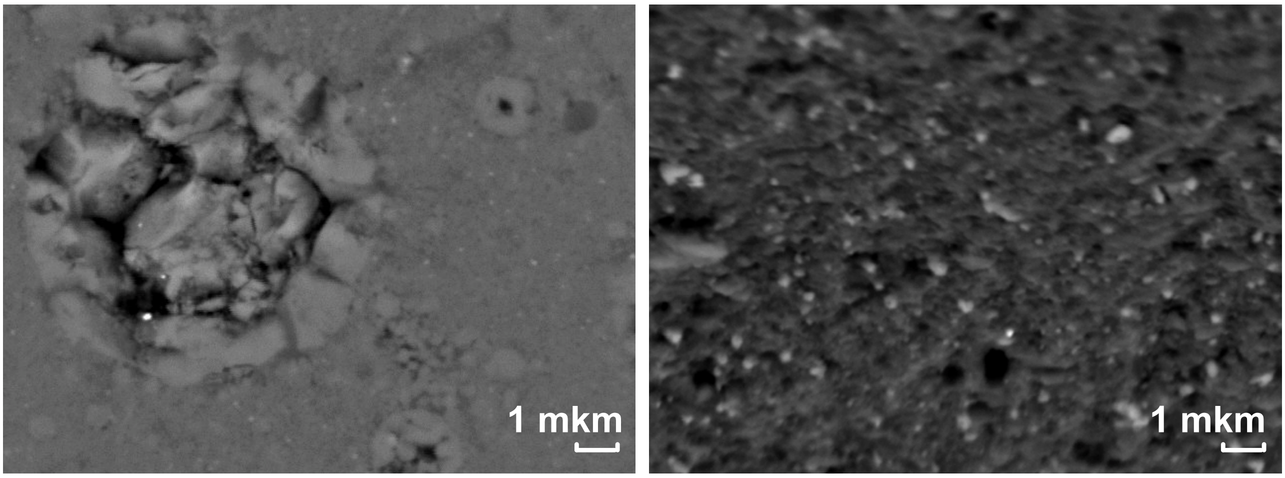

Figure 1. SEM-pictures chipped ceramic samples obtained from powder samples before and after the deagglomeration in the planetary mill.

The hardness of the materials obtained as measured by the Vickers indenter method of reduced imprint was 21 GPa for non-activated powder and 17 GPa for activated when the relative density of sintered ceramic blanks with respect to the single crystal osbornita 92% and 93.5%, respectively. A significant increase in the density of the sintered body is mainly due to the elimination of agglomeration raw product.

On the SEM-images show small enough porosity of the material. Shows a SEM-picture of a small number of pores in the material of the maximum size of not more than 300 nm, the average grain size of 100 nm. Decrease in the microhardness of the sintered samples similarly can be explained by the phases of iron in the sintered sample.

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INFLUENCE NANOPOWDER IMPURITIES IN THE RAW MATERIALS ON THE PARAMETERS OF SPS-CERAMICS

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In previous studies [1-4] showed that there is a fundamental possibility of a full cycle of the ceramic with submicrostructure by consolidating product plasmodynamic synthesis. Dispersed and phase characteristics of the base product [5] have a significant impact on the physical and mechanical properties of the sintered ceramics. Was made from a mixture of milled on a planetary mill and a large fraction of the ultrafine fraction in a ratio of 3:1.

Figure 1 shows the results of XRD analysis of the obtained sample ceramics. Comparing XRD-powder billets and pictures sintered product shows that occurs during sintering nitridoobrazovanie. It is also evident from the increase in physical broadening of the strongest reflexes and split their highs. SCR size drops to 75 nm.

This mode SPS, selected at random, will provide the compact with the material density ρ = 5,0 g/cm^3, which is 92% of the density of a single crystal.

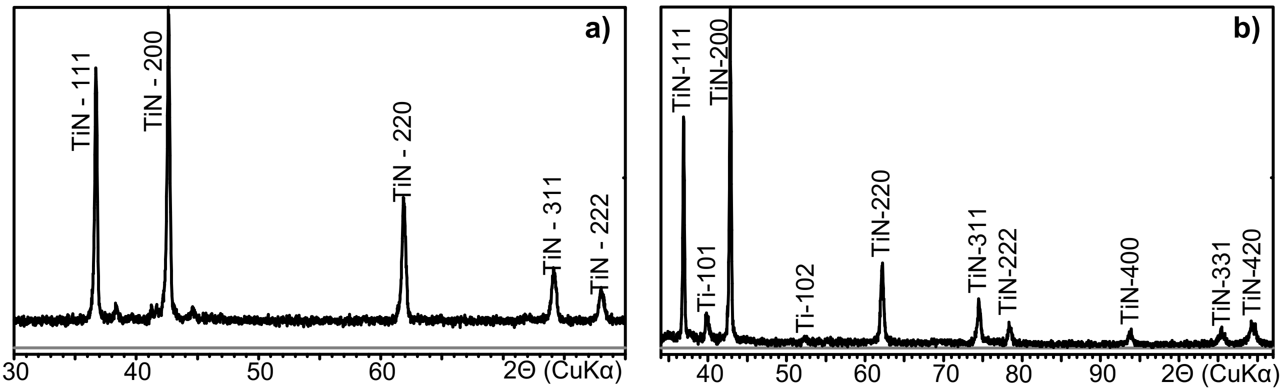

Figure 1 - The results of the powder X-ray diffraction TiN, obtained by grinding coarser fractions (a) and XRD-pattern of a polished surface of the obtained sample tablets SPS-TiN-ceramics from the milled coarse fraction of mother (75%) and addition of UDP (25%) (b)

This confirms the assumption that the cause of focal defects is a strong agglomeration of the product. The hardness of the resulting materials measured by Vickers indenter method of reduced imprint was 17 GPa.

This sample was tested for cutting properties, for boring bars of hardened steel (55HRC) compared to industrial designs ceramic. The sample showed good cutting properties.

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GAS DISCHARGE ION SOURCE FOR MODIFICATION OF POLYMERS SURFACE PROPERTIES [1]

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Ion source which generates beams of gas ions for modification of organic polymers surfaces by ion implantation is presented. Originally this devise is conventional ion source Mevva-5.Ru based on a vacuum arc discharge [1]. For treatment of polymers such as polyethylene, polyvinyl alcohol and polytetrafluoroethylene is required to generate of argon ions. The main feature was to provide very low mean power density of ion beams for minimizing of destruction polymeric molecules [2]. For generation of argon ion beam we made minimal internal changes in construction of ion source discharge chamber and in external electrical circuit. Thus we realized operating of discharge system in a hollow cathode glow discharge mode. Discharge were operated in pulse mode with duty cycle lower 10^{-4}. The current density of ion beam was 10-50 $\mu A/cm^2$, mean energy of ions was 20 keV. Implantation was performed with fluence 10^{14}-10^{16} ion/cm^2. Structure of polymer species surfaces after ion implantation were analyzed by infrared spectroscopy and scanning electron microscopy. Surface resistance of polymers after ion-beam treatment was evaluated from analysis of volt-ampere characteristics by measuring the leakage current at a voltage from 100 V to several kilovolts, which was applied at the small space of the implanted surface.

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CUBIC TUNGSTEN CARBIDES: SYNTHESIS AND LATTICE CONSTANT CONTROL [1]

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Tungsten carbide is useful material for cutting, drilling, milling tools and for catalytic systems due to extreme hardness, high temperature resistance and catalytic activity [1-3]. Cubic tungsten carbide was synthesized by hyper high speed W-C plasma jet [4]. The cubic WC1-x phases characterized by different lattice parameters were detected by XRD. Also powders contained small amount of tungsten carbide W2C, tungsten W and graphite gC. The influence of precursor mass (m), its C/W ratio and energy input (E) on the lattice parameter (a) of synthesized cubic structure is shown. The modern literature analysis demonstrates the evidence of two cubic WC1-x lattices characterized by different dependence of lattice constants as a function of C/W ratio.

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PLASMA-CHEMICAL METHOD FOR PRODUCING METAL OXIDE POWDERS AND THEIR APPLICATION [1]

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Micro- and nanoparticles of Al_2O_3, ZrO_2, AlB_2, SiC etc. are used as reinforcing ones providing reduction of development of dislocations in accordance with Orowan's mechanism [1] in the process of alloy deformation which improves strength characteristics. Nowadays, the most promising methods of production of oxide nanopowders with high capacity are plasma chemical method. Plasma-chemical systems are characterized with high energy intensity of the heat flux: the temperature of plasma heat transfer media comprises ~ 10^4 K while their enthalpy comprises (1-2)$\times 10^2$ kCal/mol [2], which provides high specific production capacity of equipment. Alumina and zirconia powders were produced from sprayed water solutions of salts in air flow heated to low-temperature plasma state using a 70 kW high-frequency unit. The diagram of the unit is given in Fig.1. Sprayed solution is supplied to plasma jet of the heat transfer medium generated by plasmatron 3 in the plasma chemical reactor 2 via nozzles 1. The powders produced are separated by filter 5 and supplied to collector 9. Vapor-gas flow after cooling down in apparatus 6 is separated from the liquid (condensate is collected in tank 10) and prior to emission to atmosphere is cleaned in scrubber 7. In order to obtain metal oxides initial nitrate solutions of corresponding metals of these compounds were prepared with stoichiometric ratios of components and optimal temperature mode of the reactor of plasma-chemical unit was selected.

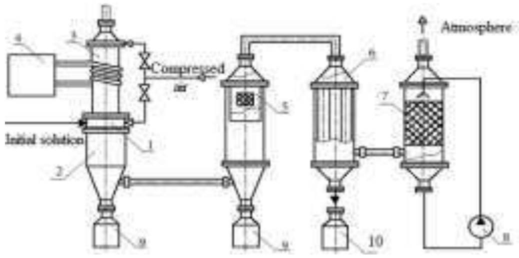

Figure 1. The diagram of plasma chemical powder synthesis unit

Preliminary study of kinetics of thermal decomposition using the method of derivatography was performed for Zr nitrates [3]. It was found that the process of decomposition has 8 stages with different kinetic characteristics. water solutions of Zr nitrates are decomposed to Zr oxides at the temperatures higher than 1053 K. Nanopowders represented a structure formed by individual spherical particles and bulk aggregated loose substance consisting of particles having irregular form. The BET surface of plasma-chemical powder has been measured to amount 60 m^2/g. Phase analysis has indicated that alumina powder is in a highly nonequilibrium state and contains 5 structural modifications.

Al_2O_3 nanoparticles were used as reinforcing particles for introduction into an Al alloy. Densely compacted master alloy containing 10 wt% of nanoparticles was introduced into the Al melt with simultaneous ultrasonic processing.

The possible use of Alumina and zirconia nanopowders in the framework of Al alloy modification technology. The possibility of industrial-scale production of powders of abovementioned oxides using plasma chemistry methods.

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COPPER OXIDES SYNTHESIS BY USING COAXIAL MAGNETOPLASMA ACCELERATOR[1]

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Nanodispersed copper oxides are widely used in high-temperature superconductivity due to its high physical and chemical properties [1-2]. Currently, obtaining of pure materials with a relatively narrow particle size distribution representing single crystal is an important issue. All existing synthesis methods of nanodispersed copper oxide are not effective enough. In this article, the obtaining of nanodispersed copper oxide by plasmodynamic method was researched.

An analysis of ultradispersed plasmodynamic synthesis product obtained using coaxial magnetoplasma accelerator with copper electrodes was carried out [3]. The getting powder was analyzed by X-ray diffractometer Shimadzu XRD 7000 using the temperature consoles Anton Paar TTK450. Using this analysis such phases as copper Cu, copper oxide (I) Cu_2O, copper oxide (II) CuO, and copper hydroxide hydrate $Cu(OH)_2$•H_2O were identified in the product. The dominant phase in the synthesis product is copper oxide CuO with an average size of coherent dispersion 14 nm. The main advantage of CuO over Cu_2O is the most stability material, so further research was gradual heating of the material to increase the mass of CuO. In the figure 1 are shown X-Ray diffraction patterns of the obtained material and annealed powder. The mass of copper oxide increased up to 98% and copper hydroxide hydrate. During the annealing the powder at 800 ºC mass fraction of copper oxide was increased up to 98%.

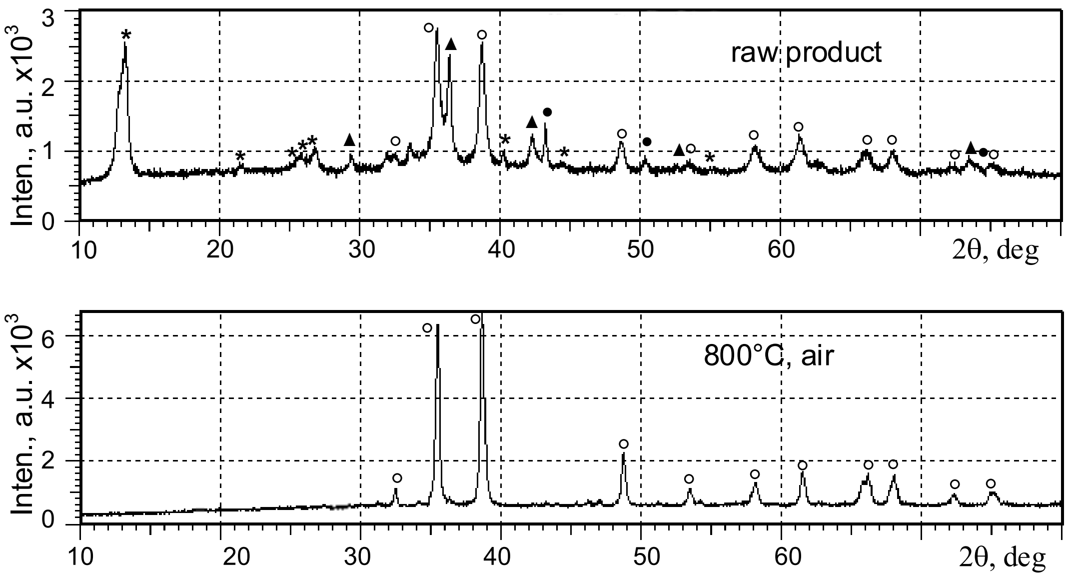

Fig. 1. X-ray diffraction patterns of the synthesized material
● Cu; ▲Cu_2O; ○ CuO; * $Cu(OH)_2 \cdot H_2O$

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THE VACUUM SYSTEM FOR TECHNOLOGICAL UNIT DEVELOPMENT AND DESIGN

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In 2012- 2014, within the framework of the project «Development of management and control systems for advanced vacuum process units» the vacuum arc accelerator unit (Fig.1) for low pressure plasma processing was developed and carried out preliminary work on its automation. At this stage of the work studied the basic principles of the use of microcontrollers in vacuum systems [6]. To control the operation of vacuum switching of the vacuum system was developed on the basis of ATMEL microcontroller, in Android program environment via Bluetooth. However, the applicable of this unit is limited only film deposition on fixed distance from anode.

Fig. 1.The pulse vacuum arc unit

The use of robots and other automation equipment in the plasma process can significantly limit or eliminate participation of the person. In many cases, it provides a significant economic effect. In addition to economic and holds social effect is the removal of a person from danger to his health and life of technological operations [2]. Furthermore, there are operations that cannot be executed by person (operation under vacuum). However, in our case application of the robot due to operational needs. The fact, that the quality of coating on the work piece in a vacuum, it is necessary to constantly turn, since the plasma flow is typically in the same direction. Planetary arrangements only apply to flat samples, but for complex shapes is not enough. Therefore, it is necessary to use a robot (hand- manipulator) to capture the details and its free movement in three axes. Furthermore, the plasma flow is not always even and homogeneous in density, so that the distance of exposure should be chosen depending on the work mode of installation. The task of the robot is to obtain information about the current situation and the implementation of moving parts. Thus, the creation of intellectual and robotic systems are closely connected with the peculiarities of obtaining and maintaining a high vacuum, which requires developers to informed choice of the necessary technical solutions.

With according this idea, the new vacuum camera and digital vacuum switching control system was developed and design. In principle, the robot can change a sample under plasma accelerator and control of physical parameters of deposited film.

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THERMAL STABILITY OF NANOCOMPOSITE MULTICOMPONENT Al-Cr-Si-Ti-Cu-N COATINGS[1]

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The research of features of structural-phase state, microhardness and nanohardness parameters of multicomponent nanostructural Al-Cr-Si-Ti-Cu-N coatings subject to the annealing temperature was carried out by X-ray diffraction analysis and transmission electron microscopy.

This coating was deposited by the plasma magnetron-arc complex «SPRUT» with the simultaneous use of Ti, Cu, Al-Si and Al-Cr-Si alloys as targets (cathodes) at the constant bias voltage [1]. One-hour annealings of studied coatings were conducted in conditions of high vacuum at the temperatures 500 °C, 700 °C and 900 °C.

The investigation results of microstructure features, elemental and phase composition of multicomponent nanostructural Al-Cr-Si-Ti-Cu-N coatings immediately after the ion-plasma synthesis are presented in detail in the paper [1].

The X-ray diffraction analysis data evidence that the structural state of coatings is X-ray amorphous both after the synthesis and after the annealing in the entire temperature range 500 – 900 °C.

In the result of electron microscopic analysis it was found that before and after annealing investigated coating are characterized by multiphase nanostructural state. At same time it was determined that annealing temperature increase leads to insignificant change of range of the characteristic size of the coherently scattering regions of the material basic volume (from 3 – 12 nm to 3 – 16 nm). The considerable enhancing sizes of the coherently scattering regions (from 2 – 20 nm to 8 – 36 nm) is observed in local areas initially formed at the synthesis of coating. It was established that phase composition of coating before annealing indicates the presence of phase TiN, CrN, Cr in the basic volume and TiN, Cr in the mentioned areas [1]. After the annealing at the temperature 900 °C detected phases TiN, CrN in the basic volume and TiN in the areas with enhanced size of crystallite are characterized by the insignificant change of lattice parameters in comparison with the initial and standart data.

It was determined that microhardness values are decreased from 19,6 to 15,6 GPa at the increase of annealing temperature. It was supposed that this feature is caused by the enhancing crystallites sizes, the change of the internal defect structure and phase composition in local areas.

Thus, studied multicomponent nanostructural Al-Cr-Si-Ti-Cu-N coatings were shown to be characterized by the thermal stability of microstructure up to 900 °C at the insignificant decrease of microhardness values.

The influence of annealing temperature on the mechanisms of transformation of element-phase composition, the parameters of microstructure and mechanical properties of the multicomponent nanostructural Al-Cr-Si-Ti-Cu-N coatings is discussed.

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THE INFLUENCE OF THE ION-PLASMA SYNTHESIS REGIMES ON THE FEATURES OF STRUCTURAL-PHASE STATE OF MULTICOMPONENT NANOCOMPOSITE Al–Cr–Si–Ti–Cu–N COATINGS[1]

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Within the concept [1] of formation of multi-component nanocomposite coatings, which assumes a simultaneous nucleation of islands of mutually insoluble or slightly-soluble phases under conditions of self-assembling of microstructure during their synthesis, Al–Cr–Si–Ti–Cu–N coatings are designed and formed. Using the methods of X-ray diffraction analysis, scanning and transmission electron microscopy, a comprehensive investigation is performed of the influence of ion-plasma synthesis operating modes on the features of microstructure and elemental and phase composition of the resulting coatings.

Coatings were deposited by the plasma magnetron-arc complex «SPRUT» with the simultaneous use of Ti, Cu, Al-Si and Al-Cr-Si alloys as targets (cathodes) at various values of the constant and impulse bias voltage.

It was ascertained that elemental composition of studied coatings obtained at the different sputtering regimes almost coincides with the predicted. The local areas with enhanced copper content were detected.

X-ray diffraction analysis evidences that the structure state of coatings formed in the process of their synthesis is X-ray amorphous.

It was established that the thickness of deposited coatings changes in the range (1,5÷2) μm at the constant bias voltage in the interval from 100 to 300 V. The coatings surface is presented by a smoothed relief. The coatings structure was found to be characterized by the nanoscale particles of different phases divided by amorphous matrix. Two structure types were found in the coatings: the nanostructured state of basic volume and the almost equiaxed areas with diameter from 300 to 700 nm which do not have precise disjunctive boundaries with the surrounding basic structural state. The characteristic sizes of crystallites of the evolving phase in basic volume were shown to be in the range from 2 to 6 nm. At the same time phase composition of basic volume indicates the presence of both the pure phases TiN, AlN, CrN, CuO and phases on their basis differing by lattice parameters. The phases CrN, TiN, Cu were detected in the mentioned equiaxed areas.

In the case of impulse bias voltage (100 – 300 V, the frequency is 5 kHz) during the same period of sputtering the coatings has thickness (3,4÷4,4) μm and are characterized by significant roughness. It was shown that this feature is connected with the formation of the strongly pronounced columnar structure characterized by columns diameter from 0,5 to 2 μm.

It was detected that microhardness values are varied from 24 to 16 GPa at the changing type of bias voltage of constant to impulse respectively. But the same time the coatings microhardness does not significantly depend on the magnitude of the bias voltage. The investigated coatings were shown to be characterized by high cracking resistance and adhesion.

The influence of deposition conditions on the mechanisms of the nucleation and growth of coatings, microstructure parameters and the element-phase composition features are discussed.

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[1] This work was supported by RF Ministry of education and science, TOR No. 11.1655.2014/K, RFBR (Grant No. 13-02-98020 r_sibir_a) and Tomsk State University Competitiveness Improvement Program.

FACTORS AFFECTING THE EFFICIENCY OF CARBON DISULPHIDE CONVERSION BY STREAMER CORONA DISCHARGE IN ATMOSPHERIC PRESSURE GAS MIXTURES[1]

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An influence of various factors (voltage and current amplitudes, energy input and repetition rate of streamer corona pulses, diameter of reaction chamber, gas mixture composition, and gas flow rate) on the efficiency of carbon disulphide CS_2 conversion by streamer corona discharge in atmospheric pressure gas mixtures was investigated. Earlier we confirmed the advantage of the use of pulsed streamer corona for CS_2 removal from air in comparison with the use of corona discharge at a constant voltage [1].

A new created installation [2] allowed us to conduct experiments on CS_2 conversion in a chamber with bigger diameter (203 mm versus 88 mm) and with a higher streamer corona pulse energy input (1.6 J versus 0,45 J). The new installation is more effective for CS_2 conversion than the old one. With the initial CS_2 concentration 10000 ppm the carbon disulphide concentration decreased by 99.95% after 10000 pulses with an integral specific energy expenditures for CS_2 conversion 8.4 eV/molecule. Also processes of conversion of main products (sulfur dioxide SO_2 and carbonyl sulfide COS) were investigated.

A diagram of dependency of differential specific energy expenditures for CS_2 conversion on the carbon disulphide concentration for two initial CS_2 concentrations is shown in Fig. 1.

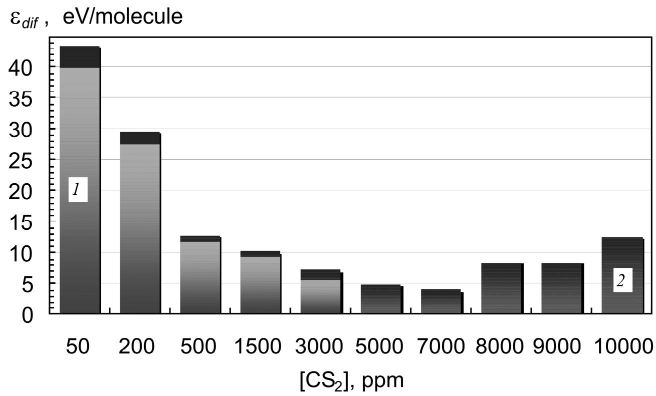

Fig. 1. Diagram of dependency of differential specific energy expenditures ε_{dif} for conversion of CS_2 on carbon disulphide concentration $[CS_2]$ in atmospheric pressure air mixture. Initial concentration $[CS_2]_0$ 3000 ppm (*1*) and 10000 ppm (*2*). Streamer corona pulse repetition rate F = 10 Hz

It is seen that minimum energy expenditures (4.0 – 4.8 eV/molecule) are observed in a range of CS_2 concentrations 5000 – 7000 ppm.

It was discovered that in the range of oxygen content 10-20% the efficiency of CS_2 conversion is almost constant. However, a decrease in oxygen content from 10% to 1% leads to a decrease in CS_2 conversion efficiency by 25%. It was shown that an increase in water vapor concentration from 0.3 to 4% leads to a slight increase in CS_2 conversion efficiency.

It was found that the conversion efficiency changes slightly with a variation in gas flow rate through a closed loop from 0 to 1 m/s and with a variation of pulse repetition rate from 1 to 25 Hz.

Thus, the use of pulsed streamer corona is a new effective method for carbon disulphide conversion.

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STUDY OF DECOMPOSITION REGULARITIES OF COMPLEX MIXTURES OF ORGANIC SOLVENT VAPORS IN A PLASMA GENERATED BY A PULSED CORONA DISCHARGE[1]

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Nonequilibrium low-temperature plasma (NP), created by various types of electrical discharges has been investigated extensively for air purification from vapors of volatile organic compounds (VOCs) [1]. Using the NP allows removal of VOCs at ambient temperature conditions, which offers significant advantages in terms of energy savings. However, as shown previously [2], removal efficiency of VOCs using NP is strongly dependent on the chemical structure of starting compounds. To compare the reactivity of different compounds to investigate gas mixtures containing several compounds together was proposed.

This paper presents the results of the use of pulsed streamer corona discharge to study the relative reactivity of various organic compounds, including halogen-containing.

For the experiment, plasma-chemical reactor with a discharge part of the following parameters: diameter 88 mm, 0.63 m length was used. Volume of the plasma-chemical reactor was 25.6 l. The central electrode was made of steel wire diameter of 0.24 mm. Discharge parameters were as following: discharge current of 200 A, the voltage amplitude of 120 kV, pulse duration of 20-30 ns, the energy per pulse - 0.5 - 0.8 J, pulse repetition rate - 10 Hz. Fig.1 shows the dependence of concentration of solvent vapors on the number of pulses. Fig. 2 shows similar results for chlorinated solvents. The initial concentration of each component is in the range of 400 - 650 ppm.

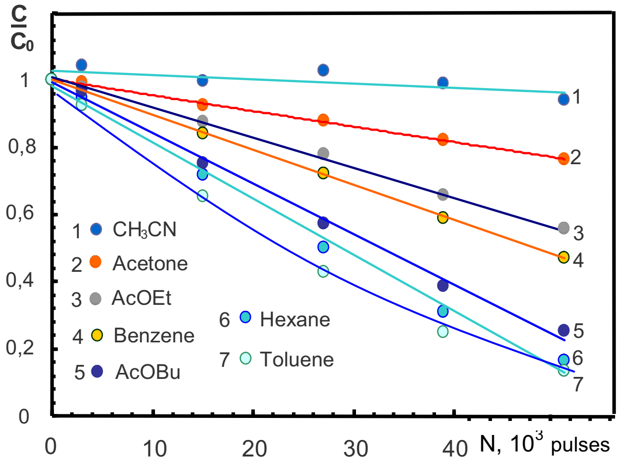

Fig. 1

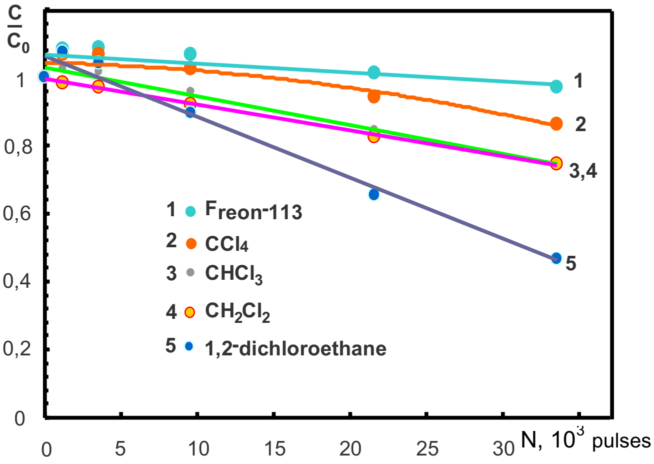

Fig. 2

The resulting regularities allow us to make a number of important conclusions:

- Chlorine-containing compounds are characterized by increased stability in pulsed streamer corona conditions. The greater degree of substitution of chlorine in the saturated organic compound - the higher stability;
- The commonly used as a solvent compounds have different resistance. Aliphatic compounds and toluene have lowest stability. Functionally-substituted compounds and benzene have intermediate resistance. The most stable compound in presented list is acetonitrile.

Regularities and mechanisms of VOC mixtures transformation under action of streamer corona discharge NP will be discussed.

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MECHANISM OF METALS SURFACE EROSION UNDER COMPRESSION PLASMA FLOW IMPACT

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The interaction of pulsed concentrated high power particles flows with solids leads to erosion of their surface. The origin of this process depends on a type of flow, its power, pulse duration, etc. Shock waves generation, ablation, hydrodynamic flow of melt and other processes can be the reason for this effect. The investigation of the regularities and mechanism of surface erosion of some construction materials under the impact of compression plasma flows was the main aim of this work.

Compression plasma flows were obtained using a gas-discharge magneto-plasma compressor of compact geometry powered with the capacitive storage of 1200 mF and operating at the initial voltage of 4 kV. Nitrogen was used as a plasma forming gas. The pressure of the plasma forming gas was 400 Pa during the discharge. The discharge duration amounted to ~ 100 μs. The treatment of carbon plain steel samples was carried out by one, three and six pulses. The time interval between pulses was 20 s. The heat flux absorbed by the surface layer (registered by calorimetric measurements) varied in the range of 9-35 J/cm^2 per pulse. A number of techniques including scanning electron microscopy, scanning probe microscopy, profilometry were used for characterization of the surface layer.

The findings showed that the increase in the density of energy absorbed by the surface and the number of pulses resulted in the growth of the mass removed. The linear character of the removed mass dependence on the absorbed energy density in the range of 9–35 J/cm^2 per pulse for steel samples of a specified size was observed. Erosion of the surface layer under the action of compression plasma flows led to a decrease in the coating element concentration in the alloyed layer in the case of impact on the coating/steel system. This effect depends on thermal characteristics of the treated material.

Numerical evaluation of different mechanisms of surface erosion as well as experimental data allow us to assume that the main cause of erosion of the steel samples surface in the impact area of compression plasma flows is the dimensional effect, i.e., the size of the sample in the plane perpendicular to the direction of the incoming flow is less than the diameter of the flow at the impact. The main mechanism of mass removal from the surface can be hydrodynamic flow of the melt to the edges of the sample and displacement of the melt outside the limits of the sample under the action of plasma flow pressure. The analysis of data of the removed mass during treatment of the sample with a size greater than the plasma flow diameter in the impact area confirmed this supposition. The last experiment gives an opportunity to evaluate the mean evaporation rate of steel during impact.

STRUCTURE OF SUPERHARDNESS TIB_2 LAYERS AT PROCESSING BY POWERFUL ELECTRON BEAMS[1]

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We presented some features of TiB_2 layers crystal structure. Layers were produced on steels with use reactionary daub containing the titan oxide, a boron and carbon. Layers have been received at pulse and continuous action electron beam processing. Properties and a structure of layers depending on a way of formation are compared. Conditions of initiation of process of a self-extending high-temperature synthesis and electron beam surfacing its products are analyzed and compared.

The surface layers saturation of metals and alloys from boron spend with the purpose of increase of their surface hardness, wear resistance, etc. Application of electronic heating with high (more 109 W/m^2) specific capacity in vacuum owing to fast not inertial achievement of limiting heats and ease of regulation of heating in a wide range of temperatures opens ample opportunities for creation of boride layers.

In [1] it was informed about formation of strengthening coating of TiB_2, CrB_2, VB_2, W_2B_5 on carbonaceous steels under influence of an electron beam on boron compound reactionary daub in vacuum. The assumption of an active role of a surface metal has been made at electron beam alloying of self-heating synthesis products which initiated by an electron beam and proceeding in reactionary daub of stoichiometric mixtures.

In the present work some features of TiB_2 layers crystal structure are studied at pulse and continuous electron beam processing's.

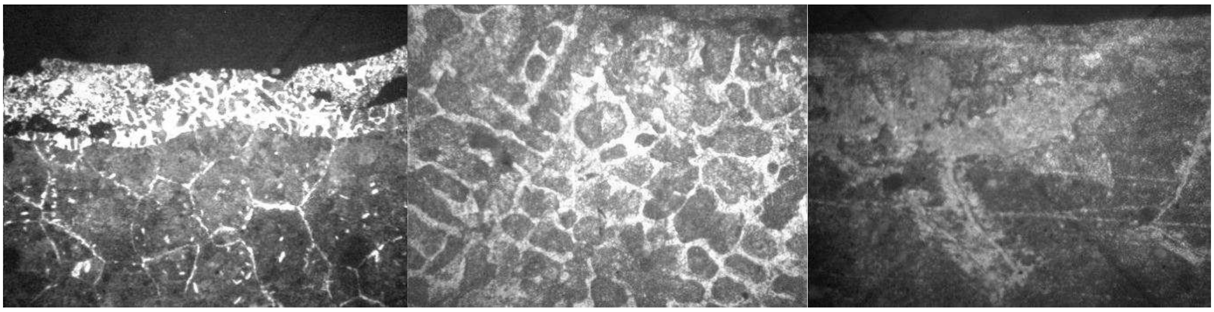

Fig.1. Microstructure of samples (TiO_2-B-C + B_2O_3) after pulse electron beam processing

As a pulse electron beam processing in proceeds at pressure 10^{-3}-10^{-3} Pa the interaction reaction oxide TiO_2 with boron compound (B_4C/B) and carbon should proceed at lower temperatures, than at pressure P= 10^{-2}-10^{-3} Pa, i.e. in the conditions of continuous electron beam processing [2].

In a range of pressure from 10^{-4} Pa to 10^{-5} Pa the temperature of thermal decomposition and dissociation of intermediate boron oxide B_2O_3 which plays an essential role in the chemical transformations proceeding at synthesis TiB_2 boride decreases. Moreover, in the presence of a protective layer B_2O_3 which is specially entered at synthesis and layer TiB_2 formation, thermodynamically formation of boron is possible. The boron as the uncontrollable impurity can participate in formation of boride coasting and is present at boride iron Fe_2B or FeB.

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[1] This work was supported partly by RFBR grants №14-08-31412_mol_a, and by the RAS Presidium program "Arctic" project № 84

DECOMPOSITION KINETICS OF SULFONOL IN ITS AQUEOS SOLUTIONS UNDER THE ACTION OF A DIELECTRIC BARRIER DISCHARGE OF ATMOSPHERIC PRESSURE IN OXYGEN

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Environmental protection issues are becoming more and more topical. Environmental problems caused by industrial production can be solved by implementing low-waste technologies, which ensure the best use of raw material and energy resources, and also by using nonequilibrium low-temperature plasma techniques. In a non-equilibrium low-temperature plasma a desired process can be performed with a required efficiency at lower energy consumption [1].

Up to date the decomposition processes of water solutions of many organic substances under the action of various gas discharge types were studied. At the same time, it would be interesting to check the capabilities of such methods for purification of water solutions from surfactants. The surfactant water solutions are widely used for industrial and domestic cleaning processes. Some surfactants are not readily biodegradable and relatively high residuals products. Effective treatment of wastewaters containing surfactants before their release to the environment is necessary.

As an example of a surfactant, sulfonol was chosen. Sulfonol is sodium salts of linear alkyl benzene sulfonates of common formula C_nH_{2n+1}-Ar-SO_2ONa (n=12-18). Sulfonol is widely used for the increase in oil measures efficiency and for production of various synthetic detergents.

A dielectric barrier discharge (DBD) was used for the solution treatment. The scheme of the experimental setup was described elsewhere [2]. A discharge was excited in a coaxial type reactor. The reactor body with a 12 mm internal diameter was fabricated from a Pyrex tube. This tube served as the dielectric barrier of discharge. The external electrode was located on the tube glass surface in a cylindrical form. The solution flow rate could be adjusted and the residence time of the solution was varied from approximately 2 to 12 s. Technical grade oxygen (99.8%) was passed in the opposite direction. Gas flow rate was 3.2 cm^3/s. All experiments were carried out for different inputted power in the range of 0.4 – 4.0 W.

The decomposition kinetics of sulfonol as well as the formation kinetics of forming products was measured. The DBD was discovered to have the high decomposition efficiency on sulfonol - up to 80%. The rate and efficiency of decomposition was increased in a rising discharge power but energy efficiency was dropped. Intermediate products of sulfonol transformation were carboxylic acids and aldehydes, and the final ones - CO_2 molecules. The destruction process is limited by decomposition reactions of aldehydes.

The sulfonol decomposition kinetics was found to be described by the equation of the first kinetic order with rate constants of (0.059 ± 0.003), (0.064 ± 0.006), (0.096 ± 0.007) and (0.136 ± 0.012) s^{-1} at the discharge powers of 0.4, 1.2, 2.1, and 4.0 W, respectively. Being based on these results the energy cost for one molecule destruction, α, was determined. Calculations demonstrated that the increase in the inputted power from 0.4 to 4.0 W leads to the decrease in α from (0.012 ± 0.002) to (0.0044 ± 0.0004) molecules per 100 eV. This is due to the fact that despite the increase in the decomposition rate with power rising the power grows faster than the decomposition rate.

The action of the discharge was accompanied by the decrease in the solution pH due to the formation of sulfuric and carboxylic acids in treated solution. Shapes of kinetic curves show that all acids are intermediates. The destruction of the one sulfonol molecule leads to the formation of one SO_4^{2-} ion. The suggestions on the mechanism of occurring reactions were also made.

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NITRIDING OF A7 ALUMINUM ALLOY IN PLASMA OF ARC NON-SELF-SUSTAINED DISCHARGE WITH THERMIONIC CATHODE [1]

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A series of experiments on the A7 aluminum alloy nitriding using plasma of PINK plasmagenerator with a thermionic cathode was carried out. The processing samples was biased by the negative polarity pulse with a frequency of 50 kHz and different duty cycle and amplitude. The experiments on the Ti deposition on samples by cathode sputtering were carried out in order to optimize the interface between the sample and the nitrogen plasma. Experiments have shown that nitriding of aluminum alloy is possible, but for thick layers (with thickness of microns and more) becomes problematic due to destruction of nitrides containing layer obtained after some thickness it reaches. It is shown that the deposition of Ti allows to form the titanium-aluminum intermetallic layer on the aluminum sample surface.

[1] This work was supported by Russian Science Foundation (project No. 14-29-00091)

POSSIBILITY OF NANODISPERSED SILICON CARBIDE SYNTHESIS BY A FREE SPACE HYPERVELOCITY PLASMA JET[1]

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Silicon carbide (SiC) is only stable compound in the Si-C system. There are many unique physical properties of this material: superhardness, high mechanical strength and Young's modulus, thermal and corrosion resistance, radiation hardness, unique semiconducting characteristics [1, 2]. So silicon carbide can be used for production of externally stable ceramics and SiC-based electronic devices [3]. The use of nanodispersed SiC powders can be used for nanostructured ceramics with higher operational characteristics because materials physical and chemical properties depend on crystallite sizes. Different methods (a combustion synthesis, a physical vapour transport (PVT), a chemical vapour deposition, a sol-gel method, liquid phase sintering, mechanical alloying and a plasmochemical synthesis) is applied for nanodispersed silicon carbide synthesis but these methods do not allow to synthesize an optimal product (with high purity and required dispersity by direct and inexpensive method) [4].

The SiC nanopowder synthesis can be realized in a hypervelocity pulse jet of the dense Si-C plasma. The hypervelocity plasma jet is generated by a pulsed heavy-current coaxial magnetoplasma accelerator (CMPA) with a graphite central electrode and pipe electrode [5]. The possibility of above synthesis method is shown in [6]. The process was carried upon the influence of a Si-C plasma jet to a copper barrier. In the present study plasma jet expires in an argon space of a reactor chamber. The power supply of the CMPA is provided by a storage condenser with a battery capacity of $C = 6$ μF and a charging voltage U=3 kV.

The powder product was obtained using the above method and was investigated by modern analytical techniques such as X-ray diffractometry (a Shimadzu XRD 7000 diffractometer, CuKα radiation) and transmission electron microscopy (a Philips CM 30 electron microscope). The product diffraction pattern is shown in Fig. 1. The XRD-data was analyzed by the Powder Cell 2.4 program and base of structural data PDF 4+. The XRD-pattern character and coherent reflexes set indicate the practical absence of an amorphous component and the presence of several crystalline phases in the synthesis product. Computer calculations showed the product consists of four crystalline phases: cubic silicon carbide β-SiC, space group SPGR (F-43m) {216}; cubic silicon cSi, SPGR (F-43/d-32/m) {227}; graphite gC, SPGR (P6-3mc) {186}; and carbon onion structures C-Onions, SPGR (P6-3mc) {186}. According to calculations the expected phase β-SiC is dominant (~ 80.0%).

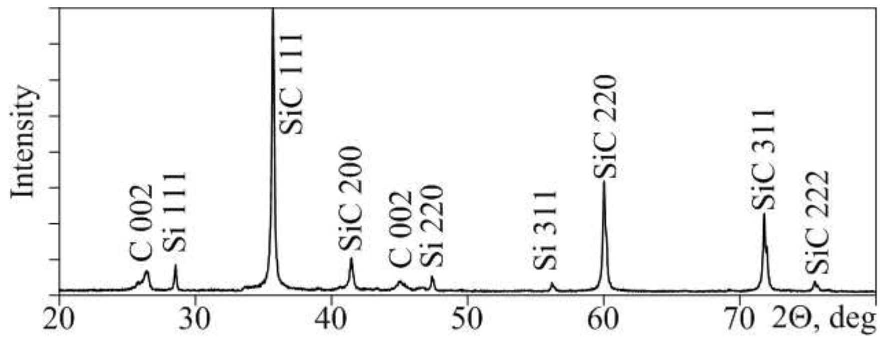

Fig. 1. The product diffraction pattern

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ON THE POSSIBILITY OF NANODISPERSED SILICON DIOXIDE SYNTHESIS BY A COAXIAL MAGNETOPLASMA ACCELERATOR[1]

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There has been an increasing interest in production of nanopowders due to new properties of ceramics on their basis. Nanostructured ceramics have higher physical and chemical characteristics because properties depend on crystallite sizes [1]. Silica nanoparticles (or silicon dioxide SiO_2 nanoparticles) can be used for biomedical researches due to their stability and low toxicity and a circuits packaging industry as the preferred filler materials [2, 3]. It is necessary to produce a powder in the form of spheres. They have novel extremely high surface area catalyst effect and can be used as drug-delivery carriers and nano-reactors [4, 5].

This research paper presents the results of SiO_2 nanopowders synthesis by plasmadynamic method. It was realized in a hypersonic pulse jet of the Si plasma. The plasma jet was generated by a coaxial magnetoplasma accelerator (CMPA) [5]. The plasma jet expired in an air space of a reactor chamber. A micron crystalline silicone powder and an air space of the reactor chamber were used as precursors. The power supply of the CMPA is provided by a storage condenser with a battery capacity of C = 6 μF and a charging voltage U=3 kV.

The powder product was obtained using the above method and was investigated by modern analytical techniques such as X-ray diffractometry (a Shimadzu XRD 7000 diffractometer, CuKα radiation) and transmission electron microscopy (a Philips CM 30 electron microscope). The XRD data show presence of only amorphous SiO_2.

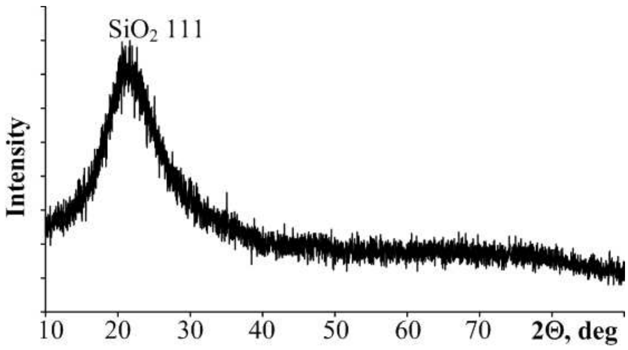

Fig. 1. The product XRD diffraction pattern

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CHANGE OF THE RELIEF OF THE SURFACE OF MAGNESIUM UNDER ACTION OF PULSE POWER IONS (C_+) BEAMS[1]

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Studying of structurally-phase transformations in metals and alloys under action of powerful beams of the charged particles is spent already long time, however, despite of an abundance of experimental data of unequivocal parities about communication of parameters of ion beams with results of influence on materials is not received. Formation of a superficial relief under action of pulse power ion beams also is a question on which there is no unequivocal answer [1-5]. Generally this process depends on properties of a stream of particles, characteristics of a material and conditions of processing. Especially it concerns such metals, as aluminium and magnesium. In this connection, research of interaction of pulse power ion beams with their surface represents scientific and practical interest. An irradiation spent on accelerator " ТЕМП-4М " (the vacuum diode with magnetic isolation), working in a two-pulse mode (energy of C_+= 250 keV, pulse duration =100ns). Not separated beam of ions represents mix C_{n+i} (basically C_+) and C_n.

The average size of microcraters on a surface of magnesium after its processing of HPIB remains constant and does not differ essentially from the craters, the ions of argon received to implantation. With growth of density of capacity of HPIB concentration of craters are increases. Under action of HPIB on a surface of magnesium microparticles and ridge fold structure are formed.

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IMPACT OF E-BEAM ON THE VISCOSITY CHARACTERISTICS OF OIL

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The aim of the work is study of a pulsed electron beam impact on the rheological properties of oil. It has been shown that e-beam action on oil with high content of wax results in reduction of its viscosity while that on oil with high content of aromatic hydrocarbons results in the viscosity increase. Impact of the electron beam to the individual oil components found that paraffin hydrocarbons by radiolysis cleaved, giving lower molecular weight products, which leads to lower viscosity. Aromatic hydrocarbons are transformed in polyphenylenes, which leads to an increase in viscosity.

Influence of an electronic bunch on aromatic oil with the maintenance of aromatic hydrocarbons of 85,1 % at a dose of an irradiation 25 and 75 kGr leads to essential increase in viscosity in the field of small speeds of shift. We conduct research of interaction of an electronic bunch with oil hydrocarbons, as its basic components. As objects aromatic (benzene) and paraffin hydrocarbons (hexane, octane) have been chosen aromatic. The basic products radiolysis in a liquid phase are in this case normal alkanes with molecular weight less and more than at initial, and also dimer and their various isomeasures. In both cases allocation of gases was observed. Nonsaturated hydrocarbons have been noted in small quantities.

The mechanism of formation of products radiolysis in monomolecular and bimolecular processes connect with attraction of reactions in which the free radicals resulting rupture C-H and C-C communications of the raised molecules alkanes participate. Thus the radicals formed at rupture C-H communications present the basic part of radicals. The exit of radicals of the smaller size, than a parental molecule, makes smaller size, than an exit of radicals with rupture C-H communications. Rupture C-C communications can occur as at excitation, so at ionization.

Generalizing the received results it is possible to make the conclusion that action of an electronic bunch on individual components of oil leads destruction paraffin hydrocarbons with formation of easy fractions and gases that leads to decrease in viscosity of oil. Aromatic hydrocarbons are sewed in polyphenylenes that leads to increase in viscosity of oil.

PROTECTIVE CHROMIUM COMPRISING LAYERS ON THE STAINLESS STEEL PRODUCED BY THE USE OF DEPOSITION FROM GAS AND VACUUM DISCHARGE PLASMAS[1]

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The present work investigates the availability of obtaining protective layers on the surface of stainless steel current collectors of fuel cells (DMFC and DEFC) using the technique of vacuum deposition of chromium. In the DMFC and DEFC proton exchange Nafion membrane electrolyte is applied. Nafion membrane represents fluorocarbon polymer, which contains sulfonic acid groups. In the fuel cell operating conditions working surfaces of current collectors contacting with membrane electrode assembly are subject to electrochemical corrosion as a result of corrosion activity of the medium containing SO_4^- and F^- anions.

The coatings are formed with the aim of achieving corrosion resistance of stainless steel current collectors of fuel cells with a polymer membrane electrolyte. Chromium containing coatings onto stainless steel samples and stainless steel current collectors have been obtained by two methods, that is by ion-plasma sprayed and ion-beam assisted deposition (IBAD) from vacuum arc discharge plasma. Ion plasma deposition coating formation was carried out by arc erosion of the cathode plasma generated with a cathode arc source of chromium in an environment of reactive gas: nitrogen – to obtain a coating of chromium nitride, and carbon-oxygen-containing gas – for producing coatings of chromium oxycarbide. IBAD formation of surface layers was carried out by precipitation of chromium as well as chromium and tin alternately from vacuum arc discharge plasma. The deposition was performed in the mode using accelerated ions at the voltage of 10 kV of the deposited metal as assistance to the deposition process.

Investigation of the composition and microstructure of samples surface was carried out by RBS, SEM and EPMA methods. It has been established that the layers formed by IBAD, repeat the surface morphology of the substrate; their thickness is not greater than 100 nm. Microstructure of the chromium coatings, obtained by ion-plasma deposition, depends on the type of coating; thickness of coatings is ~2 μm. The composition of the surface layers includes atoms of the deposited metals, as well as of carbon, oxygen, nitrogen and components of the steel substrate. Corrosion tests of samples with the investigated layers and coatings were carried out by an electrochemical method of quasipotentiostatic current-potential plots at the temperature of 70–80°C. 1M $H_2SO_4 + 2\cdot10^{-6}$M HF solution was used as the corrosion environment. Corrosion resistance of the modified material depends on the composition of surface layer and the method of its formation (Fig. 1).

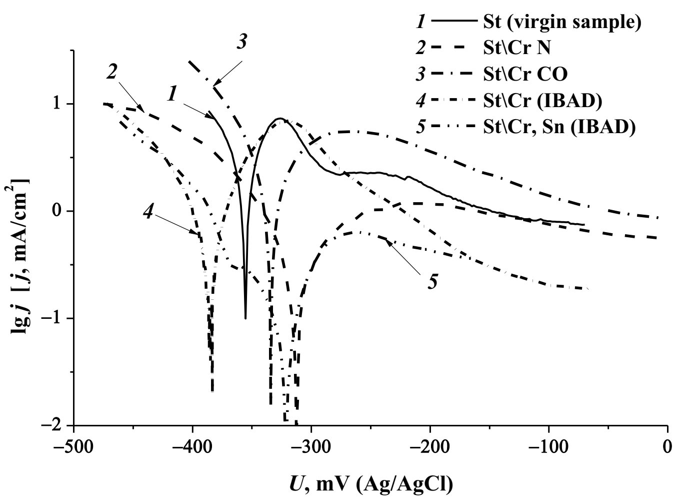

Fig. 1. Current-potential plots in 1M $H_2SO_4 + 2\cdot10^{-6}$M HF solution of stainless steel (St) samples with coatings produced by cathode arc plasma erosion sprayed and with layers prepared by ion beam assisted deposition from vacuum arc discharge plasma

The obtained result demonstrates the increase of stability of the investigated materials with prepared layers to electrochemical corrosion in the fuel cells operating conditions with Nafion membrane electrolyte.

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USING THE LOW-TEMPERATURE PLASMA IN CEMENT PRODUCTION

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Using the low-temperature plasma is known to be one of the progressive methods of physico-chemical process intensification allowing to use liquid-phasic reactions instead of hard-phasic ones in the age of high-speed technologies. Using the high-concentrated heat streams in the production of cement is stipulated by developing the effect of "thermal strike", which may provide a high reaction ability of raw-material mixture intensify the decarbonization processes, promote the increase in the amount of the liquid phase up to 90–100 % as well as the decrease in viscosity of the liquid phase 27,38–83,93 times relatively to the traditional technologies, the complete assimilation of the mineral-forming oxides and, as the consequence, the high clinker quality. The definite succession of preparing the mixture consisting in pre-dosing the components, the following grinding up to the fraction not more than 160 mcm and homogenization is considered as the distinctive feature of the technological schema in cement production based on the plasma-chemical technology. Moreover, the granulation or briquetting the raw-material mixture which is necessary to remove its blowing in exposure to the high-concentrated heating streams is considered as the necessary technological stage. The thermal processing the prepared granulated mixture is performed using the experimental installation – the plasma-chemical reactor [1], the temperature in which is 3000 °C. The time period of isothermal self-control under conditions of the low-temperature plasma may change from 10 to 12 minutes.

The instaneous reaction of clinker formation along with the high temperature gradient in cooling the melting are known to stipulate the synthesis of the fine-disperse matrix model of cement clinker [2]. The structure of the melted sample is presented by metastable minerals of alite in the dimensions up to (3–20)×(80–400) mcm and the ratio of their length to the width 26,6–397. The elongated crystal form stipulates the higher cement activity based on the melted clinkers because the more rapid developing sides are less stable in hydration during the growth process of the crystal. At the same time, some structure elements of the compound above are more deformed relatively to C_3S: alite has the formulae $54CaO \cdot 16SiO_2 \cdot Al_2O_3 \cdot MgO$ and is formed in substitution of two ions Si^{4+} for two ions Al^{3+} and introducing Mg^{2+} into the interjunction of the lattice. This may increase in the hydraulic activity of viscous substance produced based on the melted clinker [3, 4].

The intensive heat release which exceeds the traditional one 1,3–4,5 – fold in the process of cement hydration, synthesed based on the plasma-chemical technology is performed. The cement gel, portlandit and additive growth nidi of the new formations having the column habitus are clearly revealed in the structure of the cement stone produced based on the melted clinker. The calcium hydrosilicates presented are non-traditional ones for the cement systems. The appearance of the similar compounds is realized in introducing the nano-crystalline modificators. However, the absence of the additives in the system may testify the influence of a type of the viscous substance used – the melted cement clinker, in hydration of which the new formations are formed, covering the available pores and microcracks. This allows to increase in the pressing strength of the samples up to 84,2 MPa.

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MAGNETRON SPUTTERING OF Al IN THE Ar/O_2 MIXTURE UNDER ELECTRON BEAM INJECTION: DISCHARGE CHARACTERISTICS AND PROPERTY OF DEPOSITED AlO_X COATINGS

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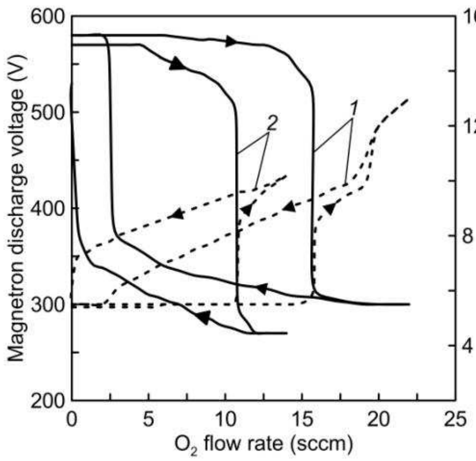
The effect of low-energy electron beam injection on characteristics of magnetron discharge supported in pulse DC (2 A, 50 kHz, 10 μS) and HiPIMS (30 A, 1 kHz, 50 μS) regimes have been investigated. Injection of electron beam with current of 2-10 A accompanied by generation of plasma in the working chamber leads to a reducing of discharge voltage in the magnetron of 50-100 V and decreasing of minimal working pressure of 15 % (when operates in the Ar medium).

Dependences of discharge voltage of magnetron and pressure of gas mixture (partial pressure of O_2, Ar flow rate was constant of 30 sccm) on O_2 flow rate have a hysteresis (see fig. 1a) that is characteristic of the reactive regime as in the case of self-maintained discharge and during electron beam injection. Transition from a metallic to oxide mode of target sputtering takes place in a narrow range of O_2 flow rate. It is shown that the magnitude of O_2 flow rate at which transition to the oxide regime of target sputtering take place shifts to smaller value with increasing of electron beam current. This behavior is due to the increasing of flow of active particles that come from plasma of electron beam, interacts with the target and changes of conditions of steady-state compound coverage at the target [1].

The transition from a metallic to oxide mode in the case of HiPIMS of Al target without injection of electron beam (see fig. 1b) takes place in the wide range of flow rate of reactive gas (~2-12 sccm), that is agrees with results of [2]. The principal distinction of mode of target sputtering under electron beam injection is abrupt transition to oxide mode with increasing of O_2 flow rate.

AlOx coatings were deposited by the reactive magnetron sputtering of Al target in different modes of combined operation of magnetron and the electron source with plasma cathode. The phase state of coating was investigated by XRD.



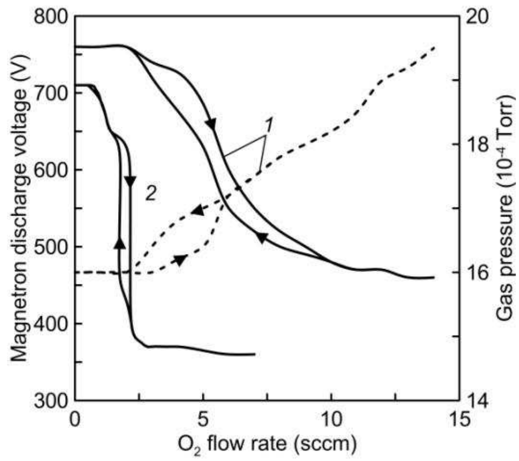


Fig. 1. Dependences of magnetron discharge voltage (solid) and gas pressure (dashed) on O_2 flow rate. Pulse DC (*a*) and HiPIMS (*b*) regime. 1 – self-maintained discharge, 2 – mode with electron beam injection, beam current 2 A (*a*) and 10 A (*b*).

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THE PLASMA DYNAMIC SYNTHESIS OF ALUMINUM NITRIDE WITH USING OF COAXIAL MAGNETO PLASMA ACCELERATOR[1]

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Aluminum nitride was firstly synthesized in 1877, but only in the late of 20th century this material attracted the attention of scientists due to a number of its unique properties. The high thermal conductivity, low coefficient of thermal expansion, thermal stability, low dielectric constant, non-toxic, high mechanical strength make it one of the most important materials for the manufacture of ceramics [1-3]. To date, there are many different ways to obtain this material [4].

It is known that synthesis by plasma methods has such advantages as the fast speed of reaction due to the high plasma temperature (~ 10^4 K), the possibility of obtaining ultrafine monocrystalline product due to the high cooling rate (> 10^6 K / s) and the possibility of using precursors without special pre-treatment [5]. The obtaining of ultrafine aluminum nitride powders can be realized by plasma dynamic method in systems based on coaxial magneto plasma accelerator (CMPA) with using different precursors.

The series of experiments has been carried out with using of aluminum central electrode and barrel-electrode in nitrogen atmosphere and in argon atmosphere using melamine as nitrogen-containing precursor and in nitrogen atmosphere with melamine. Synthesized products have been analyzed by such methods as X-ray diffractometry (XRD) using Shimadzu XRD 7000S diffractometer and transmission electron microscopy (TEM) using Philips CM30 microscope.

It was found that the product with the highest content of aluminum nitride is obtained in experiments with using of melamine and nitrogen atmosphere. The possibility of synthesis aluminum nitride in hyper speed plasma jet is confirmed by the results of TEM analysis. It is clearly seen that the synthesized product consists of well-crystalized monoparticles predominantly with sizes of 60-120 nm (figure 1).

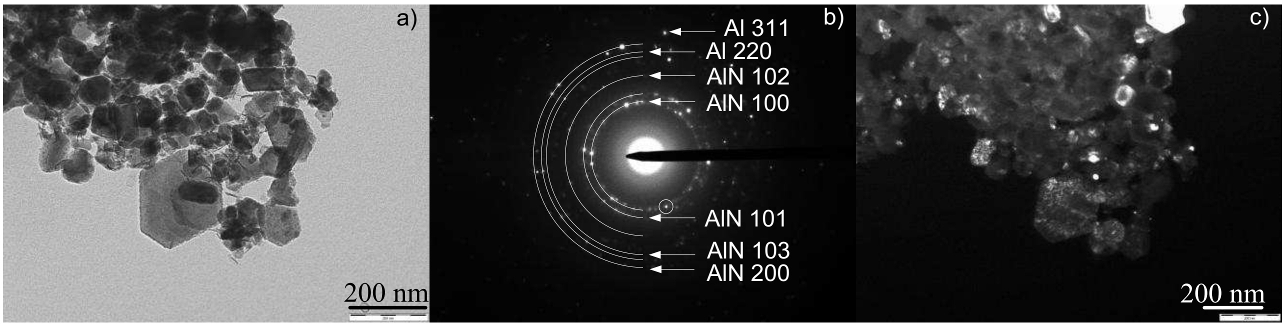

Fig. 1. TEM-images of synthesized product: a) bright-field image; b) SAED; c) dark-field image

Thus, the present results indicate the possibility of synthesis of aluminum nitride in the system based on coaxial magneto plasma accelerator, using both gaseous and solid precursors.

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PLASMODYNAMIC SYNTHESIS OF POWDERED FERRUM OXIDE WITH A HIGH CONTENT OF ε-FE_2O_3[1]

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Previously in the article [1] the possibility of plasmodynamic synthesis and preparation of heterophase ultrafine powder containing metastable crystalline phase of iron oxide in the nanodispersed state was shown. The unique feature of this structure is the appearance of the natural resonance at frequencies of the order of 0.1 THz.

In the development of this area an experimental study on the plasma dynamic synthesis and production of iron oxides was carried out. The synthesis process is realized in the hyper speed iron-erosion plasma jet flowing into the chamber filled with a gaseous atmosphere containing the mixture of oxygen with nitrogen or argon. The synthesized product was analyzed using X-ray diffractometry method (Shimadzu XRD 7000S diffractometer). It was found that the product consists of several crystalline phases such as magnetite **Fe_3O_4,** hematite **α-Fe_2O_3** and **ε-Fe_2O_3**. The mass fraction of **ε-Fe_2O_3** increases to 50% when the content of oxygen O_2 in the gas mixture is increased up to 80% at normal pressure and room temperature. It is known [2] that the metastable phase **ε-Fe_2O_3** exists in nanodispersed condition. In the resulting product the average size of coherent scattering regions is about 0.4 nm at the level of internal microdistortions about $\Delta d/d = 0.4 \cdot 10^{-3}$. Using magnetometer it was found the occurrence of natural resonance and absorption of electromagnetic radiation at a frequency of about 125 GHz, which is comparable with the known data.

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THERMAL STABILITY OF Ti-C-Ni-Cr AND Ti-C-Ni-Cr-Al-Si NANOCOMPOSITE COATINGS[1]

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The microstructure, mechanical and tribological properties of Ti-Ni-Cr-C и Ti-Ni-Al-Si-Cr-C coatings on basis of amorphous carbon after annealing at 700 °C, 1 h were investigated.

The investigations of perpendicular cross-section of coatings by transmission electron microscopy (TEM) have revealed peculiarities in the distribution of nano-sized particles. At a distance of more than 0.5 microns from the substrate a structure of coating is homogeneous and is represented by an amorphous phase (a - C) with uniformly distributed therein particles of TiC and NiCr (< 10 nm). It was found that annealing at T = 700 °C does not lead to a change in the particle size of crystalline phases. At a distance of less than 0.5 microns from the substrate are observed NiCr particles (or particles conglomerates) up to 30 nm.

The studies of the microstructure of Ti-Ni-Al-Si-Cr-C coatings after annealing at T = 700 °C, 1 h by TEM also showed the stability of amorphous and nanocrystalline phases (TiC and NiCr).

An important feature of the observed bright-field and dark-field images of Ti-Ni-Al-Si-Cr-C coatings cross-section is the presence of a pronounced strip contrast parallel to the substrate plane. Indicated strip contrast may be due to the of different thickness of the coating areas, which is related to uneven etching rates of sections with different contents of amorphous and crystalline phases by ion beam

It is assumed that, as in the case of the particles in initial coatings after annealing at T = 700 °C, 1h there is a significant fraction of particles that do not have high internal stresses.

The investigations of mechanical properties of the samples of titanium alloy with Ti-Ni-Cr-C coating showed that the microhardness of the composition retains its values up to T = 900 °C. Moreover, some increase in hardness from ≈ 14 GPa at initial state to ≈ 18 GPa after annealing is observed.

Ti-Ni-Al-Si-Cr-C coatings on specimens of titanium alloy in the initial state have a somewhat lower hardness (10.7 GPa). Annealing of these coatings leads to some increase in the microhardness values up to ≈ 13 GPa (at 500 ° C and 700 °C) and then leads to decrease up to values ≈ 9.4 GPa (900 °C). At present, the physical causes of such behavior microhardness not clear.

Ti-Ni-Cr-C coatings on basis of amorphous carbon have a low values of coefficient of friction ($\mu \approx 0.16 - 0.17$) at annealing at a temperature T = 700 °C. Increasing the annealing temperature to 900 ° C leads to increased values of friction coefficient which is $\mu \approx 0.4 - 0.5$. These values can be compared with the values of coefficient of friction of titanium alloy without coating ($\mu \approx 0.5 - 0.7$).

The value of friction coefficient of Ti-Ni-Al-Si-Cr-C coating in the state after annealing at T = 700 °C is practically identical with the initial value ($\mu \approx 0.34$). The dependence of the friction coefficient on the distance traveled by the indenter have almost linear form and does not change during the annealing of 700 °C, 1 h.

After annealing at T = 900 °C, the value of coefficient of friction is also preserved at the level of $\mu \approx 0.34$, but behaviour of dependence of the friction coefficient of the distance traveled by the indenter of varies considerably. Indicated value of friction coefficient is achieved virtually with testing begins. The changing behaviour of indicated dependence may give evidence about degradation of the coating structure, as well as about the possible allocations of new phases, which increase the coefficient of friction.

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SIMULATION OF INTENSE ELECTROHYDRODYNAMIC FLOW BASED ON DIELECTRIC BARRIER DISCHARGE [1]

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Electrohydrodynamic (EHD) flow is a physical phenomenon of collective motion of a gas caused by charged particles drift in high electric field and transfer their momentum to the neutral medium in collisions.

With electrohydrodynamic interaction of charged and neutral particles associated promising atmospheric plasma technology with many potential applications in aeronautics, which allows controlling the airflow over the surface of the wing, reducing drag and impeding the transition to turbulence [1].

EHD flow systems using to intensify the heat dissipation in modern high-performance computers and as an electrical pump of a gas mixture in lasers [2]. An advantage of electric pumping is the absence of moving parts and related failures due to the rotor wear or the thermal and mechanical fatigue of fans [3].

Intense EHD flow generated by plasma discharge on the surface of the dielectric tube [4] was simulated in the atmospheric air depending on the transparency of the collector grid and on the collector-emitter distance. Transparency was varied by changing the spacing and the radius of the wire from a commercially available range of grids. The typical intensity distribution in X-Y plane of the amplitude of EHD flow speed at 20 kV bias collector voltage, 0.7 grid transparency is shown in Fig. 1.

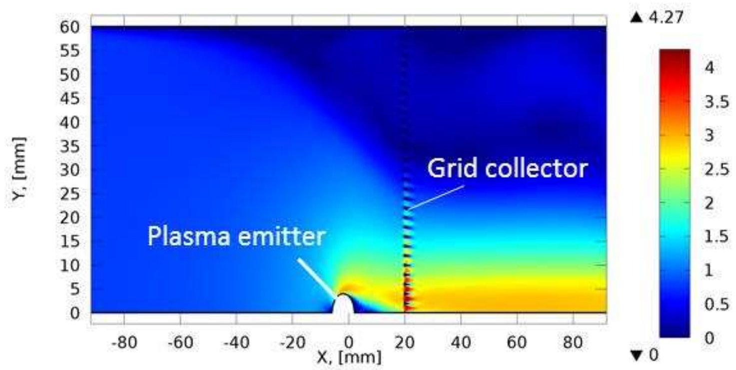

Fig. 1. Numerical simulation results: air velocity as colored surface map with units in m/s

Electrohydrodynamic flow induced by dielectric barrier discharge was described by the Poisson's equation, current continuity equation, Navier-Stokes and momentum continuity equation for steady-state incompressible air flow [5]. The calculation results show that the grid electrode has a strong deceleration of EHD flow, so optimizing its design provides significant potential increase of speed and the flow quantity. Optimal transparency of the grid collector, the collector-emitter distance were founded from the mathematical modeling of the EHD flow and airflow speed up to 3 m/s was achieved.

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INFLUENCE OF PREVIUOS COMPRESSION PLASMA FLOWS IMPACT ON NITRIDING OF TITANIUM[1]

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One of the most important approaches for titanium modification concerning its structure and mechanical properties improvement is associated with ion nitriding process. Usually the nitriding of titanium results in formation of superhard titanium nitride TiN and martensite phases α'- and α''-Ti being solid solutions of nitrogen in the titanium crystal lattice. The nitriding processes are usually based on the diffusion of nitrogen inside the bulk titanium phase. To increase the time of the nitriding the temperature of the process should be risen. But the working temperature increase would result in phase transformation of titanium solid phase with the cubic titanium phase formation. Therefore the convenient temperatures for titanium nitriding are 400 – 500 ºC that in turn increases the time of the treatment.

In the present work the previous influence of compression plasma flows on titanium was suggested. The compression plasma flows are generated by quasi-stationary plasma accelerators and characterized by a relatively long existence period (up to 10^{-4} s). The earlier works [1-2] showed the possibility of compression plasma flows application for modification of surface layers in different materials. The energy density absorbed by the surface from the plasma flow is varied from 5 to 40 J/cm^2 that is usually enough for melting of the surface layer. The influence of the compression plasma flows with the pronounced energetic parameters on titanium samples results in melting of the layer with depth of 5 – 25 µm. The time of the melt existence is comparable with the pulse duration of the plasma. Due to intense heat conductivity towards the unmelted volume the cooling rate as well as solidification rate is very high (10^6 – 10^7 K/s). These conditions promote to disperse structure formation, the grain sizes being less than 1 µm.

A commercial pure CP titanium alloy was chosen for the experiment. The treatment by compression plasma flows was carried out in a magneto-plasma compressor of compact geometry in the residual hydrogen pressure (400 Pa). The absorbed energy density was varied in the range of 9 – 23 J/cm^2. The samples were treated by three pulses with the duration of 10^{-4} s. The treated titanium samples were nitrided at the temperatures 400 – 600 ºC during the time of 1 – 3 hours.

Therefore the previous compression plasma flows influence on titanium samples provides the formation of deep modified layers with disperse structure. The consequently diffusion nitriding of the treated titanium will occur implying the grain-boundary diffusion that is characterized for nanostructured materials. It will increase the nitrogen penetration depth and working temperature. Moreover, the enhancement of nitrogen transport inside the modified layer of titanium will prevent from the titanium nitride TiN formation that can increase the brittleness of the modified layer.

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ACCURACY AND ROUGHNESS OF TIN COATINGS DEPOSITED BY VACUUM ARC PLASMA

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Coating deposition by vacuum arc plasma is effective way of part running ability enhancement. Coating thickness and roughness depend on both preprocess machining surface condition and deposition conditions [1,2,3,4]. Achievable surface roughness of coated by vacuum arc plasma deposition high (5-6) level of accuracy parts with 0.1…0.8 μm surface average roughness strongly depends on deposition conditions [5]. Thereby assurance of given arithmetic average roughness and coating thickness values when hardening high precision parts is an actual problem.

TiN coatings were deposited on 13Kh11N2V2MF-Sh; 30KhGSNA; ZhS6K; VT-18; 38KhA; KhN68VMTYuK-VD substrates. Surface average roughness and TiN coating thickness measurements were done. Coating thickness and surface roughness were studied as a function of substrate surface inclination and distance from plasma flow. Experiments were carried out on substrates with different types of preprocess machining. The influence of coating thickness, deposition conditions, and deposited materials on coated surface roughness were studied.

It was established that surface roughness increase with increasing of coating thickness and arc current values and decrease with reactive gas pressure increasing. Substrate temperature and negative voltage bias values according to experimental data are roughness neutral. The impact of substrate surface inclination and distance from plasma flow on coating thickness and surface average roughness was revealed. The coating deposited by vacuum arc plasma thickness distribution law was assigned.

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A DEPOSITION OF FUNCTIONAL COATINGS BASED ON INTERMETALLIC SYSTEMS TIAL ON THE SURFACE OF PUNCHING TOOLS FOR COLD HEADING MACHINES BY VACUUM ARC PLASMA

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The parameters of vacuum arc discharge was investigated. The methods for the synthesis of intermetallic coatings based on system of Ti-Al are investigated1. Intermetallic synthesis by simultaneous deposition from two electric vaporizers Ti and Al cathodes. X-ray diffraction was carried out on a DRON-3 diffractometer are studies for determination phase composition coatings. The mechanism of phase formation intermetallic based on system of Ti-Al synthesis using vacuum arc plasma are studies. The technology of deposition coatings based on a system of Ti-Al on the surface of punching tools for cold heading machines was developed based on experimental results. Production tests of punching tools with coatings Ti-TiAlN/TiAl were carried out on cold heading machines M12B. , the results of production tests showed the increasing productivity of punching tools with coating Ti-TiAlN/TiAl by 6-7 times in comparison to processed by technology used at the factory.

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COMPUTER MODELING OF LOCAL ION NITRIDING PROCESS WITH HOLLOW CATHODE EFFECT

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Using the hollow cathode effect (HCE) during ion nitriding leads to local intensification of the process of diffusion and ultimately reduces the processing time[1,2]. However, the process becomes more complicated. For local ion nitriding with HCE the heating rate under technological screen is higher than at other areas of the part surface. Consequently, non-uniform temperature distribution occurs in part during the process. It is known[3,4] that the temperature during nitriding plays a significant role in the activation process of nitrogen diffusion into the metal and the formation of the diffusion layer. Therefore, simulation of thermal and diffusion processes at the local ion nitriding is an important task. Better understanding of the processes occurring in the surface layer of the material during processing will allow increasing the efficiency of nitriding by assigning optimal process parameters.

In this paper a computer model that describes the distribution of the temperature and the diffusion layer depth after the local ion nitriding with HCE for parts of different configuration is presented. The influence of the HCE during the ion nitriding on the temperature distribution in gear part was studied. The influence of HCE on hardened layer depth after ion nitriding with HCE for a sample of steel 38KhMYuA steel was investigated.

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2D MODELING OF KRF LASER WITH NONUNIFORM PUMPING DISCHARGE[1]

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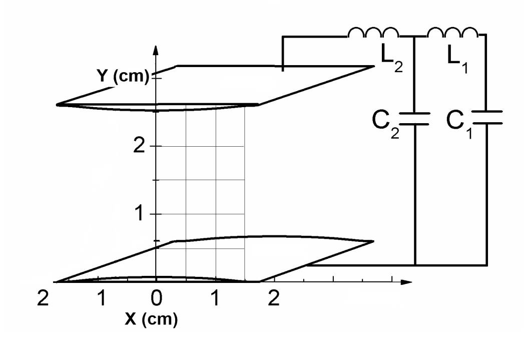
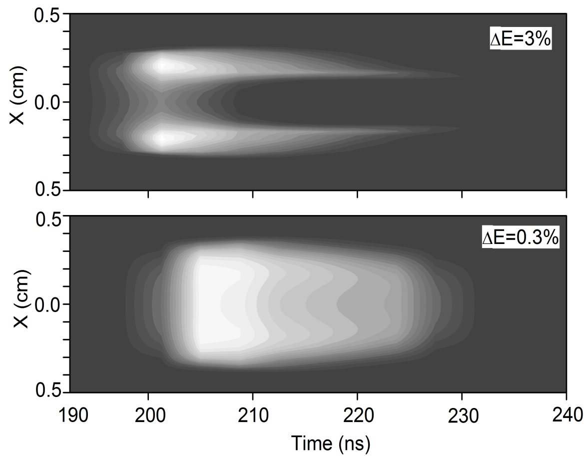
Electric discharge KrF excimer lasers (248 nm) are widely used in various fields of physics, medicine, microelectronics, photochemistry and biology. Many applications of KrF lasers require short radiation pulses and high radiation power. Experiments show that for excimer lasers with a pulse duration at the FWHM of 20–30 ns it is typical that lasing begins near the current maximum and the most of the energy is produced when the pumping power is decreasing. A prerequisite for lasing under such conditions is a preservation of the uniformity of the discharge after the current maximum.

In this report we present results of numerical modeling of the discharge pumped KrF laser with a pulse duration at the half maximum of 30 ns. Calculations were performed using a 2D model of the KrF laser taking into account nonuniformity of the discharge across its width. The model includes the continuity equation of the current density (div (j(X,Y)) = 0) and equations for the electric circuit. In addition at each point of the computational grid the Boltzmann equation, equations for concentrations of plasma components and equation for the photon concentration were solved (Fig. 1a). Calculated laser energy, the shape of the irradiation autograph and temporal evolution of the discharge current and voltage on electrodes were compared with the experimental data [1].

It is shown that before the start of the lasing over 80% of the formed KrF* molecules are lost in the processes of quenching. Therefore the creation of inversion requires a high rate of formation of KrF* molecules. The efficient pumping of the KrF-laser occurs in the range of electron concentrations from 10^{15} to $7\cdot10^{15}$ cm^{-3}. At smaller electron concentrations the rate of production of excimer molecules is not sufficient to create inversion. For electron concentrations above $7\cdot10^{15}$ the quenching of molecules by electron impact is greatly increased. Spatial distribution of the power density of the pumping in the active volume is determined by the shape of the electrodes. In the case of a high electrode curvature and average pumping power above 1 MW/cm3, laser generation has a failure in the center of the discharge where the concentration of electrons occurs exceeds the optimal value.





a b

Fig. 1. (a) Sketch o the discharge gap and the pumping circuit; (b) Temporal evolution of the laser power density (MW/cm3) across the discharge width during the discharge pulse for two different shapes of electrodes (ΔE is the difference of the electric field in the center of the discharge X=0 cm and at X=1 cm).

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INVESTIGATION OF PROPERTIES OF ZIRCONIUM (FILM)/SUS321 STEEL (SUBSTRATE) SYSTEM SUBJECTED TO A PULSED ELECTRON-BEAM TREATMENT[1]

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As part of this work the research on the development of biocompatible layer on the surface of the implant prototypes using vacuum arc deposition and subsequent pulsed electron-beam treatment was carried out. SUS321 stainless steel was using as the object of study (it analogues are used for manufacturing of intravascular stents, spokes for transosseous osteosynthesis devices, etc.). Studies were made for flat samples with size of 10x10x4 mm.

As the coating material for improving of surface biocompatibility of the implants was chosen Zr having better bioinert properties. Deposition of zirconium coating was carried out using the method of plasma-assisted vacuum arc deposition. The process was conducted on an automated vacuum ion-plasma unit «QUINTA». The thickness of the deposited film is varied in the range of 0.4-0.6 μm. After coating deposition the irradiation of samples by low-energy pulsed electron beam on vacuum unit «SOLO» was carried out. Parameters of an electron beam treatment are varied within the following limits: the pulse energy density of the beam is 15-25 J/cm^2 with pulse duration of 150 μs and the number of pulses equal to 3.

The investigation of the surface of samples was performed by scanning electron microscopy, electron microprobe analysis, X-ray analysis and profilometry. Mechanical and tribological properties of film/substrate system were investigated using nano-indentation and scratch test.

Based on the conducted research, the optimal mode of pulsed electron beam surface modification of Zr/SUS321 system with coating thickness of ≈ 500 nm is the treatment with an energy density of 15 J/cm^2, pulse duration of 150 μs, pulse repetition rate of 0.3 s^{-1} and number of pulses 3. This mode is characterized by a low level of cracking, changing of the phase composition of Zr/SUS321 system surface layer, leading to an increase in strength properties and wear resistance.

The optimal mode of treatment was demonstrated on real samples of intravascular stents on which by plasma-assisted arc method was deposited Zr-film with thickness of ≈ 500 nm. Drops on the surface are explained by the peculiarities of the vacuum arc evaporation and the need to use special filters to screen out the droplet fraction. After irradiation on the surface of the samples forms a homogeneous modified layer, characterized by the absence of drops and cracks.

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CHANGES IN THE ELECTRO-PHYSICAL PROPERTYIES OF MCT EPITAXIAL FILMS AFFECTED BY A PLASMA VOLUME DISCHARGE INDUCED BY AN AVALACHE BEAM IN ATMOSPHERIC-PRESSURE AIR[1]

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Nowadays various discharges and electron beams are widely used for modification of near-surface layers of materials [1]. Feature of these discharges is the combined effect of dense nanosecond-discharge plasma with the power density of energy contribution of hundreds of megawatts per cubic centimeter, a supershort electron beam with a wide energy spectrum and optical radiation of different spectral ranges of the plasma discharge.

The aim of this work is to study the effect of a nanosecond volume discharge plasma forming in an inhomogeneous electrical field at atmospheric pressure on the HgCdTe (MCT) epitaxial films of the p-type conductivity grown by molecular beam epitaxy.

For experiment, three series of specimens epitaxial CdHgTe films p-type conductivity (p = 1.1 ÷ 2.5×1016 cm-3, μp = 300 ÷ 500 cm2V-1s-1), grown by molecular beam epitaxy at the Institute for Semiconductor Physics of the Siberian Branch of the Russian Academy of Sciences (Novosibirsk) were prepared. The as-grown specimens were located in a gas diode on a copper anode. Use was made of a Radan-220 generator as a pulse-voltage source forming voltage pulses with the amplitude ~ 230 kV (open-circuit voltage), high-amplitude pulse duration ~ 2 ns (at a matched load), and rise time ~ 0.5 ns. The specimens were irradiated in the pulsed-periodic mode at the pulse repetition rate 1 Hz. The action was realized through 100–1200 pulses for a series of specimens irradiated in air. The electrophysical parameters of the MCT specimens before and after irradiation were found from the Hall-effect measurements using the Van-der-Pauw method. The measurement were performed at a direct current through the specimen (I = 1 mA) for two directions of the current and two directions of the constant magnetic field.

Analysis of the results of measurements of the electro-physical parameters of the MCT epitaxial-film specimens subjected to pulses of a nanosecond volume discharge reveals that upon irradiation by 100–1200 pulses all the specimens exhibit an increase in conductivity. The specimens irradiated by 100 – 400 pulses, however, exhibit a decrease in the Hall coefficient. In so doing, the field dependence of the Hall coefficient is characterized by a shift of the inversion point of the Hall coefficient sign to the region of higher magnetic fields from 0.17 T to 0.28 T.

An increase in the number of volume-discharge pulses up to 600 results in the inversion of the Hall-coefficient sign in the range more than 0.2 T. A still further increase in the number of pulses exposure leads to a decrease in the value of the Hall coefficient. It has been suggested that, on or near the surface of the film formed by a layer of highly conductive n-type, whose parameters are such that the measured field dependence of the Hall coefficient corresponds to the n-type conductivity. Also the lack of relaxation of electrical parameters of irradiated specimens within 3 months is noted.

Thus, our experimental data show that the action of pulses of nanosecond volume discharge in air at atmospheric pressure leads to changes in the electrophysical properties of MCT epitaxial films due to formation of a near-surface high-conductivity layer of the n-type conduction. The preliminary results show that it is possible to use such actions in the development of technologies for the controlled change of the properties of MCT narrow-band solid solutions and production of structures whose structure is heterogeneous with respect to conduction.

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THE IMPACT OF THE PLASMA VOLUME DISCHARGE IN THE ATMOSPHERIC-PRESSURE AIR ON THE DISTRIBUTION OF THE SURFACE POTENTIAL IN A V-DEFECT REGION OF EPITAXIAL HgCdTe FILMS [1]

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Triple semiconductor compounds of HgCdTe are one of the main materials used for manufacturing the intrinsic IR photodetectors for the wave bands of 3-5 and 8-14 micrometers [1]. The working characteristics of the manufactured photodetector devices are mostly impacted by the structural V-defects that originate during the growth process. For this reason controlling the alteration of the V-defect properties is one of the most important problems in the field of HgCdTe technology [2].

At the present time the plasmas generated by nanosecond pulses have gained wide adoption for using in order to modify the near-surface properties of materials [3, 4]. In the present report we demonstrate the experimental data obtained as a result of studying the impact of nanosecond plasma volume discharge in the atmospheric-pressure air on the distribution of the surface potential in the V-defect regions of epitaxial HgCdTe films.

For our experiments the samples of epitaxial HgCdTe films of the n-type conductivity grown by MBE on GaAs (013) substrates with ZnTe and CdTe buffer layers were prepared at the Institute for Semiconductor Physics of the Siberian Branch of the Russian Academy of Sciences (Novosibirsk). The as-grown samples were placed in a gas diode on a copper anode. We used a Radan-220 generator as a pulse-voltage source forming voltage pulses with the amplitude ~ 230 kV (open-circuit voltage), high-amplitude pulse duration ~ 2 ns (at a matched load), and rise time ~ 0.5 ns. The samples were irradiated by 1200 pulses in the pulse-periodic mode at the pulse repetition rate of 1 Hz.

Our studies were performed by means of Kelvin Force Probe Microscopy (KFPM) under normal conditions using a commercial atomic-force microscope (AFM) “Solver HV” (produced by NT-MDT, Zelenograd). We used silicon-based probes doped by bromine and with platinum coating (probe type NSG11/Pt, produced by NT-MDT) In order to obtain the profile of the surface potential distribution we measured the distribution of the contact potential difference (CPD) between the AFM probe and the epitaxial film surface. The measurements of the CPD distribution were carried out together with the study of the surface morphology.

The experimental data obtained for the variation of the contact potential difference (ΔCPD) between the V-defect and the main matrix of the epitaxial film show that the mean value of ΔCPD for the original surface differs from the one for the irradiated surface for 55 eV. At the same time the mean value of ΔCPD changes its sign indicating that the original surface of the epitaxial HgCdTe film predominantly contains the grains with increased cadmium content while after the irradiation the grains possess an increased content of mercury. Therefore, during the irradiation process a decrease of the mercury content in the near-surface region of the semiconductor takes place resulting in the alteration of the electrophysical properties in the film’s near-surface region.

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INFLUENCE OF PLASMA VOLUME DISCHARGE IN ATMOSPHERIC-PRESSURE AIR ON THE ADMITTANCE OF MIS STRUCTURES BASED ON MBE *p*-HgCdTe[1]

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Plasmas generated by nanosecond-pulse discharges have some advantages such as high power density, high reactive efficiency, high average electron energy, which can be widely used in potential application fields of surface properties modification.

The aim of this work is to study the effect of a nanosecond volume discharge plasma forming in an inhomogeneous electrical field at atmospheric pressure on the electrical properties of MIS structures based on HgCdTe (MCT) epitaxial films. For experiment, the samples p-type conductivity ($p = 1.1 \div 2.5\times10^{16}$ cm^{-3}, $\mu_p = 300 \div 500$ cm^{2}V^{-1}s^{-1}), grown by molecular beam epitaxy at the Institute for Semiconductor Physics of the Siberian Branch of the Russian Academy of Sciences (Novosibirsk) were prepared. The as-grown specimens were located in a gas diode on a copper anode. Use was made of a Radan-220 generator as a pulse-voltage source forming voltage pulses with the amplitude ~ 230 kV (open-circuit voltage), high-amplitude pulse duration ~ 2 ns (at a matched load), and rise time ~ 0.5 ns. The specimens were irradiated by 1200 pulses in the periodic mode at the repetition rate 1 Hz.

The admittance of MIS-structures based on graded-gap MBE p-$Hg_{0.78}Cd_{0.22}Te$ was experimental investigated after exposure of plasma discharge. Also admittance reference samples grown under the same technology was examined. As a insulator coating layer used Al_2O_3 at a thickness of about 77 nm deposited by plasma-enhanced atomic layer processes [1].

It is shown that the effect of the pulse volume nanosecond discharge in air at atmospheric pressure significantly alters capacitance-voltage characteristics of MIS structure, as well as the temperature dependence of the differential resistance of the space charge region in the strong inversion. This discharge changes almost all the parameters of MIS structures associated with the insulator, transition layer between insulator and semiconductor, as well as with the near-surface layer of the semiconductor.

The most important feature of MIS structures based on p-$Hg_{0.78}Cd_{0.22}Te$ after influence of the pulsed volume nanosecond discharge in air at atmospheric pressure is a significant increase in the positive fixed charge in the insulator (10-50 times). For some samples the positive fixed charge induces an inversion layer in after-electrode regions, which is the source of minority carriers in the formation sub-electrode inversion layer [2], resulting in a very small values of differential resistance of space charge region in the strong inversion mode and in the low-frequency behavior of the experimental capacitance-voltage characteristics at high frequencies (e.g., 1 MHz at temperatures of (40-77) K). Impact of pulse volume nanosecond discharge in air at atmospheric pressure leads to an increase of the effective density of the moving charge (in 2-17 times) and the appearance of features hysteresis capacitance-voltage characteristics, which associated with the exchange of charge carriers between HgCdTe and states in the transition layer. Impact of pulse volume nanosecond discharge in air at atmospheric pressure also leads to an increase in the average density of surface states in the depletion mode.

It should be noted that the samples exposed to show considerable variation of main parameters of MIS structure, since a change in properties after exposure to pulsed volume nanosecond discharge in air at atmospheric pressure is not uniform over the area of the epitaxial film.

A possible reason for changes in the electrical characteristics of MIS structure based on graded-gap MBE p-$Hg_{0.78}Cd_{0.22}Te$ after exposure to a evolution of the impurity-defect system in semiconductor layer near the interface, which is accompanied by the formation on the surface of the insulator film of nanometer thickness, which has a positive fixed charge.

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NITRIDING OF 40CR STEEL IN DIFFERENT OPERATING MODES OF NON-SELF-SUSTAINED GLOW DISCHARGE WITH HOLLOW CATHODE[1]

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The non-self-sustained glow discharge with the hollow cathode allows to reach a plasma density of up to 10^{18} m^{-3} with a high homogeneity of plasma density[1]. In the work [2] is shown high efficiency of steel nitriding in the plasma of such discharge. Samples was connected to potential of the hollow cathode.

In the work a study of influence of operating modes of non-self-sustained glow discharge with hollow cathode on the process of nitriding of 40Cr steel was carried out. The scheme of an experimental installation is shown on the figure 1. For ignition of the non-self-sustained glow discharge was used power supply with output voltage of up to 300 V, output pulsed current up to 500 A, pulse frequency of up to 1 kHz and possibility of duty factor changing from 1 to 100%.

The nitriding efficiency in different operating modes of the pulsed non-self-sustained glow discharge plasma was estimated by measuring of the Vickers microhardness of samples.

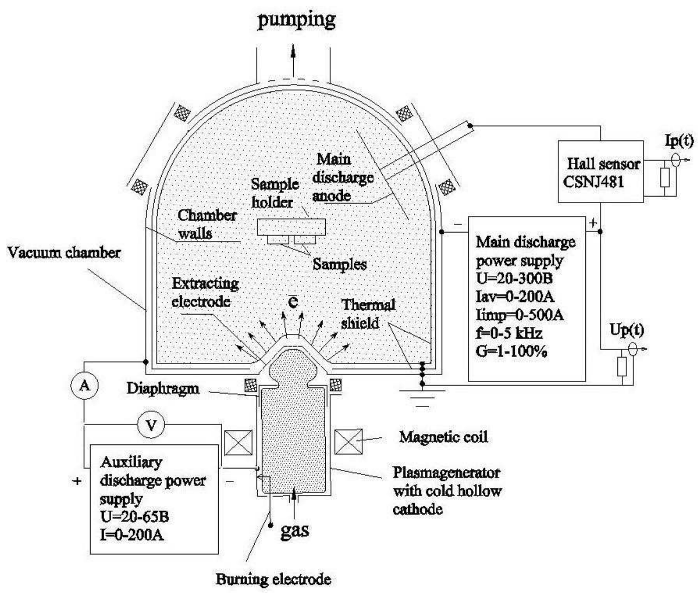

Figure 1. Schematic of the experimental setup (top view).

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EFFECT OF IRRADIATION WITH ACCELERATED Ar^+ IONS ON THE STRUCTURE, PHASE COMPOSITION, AND MECHANICAL PROPERTIES OF THE 1960 ALLOY (Al-Zn-Mg-Cu) AFTER ITS NATURAL AGING

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The effect of Ar^+ ion irradiation with an energy of 40 keV on the structural and phase state of the 1960 alloy of the system Al-Zn-Mg-Cu after natural aging has been studied.

Samples were irradiated by continuous Ar^+ ion beams using an ILM-1 facility for ion beam implantation, equipped with a PULSAR-1M ion source based on a glow discharge with a cold hollow cathode. The irradiation dose was varied in the range of 10^{15}–10^{17} cm^{-2}; the ion current density was 200 $\mu A/cm^2$.

Electron microscopic examination of thin foils prepared from the section parallel to the irradiated surface at a distance of about 150 µm from it has revealed that the initial state of the 1960 alloy after natural aging is characterized by a subgrain structure with a grain size of 5-10 µm with high dislocation density. The high density of dislocations is caused by hardening stresses. The alloy structure contains a insignificant amount of intermetallic Al_7Cu_2Fe particles of the crystallization origin, but their sizes and density distribution are considerably lower than those in the deformed state. The length of particles elongated in one direction does not more than 0.2 µm. Natural aging results also in the formation of θ''- and η'-metastable-phase particles in the form of thin discs. The diameter of θ'' particles reaches 15–20 nm, whereas for η' particles it is no more than 10 nm. In the initial state, the alloy has the following mechanical properties: σ_u = 658 MPa, $\sigma_{0.2}$ = 566 MPa, δ = 10 %.

Irradiation of the 1960 alloy in the naturally aged state at Ar^+ ion doses < $1\cdot10^{17}$ cm^{-2} (E = 40 keV) did not cause changes in its subgrain structure. Irradiation to a dose of $1\cdot10^{17}$ cm^{-2} leads to the transformation of the subgrain structure into a recrystallized one: equiaxed-shaped grains with high angle boundaries are predominantly observed; the grain diameter is more than 10 µm. The grain boundaries are free of precipitates. Crystallization-induced Al_7Cu_2Fe intermetallic compounds and β'-phase particles dissolve at all doses. However, there is the formation of new phases: particles of a stable η phase up to 30 nm in diameter and a metastable T' phase ~200 nm in diameter. No significant effect of irradiation on the precipitation process of metastable θ'' and η' phases were found.

Irradiation of the naturally aged 1960 alloy with a low dose of Ar^+ ions does not change its strength characteristics at some increase in plasticity. An increase in the dose to $1\cdot10^{17}$ cm^{-2} significantly increases the ductility (to δ = 14%), slightly decreases the yield strength ($\sigma_{0.2}$ = 550 MPa), and retains the tensile strength at the same level. It should be noted that this result is interesting and new, but it is nonrepeatable by only methods of thermal processing.

This work was supported by the Russian Foundation for Basic Research, grant no 14-08-01049_A.

DESTRUCTION OF ORGANIC DYES IN WATER SOLUTIONS UNDER THE ACTION OF LOW-TEMPERATURE PLASMA JET

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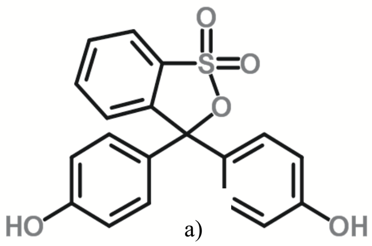
Today the problem of water purification from pollutants, mostly organic ones, is very relevant. Purification of water by gas discharges that are excited over the solution, in the solution or in both phases at the same time is a very promising method.

There are new methods of organic compounds destruction in water solutions produced under the influence of plasma jet, the latter being generated by switching power supply at the atmospheric pressure.

The objects of the research were as follows:

1. – water solution of phenol red dye ($C_{19}H_{14}O_5S$, PR) (Fig. 1a). It was stabilized by the NaOH buffer solution to pH=7. The concentration of phenol red dye was 1.1×10^{-4} mol/l.

2. – water solution of methyl orange dye ($C_{14}H_{14}N_3NaO_3S$, MO) (Fig. 1b). It was stabilized by the NaOH buffer solution to pH=7. The concentration of methyl orange dye was ~ 7.64×10^{-6} mol/l.


a)

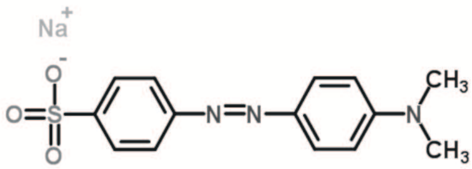

b)

Fig. 1. Chemical structures of phenol red (a) and methyl orange (b) dyes.

The electronic absorption spectra (EAS) of the solution were determined with a spectrophotometer SF-56 (Russia), pH being determined with a pH-meter calibrated by buffer solutions.

The destruction kinetics of above mentioned compounds and kinetics of H_2O_2 formation by the permanganate method were studied. Obtained results showed that the destruction of both dyes occurred under the influence of plasma jet. This process was accompanied by decreasing of pH of the solution to pH=3,4-3,5. Dyes destruction was assumed to result from their reactions with the OH radicals. An indirect evidence of OH radicals presence was H_2O_2 accumulation in liquid phase.

The scheme of processes that proceeded in the solution was assumed. It includes processes from the [1] for the H_2O_2 formation and additionally includes processes for dyes destruction and active plasma species accommodation on the solvent surface. The scheme clearly describes the destruction and formation of controllable solution components kinetics. It may be suitable to predict the results of described discharge influence on water solution of acid-base dyes.

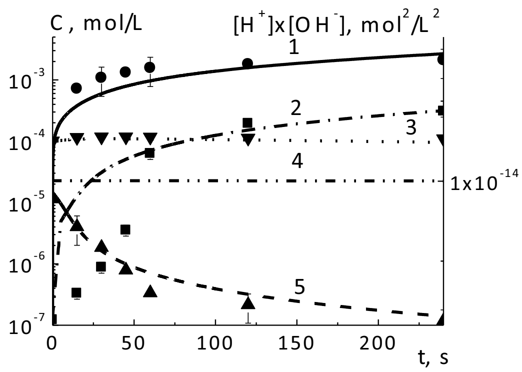


Fig. 2. Kinetics of the phenol red destruction and some products formation: 1 – H_2O_2; 2 – H^+; 3 – Hind; 4 – $[H^+][OH^-]$; 5 – Ind^-. Points – experiment, lines – calculation.

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THE ININFLUENCE OF THE LENGTH OF THE HOLLOW CATHODE IN THE CURRENT-VOLTAGE CHARACTERISTIC OF A GAS DISCHARGE

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Despite the rather long-term studies of the gas discharge with a hollow cathode, currently works on the study of physical phenomena in the plasma of this type of discharge. Hollow-cathode discharge successfully used for technological purposes for the production of coatings and materials processing. Of particular interest is the work on the generation of uniform plasma inside the hollow cathode, aimed at creating ion beams, plasma flows with uniform flux density across the beam. It is known theoretical studies aimed at optimizing the different characteristics of the discharge. In [1-3], we examine the effect of different parameters on the uniformity of the plasma inside the hollow cathode discharge characteristics and the cathodes of different lengths. One of the important issues raised by these studies - a clarification of the influence of geometry on the cathode current distribution on its surface. Purpose - to communicate the current density on the side and end of the cylindrical hollow cathode with its linear size at different experimental conditions. Experimentally determined the effect of the length of the cylindrical hollow cathode material on the current-voltage characteristic of a gas discharge in argon at a pressure in the range 0,02 ÷ 0,2 Torr.

The hollow cathode consists of a cylinder made of stainless steel mesh or metal foil of various metals. Inside the cathode is freely movable walls insulated from the electrode (collector). Feature is that the current is measured simultaneously on the lateral surface of the cathode (mesh) and in the movable end (collector). Distance from the cathode to the anode is not changed. Cathode diameter 34-32 mm, the range of variation of the cavity length L = 0□16 see. It was found that increasing the length of the hollow cathode current increases significantly: more than 40 times. For example: current = 1mA at length = 0.2 cm. and 44ma when 9cm. The sharp rise in current begins at a ratio of length to diameter approximately equal to two. The pressure P = 0,15torr, gas - Argon and the potential difference: cathode-anode = 700V.

The report shows the dependence at various parameters and the internal surface of the cathode materials. The dependences of the potential of ignition and quenching on the length d of the hollow cathode and the pressure p in the chamber and built Paschen curve in the presence of a hollow cathode in the product p * d = 0,04 ÷ 2.0 mm Hg. v. * see. It was found that a decrease in pressure in the chamber current is reduced; potential extinction weakly depends on the length of the hollow cathode and decreases with decreasing pressure in the chamber. Potential ignition increases with decreasing product p * d.

Current is measured on the end of the hollow cathode to the collector. It was found that at a voltage between the electrodes ≈ 520V dependence of the current on the collector of L has a characteristic maximum in the range between the cathode length to diameter ratio of 2 - 3. We present a theoretical calculation based on the works [1,2] the current-voltage characteristics, taking into account the rapid ionization electrons produced in the cathode layer discharge. For maximum length of the cathode experimental dependence is consistent with the theory with a coefficient of secondary ion-electron emission k_{i-e} = 0,01. A qualitative explanation of the results. Results obtained for a cathode made of mesh. The relative error in measuring the voltage was 3%. Current accuracy not worse than ± 0,25 mA. The pressure in the chamber is determined with an accuracy of 25-30%.

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AUTOMATIC CONTROL SYSTEM OF HIGH-PRECISION WELDING OF PREPARATIONS BY THE LASER RADIATION AT INFLUENCE OF THE PLASMA TORCH

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One of the trends of modern engineering is the widespread use of automated system of laser welding as one of the effective ways to reduce the costs of production by increasing the ratio of utilization of materials [1]. Provision of stability of properties and quality of weld, as well as high economic indicators, requires the application of automatic control system in the technological process. Elaborated and currently used technological methods do not allow to solve fully all the problems of automation of the welding process in mechanical engineering.

The quality of the obtained product has a complex dependence on the technological parameters of the process (radiation power density, speed of the movement of laser radiation, gaseous atmosphere, etc.) that causes the need to control the process by maintaining those parameters within the required limits. [2] This necessitates to use new approaches to the control of the process of high-precision laser welding and improvement of automatic control system.

In the real work on the basis of the conducted patent researches the control system of process of laser welding at influence of a plasma torch with various geometry of a seam and forms of details is developed. The control method of provision of a spot of a laser radiation of rather curvilinear joint weld which passed through the plasma torch based on keeping track of by edges of the welded details on the reflected low-current laser radiation from a detail surface is developed. It allows to make in the automatic mode positioning of focus of a laser radiation concerning a joint of the welded details under the influence of a plasma torch.

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OPTICAL CHARACTERIZATION AND RAMAN SPECTROSCOPY OF AMORPHOUS HYDROGENATED CARBON FILMS PREPARED BY DC DISCHARGE[1]

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The important scientific and applied significance of analysis of carbon films is caused by that carbon can form materials with a wide spectrum of physical properties and various type of a chemical bond. For this reason carbon films are rather perspective material for wide technical application [1, 2].

Carbon films are gaining by various methods of ion-plasma technology. Depending on a method and conditions of production a film can be diamond, amorphous, amorphous hydrogenated or polymeric.

The deposition processes from plasma of hydrocarbons have found the wide spread occurrence for producing of carbon films. One of formation methods of such plasma is DC glow discharge. It allows to use various materials (metals, dielectrics, polymers, semiconductors) as substrates. In glow discharge in the deposition process the surface of a growing film is exposed to continuous bombardment by the positive ions with energy which depends on interelectrode voltage. These ions play a role not only in surface process, but also in formation of film composition and microstructure, and, hence, concrete optical properties. In the growth process of carbon films neutral particles (hydrocarbon radicals) which are formed at activation of gas environment by electrons in a discharge gap [5] also take part. The balance of the processes promoting growing of a film thickness, defines speed of its deposition and an internal structure. Using glow discharge parameters (gas pressure, ion current and interelectrode voltage), influencing on energy and quantity of the ions flying on a substrate it is possible to change speed of films deposition and to control their optical and mechanical properties.

Carbon films were deposited in DC glow discharge plasma in a ethanol vapor at distance between a substrate and the cathode of 0.2 sm, pressure of vapor 0.15 тор, discharge voltages 595-1376 V and density of an ion current 0.18-11 $\mu A/sm^2$. As substrates the silicon alloyed by arsenic was used. The substrate was fixed on the holder of substrates which was placed directly behind the cathode. Before the deposition process substrates were treateds with argon ions during 10 minutes.

Characterization of structure and phase composition of deposited films were determined by Raman spectroscopy method. Wave length of incident radiation excitation was 514.5 nanometers; a range of measurements was 800-2200 sm^{-1}. Raman spectra contain G- and D-bands typical for amorphous carbon [3, 4]. Under decrease of discharge voltage from 1214 to 685 V a shift of G-band to high-frequency area arises. This evidences about growth of nanoclusters with structure of rings or short chains in system of carbon sp^2-bondings of structure [3]. However broadening of G-band demonstrates that all system is disordered.

Optical parameters of films such as a thickness, a refraction index and absorption index were measured by using scanning ellipsometer. Measurements were carried out under angle of incidence 55º. It's found out, that examples prepared at rather high discharge voltages (1100-1370 V), are consist of two layers. Each layer has own optical parameters (index of refraction, absorption and thickness). The films obtained at smaller discharge voltages (590-960 V), were no longer two-layer. Thus, the deposition method of amorphous hydrogenated carbon films in glow discharge plasma allows to obtain both single-layered and two-layer films with different optical parameters.

The equipment of Scientific educational complex "Nanosystems and modern materials" of Novosibirsk State University was used in this work.

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GENERATION OF SHOCK-WAVE DISTURBANCES AT PULSATING PLASMA-VAPOR BUBLE OSCILLATION[1]

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The complex physical and mathematical model, describing all steps of plasma-gas-vapor bubble evolution in the system of the condensed media water- ground is presented. Operation of the discharge circuit, discharge plasma channel expansion, its transformation into the vapor-plasma bubble and its pulsation, pressure wave generation and propagation of the mechanical stress waves in the ground are self-consistently considered in the model. The model allows to investigate the basic laws of stored energy transfer to the discharge plasma channel, next to the plasma- -vapor bubble and transformation of this energy to the energy of pressure wave compressing the surrounding ground. Power characteristics of wave disturbances generated by gas-vapor bubble oscillation in water depending on the circuit parameters are analyzed for the prediction of the ground boundary displacement. The dynamics of the shock-wave propagation in condensed media water–ground depending on the mode of plasma channel energy release is investigated. Simulation of the shock-wave phenomena at a gas-vapor bubble oscillation in condensed media consecutively describes physical processes underlying on technology for producing piles by electro-discharge stuffing. The quantitative model verified by physical experimental tests will allow to optimize pulse generator parameters and electrode system constructions of created equipment.

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THE PLASMA TORCH WORKING ON A MIXTURE OF STEAM AND OTHER GASES FOR THE PETROCHEMICAL APPLICATIONS

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Hydrogen is obtained from hydrocarbon by reforming with carbon dioxide, steam and air. With a development of plasma technology it has opportunity to use different types of plasma for production of hydrogen-containing gas for the chemical industry. However, the use of plasma generators is limited by their low power and relatively low efficiency of electrical energy. In spite of this, methods for producing hydrogen from methane (natural gas, associated gas) in the corona [1], barrier [2] and microwave [3] and the electric arc discharge [4, 5] are investigated. In the main, works are carried out with low power that does not allow them to apply for industrial scale. The obtained syngas can be used for different chemical processes (catalytic reforming, catalytic hydrogenating, methanol synthesis, Fischer–Tropsch process, etc.). Steam thermal plasma increases temperature and reaction velocity of a process and provide a high conversion and selectivity, the purity of the syngas. AC plasma generators can operate with different gas ratios and have a high power and efficiency [6]. The article presents the investigation of the prototype of a powerful AC electric arc plasma torch operating on a mixture of steam and air. Thermodynamic evaluation of heavy oil gasification for preliminary determination of energy consumption and plasma enthalpy is performed with the following conditions: temperature - 1500 K, the main elemental composition: C - 86%, H - 9.3%, S - 4%, N - 0.5%, O - 0.2% mass., the specific consumption of oxidant - 1,5 kg per 1 kg of fuel, the weight ratio of air / steam is 1/6. Consequently the enthalpy of the plasma is 10.89 MJ/kg, the specific power consumption per 1 kg of the reacted heavy oil - 16,34 MJ/kg, the specific power consumption for hydrogen production (from the fuel to syngas) - 71,65 MJ/kg H_2.

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SYNTHESIS OF POLYCRYSTALLINE DIAMOND FILMS IN THE ABNORMAL GLOW DISCHARGE AND THEIR PROPERTIES[1]

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Unique chemical, mechanical, electrical and thermal, optical and photoelectrical properties of diamond contribute to its wide application in high–frequency, high–temperature electronics and semiconductor manufacturing of a special purpose [1, 2]. Polycrystalline diamond films (PDF) are successfully used for the production of stable radiation-resistant detectors of UV and ionizing radiation, as well as for laser and photodiode structures [1]. Depending on the characteristics of polycrystalline structure of PDF, the content of alloying impurity atoms and defects, electrical characteristics, as well as the mechanism of the transport and type of the charge carriers vary widely [1]. Among the various PDF deposition methods, there are microwave plasma, hot filament, arc–jet and glow discharge CVD to be marked out. Glow discharge CVD is considered to be an effective diamond film deposition method because of its simplicity and high growth rate [2].

In this work the optical and electrical properties of PDF, deposited from abnormal glow discharge were investigated. Dominant mechanisms of absorption and transport of charge carriers and the energy spectrum of localized defect states which determine the properties of the films were stablished. PDF not inferior to diamond films produced by alternative methods. Parameters of interband absorption and electrical conductivity due to a continuous distribution of energy in the band gap states of defects of different nature. The absorption edge of the crystalline phase is separated from the films of the absorption band due to electronic transitions between localized states defects. Band gap width narrows to 0.2-0.5 eV from the intrinsic value of a diamond. Formed the new edge absorption of films in the energy range 1.2-3.3 eV, where performed Urbach rule and implemented under the direct interband absorption transitions through the optical gap 1.1-1.5 eV. The average width of 2.6-3.24 eV band gap assessment under interband semiclassical model. The relationships between them and the interband absorption due to the exponential static disordering of the crystal lattice. The dominant n-type conductivity activation component is complemented by hopping mechanism involving localized defect states, distributed near the Fermi level with a density of $5.6 \cdot 10^{17}$–2.1×10^{21} $eV^{-1} \cdot cm^{-3}$. Centers of capture and recombination of charge carriers are distributed non-uniformly along the grain boundaries of the film material.

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MODIFICATION OF THE CILINDRICAL PRODUCTS OUTER SURFACE UNDER THE RADIAL BEAM OF ARGON IONS INFLUENCE AT AUTOMATIC MODE

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Surfaces obtaining with a high degree of purification from impurities and small roughness parameter is important for increasing the corrosion and wear resistance of products, which operating in corrosive environments.

For this purpose has been developed installation ILUR-03 with the coaxial ion beam source with a broad energy spectrum for cleaning, polishing and surface doping of long cylindrical products.

Upgraded installation ILUR-03 (figure 1) allows effective cleaning from technological impurities (abrasive particles after mechanical polishing, acid residues after chemical etching, adsorbed gases), surface polishing, film deposition using magnetrons and doped of surface layer by ion mixing per technological cycle.

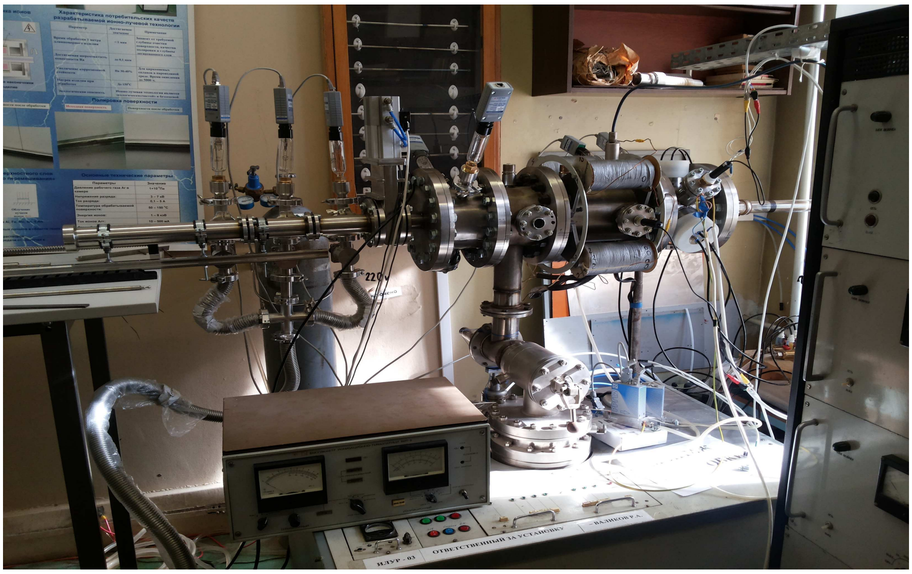

Fig. 1. Instalation ILUR-03

Ion mixing method alloys to create think surface layer, which enriched complex alloying elements at concentrations in excess of the equilibrium, which can't be achieved by volume doping. The samples after ion polishing studied by profilometry, which demonstrated that roughness decreases to Ra = 0,3 ± 0,1 μm after ion polishing.

The condition of the ion modified samples surface layer, determined by the ion scanning microscopy method, showed, that ion beam treatment create thin amorphous layer due to the accumulation of the radiation defects. This state of the surface layer facilitate the growth of the oxide film with protective properties and increases wear resistance of product.

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RESEARCH OF SHOCK WAVE GENERATION IN PLASMA ELECTROLYTE PROCESSING [1]

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Gas discharges with liquid electrodes or initiated in a liquid environment has always aroused great interest, both in terms of fundamental research and in terms of applied researches [1]. Applied interest associated with features such as cleaning metal surfaces, forming surface microrelief, imposition of functional coating, application in cleaning systems, etc. [2]. Fundamental researches aimed at identifying the nature of the discharge mechanism of maintaining, mechanism of charge transfer at the interface between the plasma electrolytes, influence of anode microdischarges to the surface [3]. Big interest also represent the processes of formation of shock waves in a liquid under the influence of electrical discharges, these researches are relevant in terms of defining the mechanism of formation of the shock wave and from the point of view of applications in mechanical engineering. The work has been tasked to determine conditions for the generation shock waves in plasma-electrolytic processing.

To solve this problem was developed experimental setup of plasma electrolytic processing, which included a complex of high-speed video recording. With high-speed video camera Fastec Inline 250 research of plasma electrolytic processing have been conducted.

Current-voltage characteristics of the full-wave mode can be divided into three sections. First section from 0 to 70 V. This region corresponds to the flow of only electrochemical reactions.The second region 70 V to 180 V – burning of separate microdischarges at the anode surface. Precisely in this range, shock waves are generated. Luminescence of vapor gas layer observed around the electrode in the third area of 180 V and higher without the occurrence of certain microdischarges. This process of discharge burning occurs intermittently, with each new pulse, arising again and again.

Researches surface of the anode at electrolyte plasma processing by using high-speed video shooting showed that that the buildup of discharge channel takes place inside cavity leader. Buildup in the initial stage occurs not on the entire cross section of the cavity channel of leader. In such a way at the initial instant we observe the formation of a leader in the liquid and its germination on environment for a short distance, and only then localized flare-up in the gas discharge channel leader. Upon reaching the plasma expands discharge channel liquid walls leader’s expansion velocity decreases sharply up to 1000 m / s.

Plasma of the discharge channel which contacting the liquid walls of the cavity acts like a piston on the fluid and generates a shock wave in the liquid. Remains an open question: “Why the generation of shock waves is observed only in the voltage range of 70 - 180 V and not more than 180 V when the well is burning microdischarges?”

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OBTAINING NANOPARTICLES OF METALS IN PLASMA-ELECTROLYTIC FORMATION OF MICRORELIEF[1]

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In recent years, metallic nanoparticles are increasingly used in different industries. Nanoparticles of platinum, silver, gold, nickel, titanium and copper are widely used especially in the energy, chemical and medical industries. But for now remains an actual issue of obtaining nanopowders given dispersion and preservation of their operational properties. The existing methods give a large spread in the size of the resulting nanoparticles or inappropriate from an economic point of view. Therefore there is a question about the development and research of new methods for producing nanoparticles, given sizes and able to maintain their operational characteristics.

The solution of this problem can be found in the application and partial modification of the method of plasma electrolytic treatment of metals [1]. Plasma electrolytic process is used to form surface microrelief of metals [2]. Its essence is to initiate at the surface of the workpiece gas discharge, combustion occurs between the anode - part and the cathode - electrolyte. In this work has been tasked to investigate the plasma electrolytic synthesis of metal nanoparticles.

To solve this problem, we used a modified experimental setup [2], which provide for holding plasma electrolytic synthesis of nanoparticles with different ripple factor of voltage in the voltage range from 0 to 300V. Basic studies were performed on samples made from nickel, copper, silver and titanium. After the plasma electrolytic processing, the samples were investigated by using a scanning electron microscope Carl ZEISS EVO 50 and scaning atomic force microscope. As an parameters of evaluation was measured linear dimensions of nanoparticles.

Particles were obtained at operating voltages: 50, 70, 90, 130 and 170V. It has been established that the increase in voltage leads to changes of the average particle size. Nickel nanoparticles were synthesized in a solution of sulfuric acid. An aqueous solution of salt was used to obtain particles of titanium and silver.

All five modes of production of nanoparticles can be divided into groups according to the size of the resulting particles and their dispersion. The first group - 40 and 60V. In this group nanoparticles have a size from 20 to 30 nm. The second group – 90 and 130 V, nanoparticles - from 5 to 25 nm. This such a large range of product particles was caused by the instability of the gas discharge. The third group at a voltage of 170 V or higher. The nanoparticles were detected in solution between 5 and 10 nm.

In plasma electrolytic synthesis, the desired dimensions and dispersion of nanoparticles can be obtained by altering the processing and parameters of the electrolyte solution in the final stages of the synthesis.

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RESEARCH OF INFLUENCE SURFACE ROUGHNESS ON THE PROCESS OF FORMATION THE MAO(MICROARC OXIDATION) COATINGS [1]

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The process of microarc oxidation known for a very long time and has been widely used in many industries [1]. A feature of this formation of coatings process is the combining high temperature plasma phenomena (burning microarcs) and electrochemical reaction in a liquid medium ($T \leq 100\ ^0C$). It is well known that the process of microarc oxidation is used at drawing of ceramic coatings on the radiating elements of infrared heaters. It is caused by the necessity of improve the efficiency of the emitters, while the emissivity of the aluminum oxide is much higher than that of aluminum. To increase the area of heat radiating elements are made with corrugated surface, which increases the cost of construction. Recently it has been suggested the use of simpler methods for increasing the specific area of the emitter: sandblasting and plasma electrolytic treatment [2]. Therefore, it is important to research the formation of MAO coatings on the surfaces which obtained after different treatments. The purpose of the work was to compare the process of microarc oxidation of aluminum plates with different roughness parameters.

To achieve this goal were prepared samples of plates made from aluminum D16T. Plates were treated with plasma-electrolytic method and sandblasted. The plates were investigated by a profilometer TR-200 and were defined the basic parameters of roughness.

Investigation of the influence of surface roughness on the flow of microarc oxidation process carried out on experimental installation with a power supply, consisting of a capacitor type MBGP-2 and K75-27with enabled parallel to the discharge circuit, with resistor PEW-100. The total capacity of capacitor bank 478 uF, with a readability of 50, 10, 10, 7, 6, 6, 2, 0.5 uF. To remove the residual charge each capacitor was shunted with resistor. Current control is achieved by connecting / disconnecting the additional capacities. Power of the experimental setup is powered by the three-phase system alternating current 380 V with neutral. The capacitor bank is used to increase the amplitude of the original EMF of power supply that lets us change the current in the circuit.

Research has shown that with increasing surface roughness increases the need for higher amperage in a non-discharge mode. This is explained by the greater surface area. However, initiation of anode microdischarges with increasing of surface roughness is observed at lower current values. Explain this fact is possible be assumed that the growth of the oxide pellicle occurs at the fastest microtops and in the lowlands slower. Gradually the amperage in the chain falls while oxide pellicle increasing. At a time when increases the strength of the current, we have a non-uniform oxide pellicle, which breaks into the depressions. Oxide pellicle has the same thickness everywhere in case of the smooth aluminum surface.

Comparison of microarc oxidation of aluminum plates one and the same roughness, but with different processing methods (sandblasting and plasma electrolyte treatment) did not produce differences. This is explained by approximately the same surface microstructure. However, it should be noted, research by SEM revealed the presence particles of sand on aluminum the surface, which can adversely affect on the adhesion of ceramics. From this point of view, the method of plasma electrolytic treatment is more preferable.

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ANTIEMISSIVE COATINGS

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The grid electrode is produced from molybdenum or tungsten. For powerful generating devices the norm of parasitic thermionic emission is about 10^{-5} A/cm^2. The constructive decisions reducing temperature of grids such as, for example, increase in their working surface or in distance between a grid and the cathode are, as a rule, not acceptable because they lead to decrease in such technical feature of lamps as the steepness of characteristics, and also increase capacities between electrodes, dimensions and weight of a lamp.

When using antiemissive coatings on the basis of platinum and its connections in the work process at high temperatures diffusion of platinum (Pt) into the substrate material is observed, resulting in depletion of antiemission layer, and a counter diffusion resulting in loss of antiemission properties of the coating [1]. With increasing time of operation the diffusion factor of dissolution becomes dominant.

Due to the high diffusion mobility of the components the diffusion zone reaches a considerable size: the material of the substrate is fixed throughout the thickness of the formed coating Pt3Zr, and the diffusion of platinum flowing over the surface and the grain boundaries, is recorded at a depth of 10 μm or more. Diffusion along the grain boundaries occurs many times more intensively than in the bulk of grains due to the lower activation energy of the diffusion. The rate of diffusion is determined by the mass of the substance, diffused through unit area of the interface per unit time, and depends on the concentration gradient of the element in the direction normal to the interface surface, and also grain size and temperature [2].

The formation of crystallization centers and their growth, which occurs due to the attachment of the atoms from the surrounding deformed volumes, reduces the total surface of the grain boundaries and contributes to the transformation of matter into a state with greater thermodynamic stability. Because of the relatively small differences in the sizes of atoms of Mo and Pt (1.45 and 1.39 Å) in the diffusion zone at the same time the process of formation of multicomponent solid solutions of variable composition of diffusing elements in the lattice of the metal-solvent is observed.

To inhibit the flow of diffusion was used the barrier layer, the choice of which was based on the following laws:

– the phase dividing boundary is the energy barrier for diffusing atoms;

– diffusion in multilayer coatings is considerably slower than in single layer coatings;

– the diffusion rate is lower the more densely packed structure is formed and higher the more is the bond energy between atoms.

Thus, the proposed technology has allowed obtaining a multilayer coating containing as the underlayer a carbide of refractory material, which creates favorable conditions for obtaining an intermetallic compound Pt3Zr of high quality and preventing the counter flow diffusion processes that can improve the lifetime performance properties of antiemission grid coatings.

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STRUCTURE-PHASE STATES OF SILUMIN SURFACE LAYER AFTER ELECTRON BEAM AND HIGH CYCLE FATIGUE[1]

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The aim of this work is to study the structural-phase states, which are formed in the surface layer of silumin, subjected to electron beam irradiation and high-cycle fatigue testings up to the fracture. Fatigue tests were carried out in a special unit on the principle of asymmetric cyclic cantilever bending. Specimen surface irradiation prepared for fatigue tests was carried out using the unit “SOLO” with the following parameters: electron energy = 16 keV; pulse repetition frequency = 0.3 sec^{-1}; pulse duration of the electron beam τ = 50 µs and 150 µs; pulse number N = 1, 3, 5; energy density of electron beam of E_S = 10, 15, 20, 25 J cm^{-2}.

The fatigue tests carried out by us have revealed a wide set of results and essentially depend on both the specimen structure and regime of its irradiation (Fig. 1). The irradiation of silumin surface with pulsed electron beam depending on the energy density of the electron beam is accompanied either by melting the surface of the sample (regime No. 1 – 15 J cm^{-2}; 150 µs; 3 pulses), or the melting of the surface layer of the material of a certain thickness (from one to tens of micrometers) (regime No. 2 – 20 J cm^{-2}; 150 µs; 5 pulses). In the first case, the fatigue life in some cases has been below the fatigue life of the initial samples, and in the second one it has exceeded the fatigue life of the initial material in more than 3.5 times.

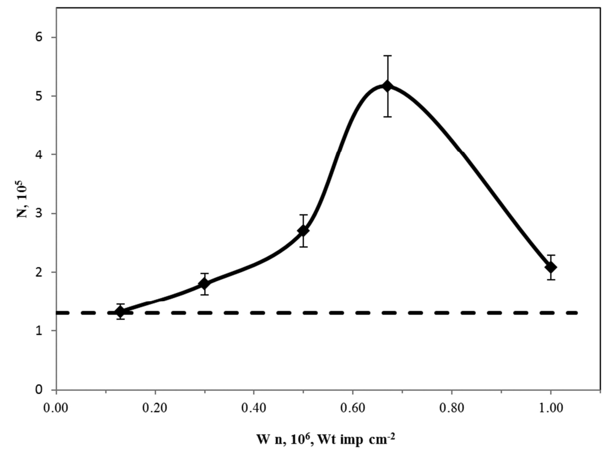

Fig. 1. Dependence of an average (averaging performed on five samples) number of cycles N to failure of silumin on the product of the Ws energy density and the number of pulses of n electron beam treatment. The values of fatigue life of the initial material are shown by the dotted line.

The irradiation of silumin surface for regime No. 1 leads to the partial melting of the excess silicon inclusions. In the surface layer numerous micropores along the boundary between the plate/matrix and microcracks are formed; they are located in the silicon plates, which weaken the material. As a result, the fatigue tests lead to the fracture of plates and the formation of long microcracks. During silumin irradiation with high-intensity electron beam in regime No. 2 on the irradiation surface the homogeneous structure of a grain type is formed, and the thickness of the molten layer varies in the range up to 20 µm. Resulting from high-speed crystallization a multimodal structure at the macro level is represented by the grains on the basis of aluminum, whose dimensions range from 30 to 50 µm. There are silicon particles on the grain boundaries; their transverse dimensions do not exceed 20 µm. Mesolevel of the modified layer consists of two-phase (silicon and solid solution on the basis of aluminum) crystallization cells detected on the surface of a fatigue fracture. The cell crystallization sizes vary in the range of 100 nm up to 250 nm. This reflects the submicrocrystalline structure of the near-surface layer.

Thus, it has been established that the main cause of multiple increase of silumin fatigue life, processed with a pulsed electron beam, is the formation of the nanoscale multiphase structure in a modified surface layer.

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FORMATION OF STRUCTURAL GLOBULAR FEATURES OF ELECTROEXPLOSIVE COATINGS[1]

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For electroexplosive sputtering (EES) of coatings the effect of electric conductor burst is used in the form of thin wires or foils. The material of the burst conductor can be any metal, alloy, carbon fibers or others. It defines the wide sphere of the practical usage of the method. By EES with the use of coaxial-edge electrodes the directed jet of the explosion products and powder samples is formed; it should be noted that they can be entered into the area of explosion. High-speed (up to 10–15 km/s) plasma jet front at the interaction with the support creates near the surface the shock-compressed layer with high pressure of (~ 10^7 Pa) and the temperature of (~ 10^4K). The aim of this work is the analysis of the possible formation mechanism of the structural peculiarities of electroexplosive coatings of different systems, caused by pulse-periodic and high-intensity character of the processes, accompanying EES.

The researches of cross sections have showed that the thickness of coatings is several tens of micrometers. The main peculiarity of electroexplosive coatings is the formation in them of globules of a mesoscopic size (from several units of micrometers to 10–20 μm). At the formation of coatings with the electroexplosion of a copper foil with a powder sample of tungsten W-Cu, part of globules with the size of 20 μm, formed with tungsten, is surrounded by a copper cover. When preparing the sections, some of the globules chip and form pores, the size of which corresponds to the size of globules. It is connected with the fact that the copper and tungsten are badly-soluble in each other and do not form any chemical compounds. At the same time at the sputtering of coatings of Ti-Y system, having a eutectic state diagram, the globule cover is yttrium. The globules with the size of some micrometers in this case do not chip. In the large ones pores are observed.

Information on the formation of similar globular structuresat the formation of coatings using any other methods, for example the method of gas-thermal sputtering, is absent in the literature. At thesame time it is well-known that the formation of globular structures of a mesoscopic size occurs in dynamically deformable materials in the conditions of shock loading. It can be supposed that the physical nature of the formation of such structures at EES with supersonic polyphase plasma jets and in the conditions of sample surface treatment with shock waves, as in the work, is common. Proceeding from this fact we will examine the possible mechanism of their formation, following the ideas represented in. The front of shock wave distribution, which occurs in the coating materials at their formation as a result of an oscillatory character of a capacity storage discharge of an electroexplosive unit, is an interfacial area of a dynamically loaded environment and an unstrained material. At this area a «chess» distribution of tensile and compressive normal stresses occurs. A strong zone curvature of tensilenormal stresses generates in these zones bifurcational structural states. The origin in these zones of maximum tangential stresses causes the generation of dynamic material rotation. Dynamic rotation appears in the areas of tensile normal stresses, surrounded by the areas of compressive normal stresses. Shearing stresses, which form rotations, are maximum on the boundaries of the areas of tensile and compressive normal stresses. Under the influence of shearing stresses in the center of the areas of tensile normal stresses large rotations with slow angular speed occur; they implement rotary modes of deformation with the mechanism of material fragmentation. It is also necessary to note, owing to this fact, the influence of the formation of «chess» distribution of tensile and compressive normal stresses, occurring on the interfacial area, on the formation of the zone of a relative mixing of the materials of electroexplosive coatings and bottom layers.

It has been established that, when using electroexplosive sputtering of coatings of different sys-tems, one of the structural elements is the formation of globular fragments of a mesoscopic scale (~ 1–10 μm). The observed features of the structure can be explained by the proceeding concep-tions of the physical mesomechanics on the occurrence of "chess" distribution of compression and tensile normal stresses, leading to the formation of mesorotation of the coating materials.

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STRUCTURE AND PROPERTIES OF SURFACE LAYERS OBTAINEDDUE TO TITANIUM SURFACE ALLOYING BY YTTRIUMVIA COMBINED ELECTRON-ION-PLASMA TREATMENT[1]

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The goal of this study is to reveal and analyze the mechanisms by which the structure and properties of the surface layer of titanium are modified through the use of a combined method based on alloying by means of plasma formed during the electric explosion of a conducting material and subsequent electron beam irradiation.

The performed investigations indicate that the microhardness of the alloying surface is barely dependent on the electron beam treatment mode and exceeds the initial material microhardness by a factor of 3–3.5. Analysis of the microhardness profiles revealed the formation of an extended strengthened layer. Under the condition that the base microhard ness is exceeded by a factor of 2.5, the layer thickness reaches 60 μm if the electronbeam energy density is 50 J/cm^2. It is established that, in this treatment mode, titanium modification is accompanied by more than seven and threefold decreases in the friction coefficient and wear rate, respectively.

In compliance with the mechanical and tribological test results, a sample irradiated by the electron beam under the aforementioned conditions was chosen to examine the elemental and phase compositions and defect substructure of the modified layer. X-ray diffraction analysis demonstrated that a structure based on αyttrium with a volume fraction of 73% is generated in the surface layer and that the volume fractions of other surface phases are much smaller (10% of α-titanium, 14% of TiC and TiO_2, and 3% of Y_2O_3).

Typical surface layer images illustrating the formation of a multilayer structure are presented. As is seen from the microelectron diffraction pattern, the surface layer 500 nm thick is amorphous. The next sublayer 1.0–1.5 μm thick has a columnar structure, under which an extended layer (30–40 μm) with a dendritic (globular) crystal structure is identified.

The study of the element distributions over the surface layer, the results of which were obtained viamicro-X-ray diffraction analysis at the given points, signifies that the amorphous layer is enriched with titanium, the next sublayer having a columnar structure is enriched with yttrium, and the subjacent layer is again enriched with titanium. The elemental composition maps shown in Fig. 3 agree well with the point-by-point analysis of the elements and enable us to define the elementdistribution regions more precisely. Indeed, it is plainly seen that the layer with the columnar structure has columns that are alternately enriched with titanium and yttrium. This is evidence of phase decomposition in the material of the given layer.

The detailed structure of the layer with the columnar structure is illustrated in Fig. 4. It is clearly seen that the columns enriched with titanium have a block structure and the columns enriched with yttrium have no block structure. These blocks are misoriented, as is confirmed by a discrepancy in the contrast of their image. The block sizes vary from 5 to 20 nm.

Thus, the surface layer of commercially pure titanium has been modified using a combined technique uniting irradiation by plasma formed in the electric explosion of titanium foils with added yttrium powder and subsequent treatment by a pulsed high-intensity electron beam.

It is revealed that multilayer multiphase submicroandnanocrystalline structures characterized by material splitting into layers enriched with titanium and yttrium are formed. It is ascertained that titanium modification with yttrium is accompanied by the generation of titanium and yttrium oxides and carbides. On the whole, the observed processes lead to the creation of a metal-ceramic surface layer and stimulate manifold decreases in the friction coefficient and wear rate (their values decrease by more than seven and threefold, respectively).

[1]The study was supported by the grant of the President of the Russian Federation for state support of young Russian scientists - PhD MK-4166.2015.2 and - doctors MD-2920.2015.8, Russian Foundation for Basic Research (RFBR projects №№ 13-02-12009 ofi_m, 15-08 -03411, 14-08-00506a), and Ministry of Education and Science of Russia (projects № 2708 and № 3.1496.2014/K). This work was carried out with partial use of the equipment of the Center for collective use «Materials» SibSIU.

STUDY OF THE EVOLUTION OF THE METALL SURFACES TOPOGRAPHY UNDER ION BEAM IMPACT USING STATISTIC METHODS

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Ion-beam treatment of materials is one of the most effective methods to improve quality of the different products surface [1]. To make complete topography analysis it is advisable to use statistic methods besides standardized parameters as R_a, R_q, R_z etc. [2-3].

Parts of the cladding tubes from zirconium alloy E110 (outer diameter 9.15 mm, length 500 mm) which outer surface have previously passed mechanical polishing used as samples for investigation. Outer surface of the samples has been treated on installation ILUR-03 [4] by radial beam of Ar^+ ions with wide energetic spectrum 0.5-5.0 keV up to doses $(5\text{-}10)\times10^{18}$ ion/cm^2. Profilograms *h(x)* were filmed on mechanical profilograph-profilometer TR-200 followed by data processing in the Microsoft Excel 2010.

It is well-known, that regular as well as random roughnesses may be present in the surface structure of material. That is why autocorrelation function of the profile roughnesses used to analyze investigated topography, as one of the most informative way of random stationary processes description [3]. As known, autocorrelation function *K(τ)* of some process *h(x)* characterize dependence of process value at given point x on the value of the same process at another point $x+\tau$ with shift τ.

As you can see at fig.1, ion treatment leads to visually noticeable increase of average size of roughnesses, with not very big decrease of peaks height and dents depth. Roughness parameter R_a decreases from 0.23 to 0.17 μm. It is observed, that regular component of profile roughnesses became more evident at autocorrelation function plot from the ion-modified sample, and plot itself became smoother.

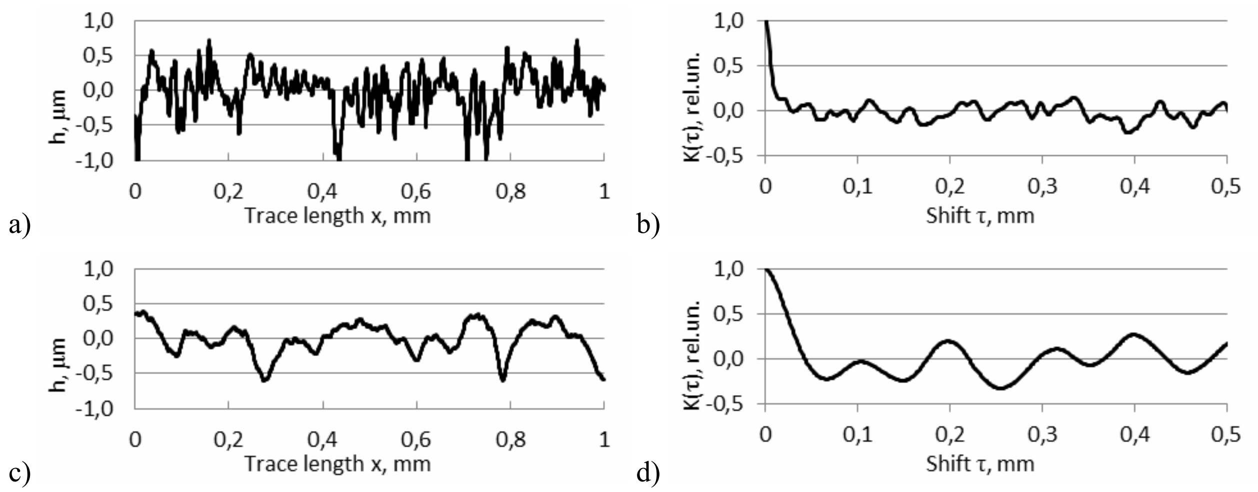

Fig. 1. Profilograms (a, c) and autocorrelation functions (b, d) from the outer surface of the samples after mechanical polishing (a, b) and ion-beam treatment (c, d)

It is well-known, that mechanical polishing process concern with great number of irregular impacts because of great difference in sizes of abrasive particles, their location and pressure on the surface treated. That is why there is a big part of random roughnesses of surface of the samples in initial state. Mechanical polishing trails smooth with increase of ion beam treatment duration, because their characteristic size does not exceed the boundaries of the ion polishing maximum efficiency for the specified ion beam parameters.

Regular relief component observed probably concern with production tubes technological process features and may be caused by such parameters as shape, size, speed, and vibration of the tool.

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SURFACE CRATERING OF STAINLESS STEEL AND TiNi IRRADIATED BY A LOW-ENERGY, HIGH-CURRENT ELECTRON BEAM: MORPHOLOGY AND TOPOGRAPHY OF TREATED SUBSTRATES [1]

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Investigation of crater formation on the surface of metallic materials, namely, 316L stainless steel and titanium nickelide irradiated with a low-energy, high-current electron beam of microsecond duration has been carried out. It has been establieshed that the craters are formed in the local areas of changed chemical composition, i.e., at the sites of location of inclusions. For stainless steel such inclusions are inclusions of manganese sulphide MnS, and for NiTi such inclusions are oxy-carbides of titanium. Studies at elevated initial temperatures showed that the number of craters decreases with increasing temperature. The latter evidences that homogenization of the surface during irradiation is associated with the dissolution of inclusions in a surrounded material.

Figure 1 shows SEM image (backscattered electrons) of the surface of irradiated TiNi. The data of chemical composition can be seen on the right plot. It has been established that the chemical composition of light particles on the bottom of microcraters practically coincides with the chemical composition of the initial particles. This clearly indicates that the craters in the material are forming in sites of presence of the inclusions of titanium oxy-carbide of nonstoichiometric composition Tix (O, C) y. Indeed, at the initial surface the chemical composition of inclusion is mainly titanium with small amounts of carbon and oxygen. Nickel in this region is absent. After irradiation, we observe a similar chemical composition in the center of the crater formed. This is due to the fact that in this case a single-shot irradiation with a small energy density melts the surface during a short period and inclusion had not enough time to be completely dissolved in the surrounding matrix. This result is very important because it complements the well-known data from the literature that cratering in titanium nickelide occurs on inclusions Ti_2Ni [1].

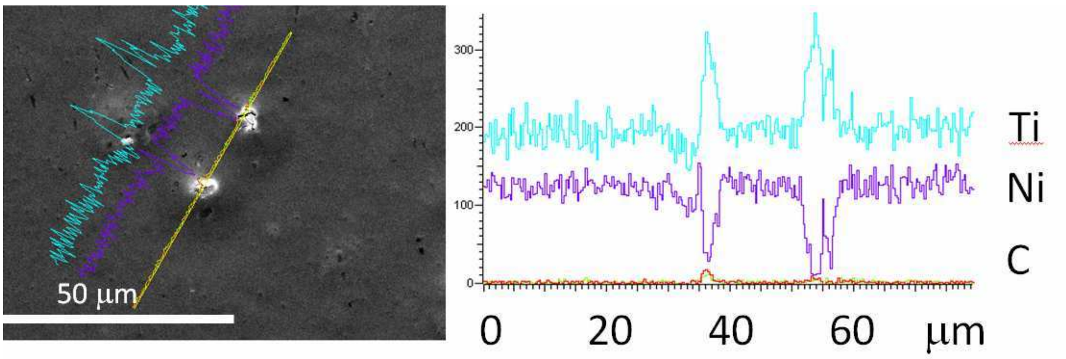

Fig. 1. SEM image of the surface of irradiated TiNi (backscattered electrons). On the right the line microanalysis of chemical composition is presented.

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