PLASMA-PROCESSING REACTOR FOR THE PRODUCTION AND TREATMENT OF NANOSCALE STRUCTURES FOR NANOELECTRONICS

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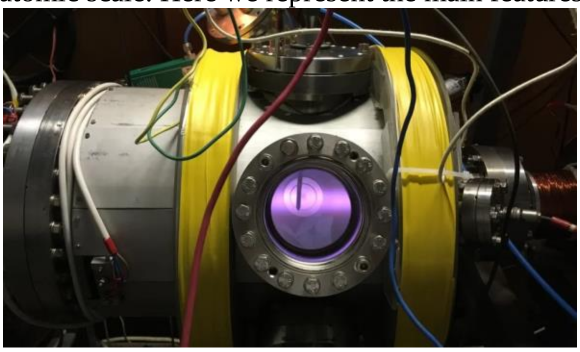
In the production of a wide range of semiconductor devices, from lasers to microwave chips, based on silicon and semiconductor compounds AIII/BV, various plasma chemical processes are widely used for etching and cleaning the surface of semiconductors, dielectrics and metals, and for the thin films deposition on the surface of semiconductor structures. For the treatment of nanoscale materials and structures in nanoelectronic processes it is important to provide "soft", defect-free etching of open surface of structures. Plasma technologies are mainly used RF and microwave discharges for semiconductor devices. Usually the energy of the ions in these discharges is difficult to control.

The work aimed on the creation of plasmas for plasma processing reactors by an electron beam is already known, for example, LAPPS [1]. It is shown that these systems are effective for the creation of plasmas with any gas composition and also capable for creating high density plasmas with cold electrons ($T_e < 0.5$ eV). A low density electron beam (1 - 10 mA/cm^2) is used to form “quiet” plasma by collisional ionization by beam electrons with gas molecules. There are no intrinsic mechanisms of acceleration of ions or plasma in this system. A medium pressure is needed to obtain sufficient ionization, thus the ion flow is influenced by collisions and directivity of the ion flow is too low.

The beam-plasma discharge (BPD) [2-3] used in the plasma processing reactor has several essential advantages [4-9] compared to widely used RF and microwave discharges lower operating pressure, which contribute higher anisotropy of the ion flux on the treated surface; low etching rate and fine control of the average ion energy (in range of 10 - 100 eV) provide treatment with minimum density of radiation defects at atomic scale. Here we represent the main features of the plasma facility based on the BPD (shown in Fig. 1).



Working gases	H_2, D_2, Ar, He, N_2
Magnetic field	Up to 30 mT at the center (Helmholtz coils)
Residual pressure	10^{-4} Pa
Working pressure	(10^{-3} – 1) Pa
Power of the electron gun	up to 2 kW
Plasma density	up to $5\text{x}10^{18}$ m^{-3} – Ar plasma up to 10^{18} m^{-3} – H_2 plasma
Electron temperature	up to 10 eV
Ion flux	up to 10^{u} m^{-2}c^{-1}

Fig. 1. View and parameters of the BPD facility.

Also the possibility of ion energy control is studied. The capability of the creation of a plasma reactor which satisfy the technological requirements for low energy etching of semiconducting materials is demonstrated.

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FOREVACUUM PLASMA SOURCE OF RIBBON ELECTRON BEAM WITH A MULTI-APERTURE EXTRACTION SYSTEM

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Electron beams of large cross-section, in particular, a beam of ribbon configuration are used for irradiation of large surfaces and the creation of a beam plasma of significant volumes, and interest in this subject continues to grow. Electron-beam plasma is used for etching, deposition and surface treatment [1]. For the technology of plasma processing of materials, an increase in the plasma concentration, an increase in the volume and homogeneity of the plasma formation, an increase in the possibility of controlling its parameters is required. To solve such problems, reliable and durable electron-beam plasma generators with stable parameters are required. One of the promising beam plasma generators is a forvacuum plasma source that generates an electron beam of a ribbon configuration. Despite the obvious progress in this direction, the problems of increasing the current density of the electron beam of the belt configuration in the absence of a transporting magnetic field, as well as increasing the homogeneity of the electron beam remain open. This paper presents the results of experiments to increase the current density extracted from an extended hollow cathode of a forvacuum electron source. The main feature of the work is the use of a multi-aperture extraction system and the absence of a magnetic field for focusing the ribbon electron beam of the emission electrode in the electron source with a plasma cathode. The optimal geometry of the multi-aperture system is found, which provides an increase in the beam current density while maintaining a high degree of its homogeneity.

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PLASMA SOURCES AND EQUIPMENT

INFLUENCE OF THE SPACE CHARGE OF AN ION BEAM ON THE TIME-OF-FLIGHT DIAGNOSTICS OF ITS COMPOSITION*

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The results of the time-of-flight diagnostics of the composition of high-intensity pulsed ion beams containing protons and heavy ions are presented. The experiments were performed on two types of ion diodes: an ion diode of focusing (see Fig. 1) and planar geometry in the mode of self-magnetic insulation of electrons (250-300 kV, 120 ns, 20-300 A/cm^2) and a focusing diode with external magnetic insulation (300 kV, 80 ns, 100-200 A/cm^2). We used a collimated Faraday cup with magnetic cut-off co-moving electrons as a recording device for ions, time resolution of which is one ns [1].

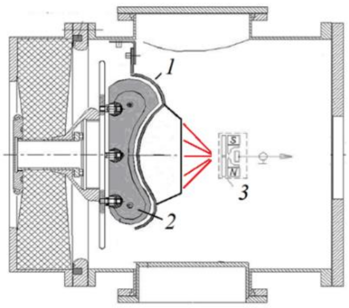

Fig. 1. Schematic of a diode chamber with a focusing diode (1 - cathode; 2 - anode; 3 - Faraday cup)

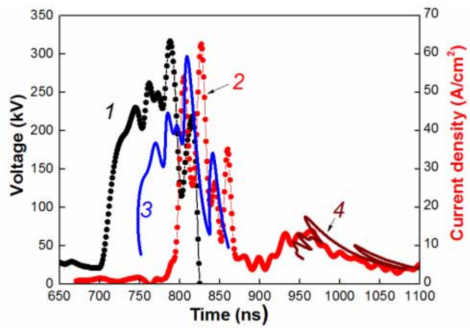

Fig. 2. Waveforms of accelerating voltage, second pulse (1); ion current density in the focus (2, points). Calculated current density of protons (3) and ions Cu^+ (4)

The time-of-flight diagnostics of pulsed ion beams, containing light ions (protons or deuterons [2]) and heavy ions (C^+ or Cu^+, N^+) showed a time delay in the experimental data of the light ions registration by the Faraday cup compared with the calculated values [1]. For an ion beam formed by a diode with planar and focusing geometry in the mode of self-magnetic insulation of electrons, the delay was 40-50 ns on the drift path of 14-16 cm with the ion energy of 250-300 keV. For an ion beam formed by a focusing diode in the mode of external magnetic insulation of electrons, the delay was 10–15 ns (on the drift path of 14 cm at the ion energy of 300 keV) and 16 ns (at the ion energy of 1 MeV on the drift path of 45 cm) [2]. Heavy ions are recorded by collimated Faraday cup before that predicted by calculation (see Fig. 2). With a low proton concentration, the delay in registration of heavy ions does not exceed the measurement error of the time-of-flight diagnostic.

It was shown that the delay of protons registration can be attributed to deceleration of light ions by a negative ion beam space charge during the transport from the diode to the collimated Faraday cup. In the studied ion diodes, the pulse duration of the accelerating voltage does not exceed 120 ns, and in ion beam drift path (10–16 cm) the total spatial separation of protons and heavy ions due to the difference in ion drift velocity occurred. The neutralization of the positive ions space charge by low-energy electrons is necessary condition for its efficient transport and focusing. Our studies have shown that low-energy electrons do not compensate the positive charge of the protons in the front of beam. However low-energy electrons compensate the positive charge of heavy ions; the concentration of the electrons is 1.3-1.5 times higher than that of ions, the total charge is negative. In the absence of an excess concentration of electrons in the ion beam, the delay in the registration of protons is absent. The effect of spatial compression of the ion beam in the direction of the drift increases its pulse power, but complicates the time-of-flight diagnostics of its composition.

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FILAMENTATION OF CURRENT-CARRYING PLASMA SHELLS *

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One of the most effective ways to obtain dense high-temperature plasma is the electromagnetic compression of a matter under the action of a current flowing through the matter. Various types of magnetohydrodynamic instabilities develop in a plasma with current, one of which is the filaments - separate current channels. It is assumed that the filaments result from the development of thermal instabilities, whose growth is determined by the nature of the dependence of the electrical conductivity on the thermodynamic parameters of the substance. If the conductivity increases with temperature, as it happens in plasma, the thermal instability should lead to the appearance of separate current channels [1]. In this paper, we analyzed the development of thermal instabilities in the process of plasma liners compression. Analysis of the growth of instabilities was based on the methods of the theory of small perturbations. The results of this theory were compared with the results of experiments [2] conducted on an IMRI-5 installation (current amplitude 450 kA, current rise time 500 ns).

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HOLLOW CATHODE PLASMA SOURCE BASED ON RING-SHAPED ANODE LAYER THRUSTER FOR PLASMA-OPTIC APPLICATIONS *

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The conceptual design of plasma source for plasma-optic application and materials modification are investigated. The source presented in this publication are based on plasma thruster's technology, that were developed by Prof. Goncharov group in Institute of Physics (Kiev, Ukraine) [1]. A specific feature of the presented plasma source is the relatively low magnetic field compared to conventional thrusters. As in the conventional anode-layer thrusters, there are two operational modes of discharge. The first mode is low current with narrow anode layer and clear-cut plasma flow, whereas the second mode operates with high current and plasma fills the entire volume of the hollow cathode. In low-current mode of the source operation, the axially converged ion beam are formed and, as follow from experiment, the energy of the ions could reach some kV. This operational mode can be used for argon or oxygen plasma cleaning as well as coating of outer pipe wall and cylindrical pieces.

The transition to the high-current mode occurs under variation of worked gas pressure and applied voltage. In high-current quasi-neutral plasma mode of operation, plasma jet is observed along system axis. This mode of the plasma source is suitable in a wide-aperture plasma optical system for the electron beam transporting [2].

For effective operation of devices, it is important to know their usage parameters, therefore the electrical characteristics of the discharge operated in different modes as well as the temporal evolution of the pulse current–voltage relations were studied in the feed rate of operating gasses (argon and nitrogen) range up to 20 sccm. The spatial distributions of plasma density and electron temperature of the high-current discharge mode were measured by using double Langmuir probe techniques. Electron temperature did not exceed 6 eV on hollow cathode's axis, and increased up to 7.5 eV in the vicinity of the anode. The maximum value of plasma density along the hollow cathode's centerline was 2×10^{12} 1/cm^3 for 5 A discharge current. Using a special collector, the measurements of the distribution in the plasma jet flowing along the axis of the hollow cathode were performed. The plasma jet is rather uniform over its cross-section.

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DEUTERIUM ION BEAM FORMATION AND ACCELERATION SYSTEM BASED ON A VACUUM ARC DISCHARGE WITH A GAS-SATURATED DEUTERATED CATHODE*

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Experimental studies on the formation and acceleration of deuterium ion beams using a vacuum arc with a zirconium cathode saturated by deuterium are presented. These experiments are a continuation of our earlier studies, in which we studied the mass-charge distribution of such a plasma with the aim of obtaining the maximum possible fraction of deuterium ions in it [1], investigated the angular and energy distributions of ions [2].

New experiments were carried out using a vacuum arc ion source MevvaV.Ru [3], in which a multi-aperture system for forming an ion beam was replaced with a string ion-optical system. Using a string ion-optical system instead of a multi-aperture one is more efficient in selecting ions from the discharge plasma in the string system, which made it possible to increase the total beam current of multiply charged ions, and, accordingly, the number of deuterium ions generated with the same discharge parameters. In addition, the use of a string system allows to improve the pumping of the anode cavity of the source, which ensures the reduction of impurity ions of the residual atmosphere in the ion beam.

Volt-ampere and emission characteristics of an ion source with a string ion-optical system with zirconium cathode saturated by deuterium were investigated, the radial distribution of the ion current density over the beam cross section was measured. These characteristics are compared with those obtained for a multi-aperture ion-optical system. It was shown that the divergence of the ion beam at an accelerating voltage of 30 kV was about ± 120 mrad, and as the accelerating voltage increased to 60 kV, the beam divergence decreased to values of ± 90 mrad. In this case, the total pulsed current of the ion beam reached values of 1.2 A and more. Earlier [1], we showed that even with a fraction of 40% deuterium atoms in the cathode, the fraction of deuterium ions in the vacuum arc plasma can reach more than 80%. On this basis, and taking into account that the average charge state of zirconium ions in the vacuum arc plasma is 2.5, it can be estimated that the total current of deuterium ions in a pulse can reach values of 0.7 A and more.

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EFFECT OF THE OUTER PLASMA SHELL ON THE FORMATION OF THE CURRENT SHEET IN THE Z-PINCH GAS-DISCHARGE PLASMA*

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Studies of the effect of the outer plasma shell on the formation of the current sheet in a Z-pinch plasma were carried out on the GIT-12 generator (4.7 MA, 1.7 μs) in the IHCE SB RAS, Tomsk. The experimental load was composed of neon, argon or deuterium gas puff surrounded by an outer plasma shell. The outer plasma shell consisting of hydrogen and carbon ions was formed by 48 plasma guns at the diameter of 350 mm. The main idea of using an outer plasma shell is to form a homogeneous, uniformly conducting layer at the beginning of the high current discharge to minimize the amount of matter not involved in the implosion process, and decrease current losses during implosion. Three single-turn B-dot probes, located at the different distances from the Z-pinch axis, gave us the information about the properties of the current sheet and its implosion dynamics. In the optical spectral range, the implosion dynamics was recorded with the help of a streak camera and a frame camera. The experimental data were compared with the motion of the center of the current sheet, obtained from the calculation of the dynamic inductance of the Z-pinch using electrophysical measurements of voltage and current. The optimization of the outer plasma shell injection parameters into the interelectrode gap by the K-shell radiation yield for argon and neon and the neutron yield for deuterium was carried out and compared with experiments without using an outer plasma shell.

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FORMATION OF PULSED LARGE-RADIUS ELECTRON BEAM IN THE FOREVACUUM PRESSURE RANGE BY A PLASMA-CATHODE SOURCE BASED ON ARC DISCHARGE*

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Wide industrial application of ceramics and polymers, which commonly do not conduct electrical current under normal conditions [1, 2], i.e. are dielectrics, requires development of new methods of dielectric materials` treatment. In particular, different methods of surface modification of ceramic and polymer materials are developed [3–5]. The forevacuum plasma-cathode sources of pulsed electron beams, operating in pressure range of 3–30 Pa [6, 7], provide surface modification of dielectric materials due to neutralization of negative charge on the dielectric surface by ions from beam-produced plasma, and by the non-self-maintained discharge between charged surface of the dielectric and grounded parts of a vacuum chamber [8]. Moreover, beam-produced plasma and ion flow from this plasma may also be used for surface treatment. For surface modification of high temperature materials, realization of modification by few (1–10) beam pulses, and some other application of beam, it is necessary to increase electron beam energy in pulse. In the forevacuum pressure range, increase of emission current (current density) and accelerating voltage are limited by breakdown of accelerating gap. Another way to achieve necessary beam energy in pulse is to increase pulse duration up to several milliseconds.

We have used an arc discharge with cathode spot (cathodic arc) for generation of emission plasma with millisecond pulse duration in the forevacuum plasma-cathode electron source. The cathode used in our experiments was made of copper and had diameter of 6 mm. To provide formation of large-radius electron beam, we have used a hollow anode made of stainless steel with height of 100 mm and diameter of 110 mm, and a redistribution electrode mounted inside the hollow anode. The emission plasma boundary has been stabilized by stainless steel fine mesh (emission electrode). The emission electrode and the mesh extractor have formed the accelerating gap. DC accelerating voltage up to 10–11 kV has been used to extract electrons from emission plasma and to form electron beam. Arc discharge current was up to 40 A at pulse duration of up to 10 ms. Influence of the redistributing electrode on the formation of emission plasma has been investigated. Influence of the redistributing electrode, geometry of emission electrode and extractor on electron beam formation in the forevacuum pressure range has been demonstrated.

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GENERATION OF FOCUSED HIGH-CURRENT ELECTRON BEAM WITH MILLISECOND PULSE DURATION BY A FOREVACUUM PLASMA-CATHODE ELECTRON SOURCE BASED ON CATHODIC ARC*

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Pulsed forevacuum plasma-cathode sources generate low-energy (usually no more than 15 keV) large-radius electron beams in the pressure range of 3–30 Pa [1, 2]. These sources provide direct surface processing of dielectric materials (ceramics and polymers) due to neutralization of negative charge on the treating dielectric surface by ion flow from beam-produced plasma and by the non-self-maintained discharge between charged surface and grounded parts of a vacuum chamber [3]. The pulsed large-radius electron beams are usually used for modification of relatively large areas, but there are applications dealing with local treatment of dielectric materials (local surface cleaning, local material evaporation, etc.). Currently, abrasive tools and laser beams are usually used for local treatment of dielectric materials [4–6]. Alternative method of local treatment of dielectrics may be realized by using focused low-energy pulsed electron beam generated in the forevacuum pressure range. In this case, for evaporation of high-temperature dielectrics (ceramics), high energy density per pulse of electron beam is required. Increase of the beam energy density per pulse may be provided by increase of electron beam current density and by increase of pulse duration.

Decrease of electron emission area to several millimeters has provided to generate focused electron beams with beam current up to 3–4 A in the forevacuum pressure range, but pulse duration has not exceed 300 μs, and operation gas pressure has not exceed 5 Pa due to breakdown of accelerating gap. Therefore, to increase the beam energy density per pulse we have used approach based on emission of electrons from relatively large area of plasma, stabilized by mesh electrode (the used radius of emission hole was up to 45 mm), and focusing of electron beam by magnetic field created by two coils. In the experiments, DC accelerating voltage was up to 10–11 kV, the beam current was up to 20 A at pulse duration of up to 5 ms. We have researched influence of geometry of the accelerating gap, magnetic field, gas pressure and gas type on generation of the focused electron beam in the forevacuum pressure range.

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DEVELOPMENT OF THREE-DIMENSIONAL SIMULATION OF DISCHARGE BREAKDOWN

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The phenomenon of electrical breakdown was studied using three-dimensional Particle-in-cell (PIC) code combined with Monte-Carlo simulated gas kinetics . This method has been used to analyze the basic properties of a dc glow and Penning discharges. Our model was verified on calculations of breakdown parameters for hydrogen Penning discharge and alumina vapor breakdown in vacuum. The simulation also shows the importance of three dimensional discharge modeling in transient regimes.

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THE MOTION OF THE PLASMA FLOW IN THE INTERELECTRODE GAP OF THE MAGNETICALLY INSULATED TRANSMISSION LINE*

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The implementation of the crowbar mode in a magnetically insulated transmission line (MITL) with the help of a plasma switch [1] is associated with the propagation of a plasma flow of a planar configuration in a transverse inhomogeneous magnetic field. The paper presents the results of an experiment on the injection of plasma bunches formed by a discharge in a dielectric capillary (see the proceedings of this conference) into the MITL interelectrode gap. Plasma was injected from an external ground electrode onto a central cathode electrode across a linearly increasing magnetic field. The dynamics of the plasma motion was recorded by the "Nanogate Frame-9" two-frame electron-optical complex with an exposure time of 20 ns. The moment of plasma bridging the interelectrode gap was recorded by changing the value of $L_t = U(t)/(dI/dt)$ according to the method described in [1] and two collimated Faraday cup placed inside the central electrode with an interval of 5 cm in radius. The change of the magnetic field magnitude at the time of the start of plasma injection was achieved by delaying the operation of plasma guns relative to the start of current in the MITL.

In fig. 1 shows the characteristic information obtained in a separate shot. Plasma guns with discharge in a polyethylene capillary (d = 1.5 mm, l = 10, 15 mm) with current Ipg = 7.4 kA (plasma bunch velocity without electromagnetic field $v1$ ~ 11 cm / µs) or Ipg = 13.4 kA ($v2$ ~ 13 cm / µs) and rise time 420 ns injected plasma into the crossed electromagnetic field of the MITL gap. The experiments were carried out for two operating modes of the MITL: mode 1 – $dB / dt \sim 5{\cdot}10^5$ T/s and the average cathode potential ~ 6 kV, mode 2 - at dB / dt ~ 8.2·105 T/s and cathode potential ~ 12 kV. The average bridging velocity of the MITL gap was taken as $v_k = \Delta_{A\text{-}C} / t_k$ ($\Delta_{A\text{-}C}$ = 4 cm), and B was taken as the average value $B = (\overline{B}^2)^{1/2}$ during time t_k. In mode 1 of the MITL for $v1$, with increasing B from 0.27 T to ~ 0.6 T, the speed v_k decrease from 7.5 cm / µs to 4.7 cm / µs. For $v2$, with an increase in B from 0.25 T to ~ 0.7 T, the speed v_k decrease from 8 cm / µs to 4.3 cm / µs almost linearly. In mode 2 of the MITL for $v2$ with increasing B from 0.54 T to ~ 0.9 T, the velocity v_k fell from 5.6 cm / µs to ~ 4.6 cm / µs. Optical diagnostics recorded an increase in the rate of penetration of plasma jets when moving to the cathode 1.2–1.3 times.

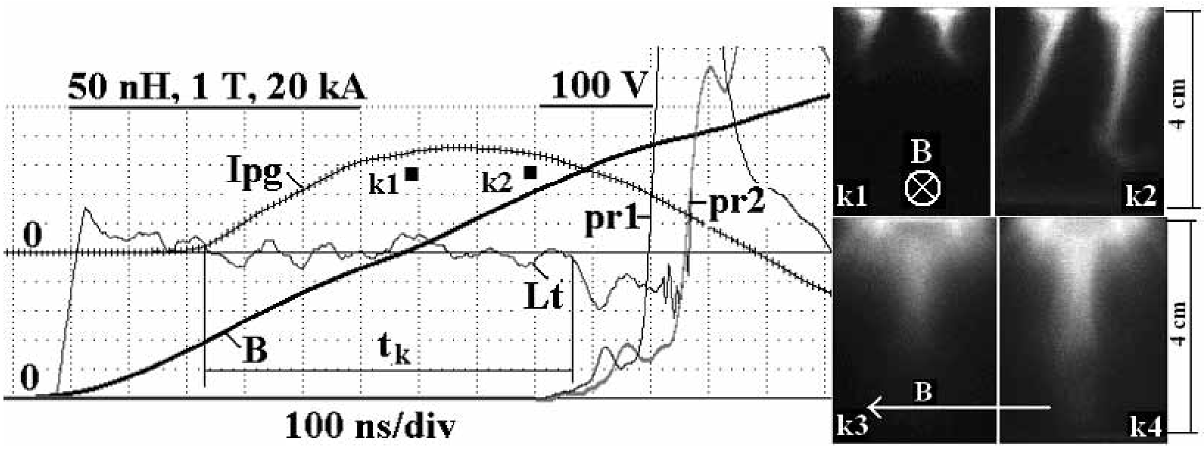

Fig. 1. Current waveform in the capillary *Ipg*, characteristic of the magnetic field in the gap *B(t)*, *Lt* value, signals from the Faraday cup pr1 and pr2, t_k – switching time of the interelectrode gap, squares k1 and k2 – frame timing "Nanogate 2". On the right, there are k1, k2 "Nanogate 2" frames, taken with an exposure of 20 ns and an interval of 200 ns, (k3, k4 – frames with "Nanogate 2" under similar conditions when changing the direction of the magnetic field).

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THE MAIN PLASMA'S PARAMETERS OF A VACUUM INSTALLATION BASED ON LOW-PRESSURE VACUUM-ARC AND MAGNETRON DISCHARGES*

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A new type of plasma chemical reactor [1] based on reconstruction the standard vacuum chamber of the serial installation VU-1B was developed to carry out the deposition process of TiN-Cu nanocrystalline composite coatings. The structural scheme of the vacuum installation VU-1B is shown in figure 1 [2]. This plasma chemical reactor is based on the principle of Cu vapors metered injection into the region of chemical reaction Ti and N through a diaphragm's metering orifice. This diaphragm shield the penetration of titanium vapors to the cathode of the magnetron discharge (Fig. 1). Synthesis of composite TiN-Cu coatings on a substrate takes place with their concomitant modification by bombardment with low-energy ions of the plasma-forming gas (nitrogen) and titanium.

A comprehensive study of gas plasma generated by vacuum-arc and magnetron low-pressure discharges was a purpose of this paper. A single cylindrical Langmuir probe was used to research the plasma [3]. The probe had located directly on the axes of the planar magnetron, as well as the electric arc evaporator and at a different distance (from 45mm to 300mm) from the sources output apertures. In nitrogen atmosphere the measurements of plasma parameters were carried out. The probe characteristic was taken for each selected mode by which the floating potential, potential of plasma and electron's temperature were determined graphically. Further some results of measurements are given, in particular, it is given the magnetron's discharge current-voltage diagram at different values of the magnetron discharge current and constant pressure [Fig. 2].

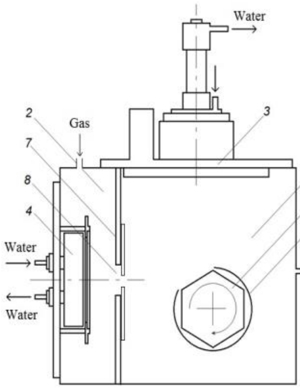

Fig. 1. The schematic diagram of the plasma-chemical reactor: 1-compartment of chemical reaction between Ti and N, 2-compartment of Cu vaporization, 3-arc evaporator of Ti, 4-planar magnetron with the copper cathode, 5-substrate holder, 6-shield, 7-diaphragm, and 8-metering orifice

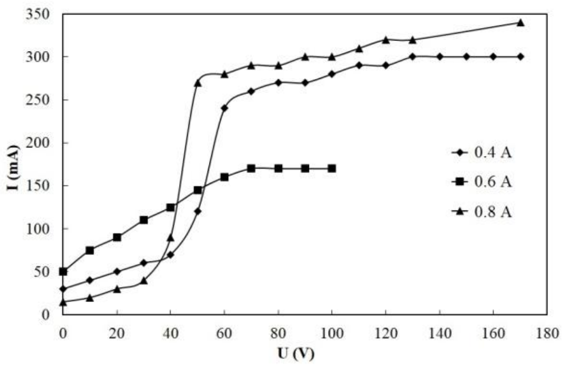

Fig. 2. The current-voltage diagram of magnetron discharge (P=8x10^{-3} Torr)

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GAS-DISCHARGE HIGH-FREQUENCY GENERATORS FOR MATERIAL PROCESSING

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The progress of acousto-and opto-electronics imposes heavy demands on the process of ionic etching of multicomponent materials, particularly, on piezoelectric crystals, that can not be etched using traditional gas and liquid etching methods [1]. The methods of the problem solution can be based on isolation of a high-frequency component of an electric field out of plasma for removal of displacement currents and recharging,. The investigated model (Fig 1) contains a plasma generator, formed by a ring cathode 1 and a housing 2, placed in a magnetic field. The housing is closed by a multicellular expander 3.

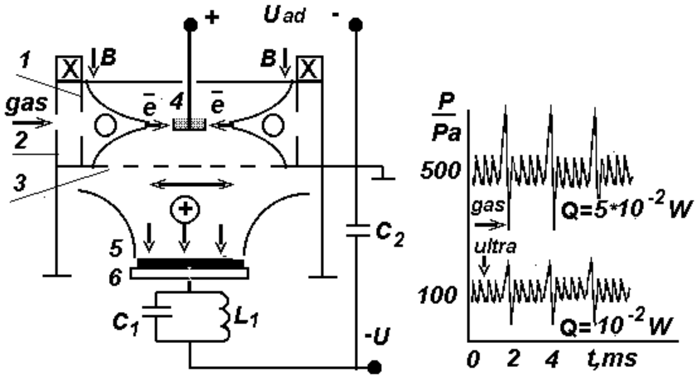

Fig. 1. Gas-discharge high-frequency generators

The operating chamber is evacuated down to pressure 0.1 Pa. Application of 600-800 V voltage to the plasma generator induces an auxiliary discharge in it (U_{ad}) with the current up to 1 A. The anode (crucible 4 with lithium niobate) is heated by intensive electron bombardment. The vaporous plasma of evaporated material enters the operating chamber through the expander cells. An extracting voltage (-U) of the order 3 KV with current up to 70 mA is applied to the electrode 6. A sample 5 is heated during 15 minutes to the temperature 600 K. The discharge voltage is increased up to 10-14 KV, and discharge current is decreased to 30 mA. Plasmoid rotation under the influence of an magnetic field and its interaction with an expander create conditions for periodic plasma penetration through the expander cells and generation of local inhomogeneities of the plasma density. This leads to stationary spatial instability of a high-voltage beam discharge. The inductive - capacitate circuit (C_1L_1) isolates a high- frequency component of an electric field with the frequency 5 MHz. This helps to remove a space charge from a lithium niobate sample surface at the expense of displacement current and recharging.

Simulation of etching on lithium niobate provides the etching speed of 5 mcm/h with the ion current density 0,5 mA/cm^2.

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FORMATION OF POWERFUL PLASMA FLOW FROM SUBSTANCE OF LIQUID ELECTROLYTE CATHODE*

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Plasma is formed predominantly from a liquid phase substance when using a liquid electrolyte as a cathode. Such a plasma is promising for creating a high-temperature vapor-gas medium in plasma-chemical reactors designed for energy-intensive plasma technologies, in particular, for the conversion of hydrocarbons into synthesis gas [1, 2]. To solve the problems of practical application requires research in the power range of tens of kilowatts. The aim of this work was to obtain a plasma flow of such capacities.

To create a plasma flow, plasma generator with a liquid electrolyte cathode and metal anode was developed. The walls of the generator discharge chamber were made of refractory material. As a liquid electrolyte cathode, aqueous solutions of sodium chloride with concentrations of 0.1-0.2 mol/l were used.

The distance between the liquid cathode and the metal anode was 20 cm. The power source was a three-phase, full-wave rectifier connected to the secondary windings of the step-up transformer. The voltage ripples was smoothed with a C-L-C filter. To study the energy characteristics, the technique described in paper [3] was used. The current was changed by the stepwise variation of the ballast resistor. It should be noted that the ballast resistor is not a required element in the electrical supply circuit. The plasma generator has an increasing current-voltage characteristic (fig. 1) and, therefore, its operating modes were stable at zero electrical resistance of the ballast resistor.

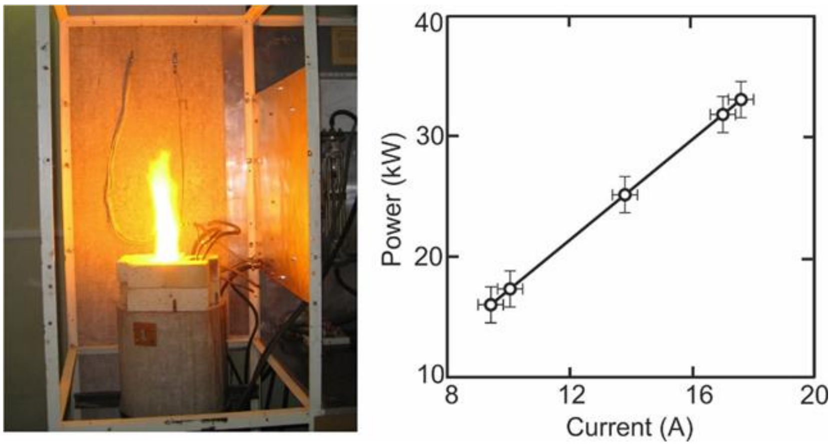

Fig. 1. Photo of the plasma flow at the exit of the plasma generator (energy consumption 30 kW) and graph of dependence of power from discharge current

During the operation of plasma generator, part of electrolyte was spent on the formation of plasma flow. The electrolyte loss was compensated by the addition of distilled water. In this case, the energy characteristics of plasma generator remained almost unchanged.

The paper studies the influence of electrolyte flow regimes through the cathode assembly on plasma flow formation.

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GENERATION OF TWO-COMPONENT BEAMS OF METAL IONS BASED ON VACUUM ARC WITH COPPER-CHROME CATHODE*

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PLASMA SOURCES AND EQUIPMENT

The beams of metal ions generated in vacuum arc sources are widely used to improve the properties of the surface by the method of ion modification [1, 2]. The use of cathodes of complex composition in the sources allows one to obtain beams containing several types of ions. This expands the technological capabilities of vacuum arc ion sources and allows simultaneous processing of ions of various types to create complex alloys in the modified surface. The generation of two-component beams of metal ions in a vacuum arc source was investigated on a copper-chromium cathode model material available and widely used in industry. Composite cathodes with different contents of these metals were used. It is shown that a change in the proportion of metal ions in the cathode can be used to regulate the fraction of ions of these materials in the ion beam. The presented results may be useful in practice, for example, to modify the electrodes surface of dischargers and to create copper-chrome alloys in their surface with different proportions.

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GENERATION OF BEAM MULTICHARGED IONS OF BISMUTH*

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Beams of multicharged ions can be widely used both for physical research problems and for practice. Vacuum arc ion sources are currently considered promising for the generation of pulsed wide-aperture beams of multiply charged metal ions. At the moment, several methods have been developed and implemented to increase the charge states of ion beams in sources: by imposing a strong magnetic field on the cathode region of the vacuum arc [1]; with modulation of the discharge current [2]; when a dense electron beam is injected into a plasma [3]; with additional heating of the plasma in an open magnetic trap using microwave radiation from a powerful gyrotron [4]; as well as the implementation of a high-current arc with a short pulse duration [5]. This paper presents new results in the implementation of the last method.

At optimal discharge parameters (arc current levels of 3.5 kA and pulse duration of 400 ns), beams of bismuth ions with record charge states were obtained. The maximum charge of bismuth ions reached 19+. The results of the parameters optimization of the high-energy beams of -multicharged bismuth ions with ion energy in a beam reaching 1 MeV with an accelerating voltage of 60 kV are presented. The possibility of using such beams for surface modification of materials is discussed.

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COMPUTER SIMULATION OF ION BEAM-PLASMA INTERACTION*

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In the paper a two-dimensional axisymmetric hybrid numerical model of the interaction of an ion beam with a plasma is presented. The model is based on the kinetic approximation for the ions whereas the electrons are assumed to be a fluid [1]. To solve the Vlasov kinetic equation, the author's modification of the particle in cells method (PIC) is used [2]. The issues of accuracy and convergence of the created algorithms and the possibility of their implementation on the computing systems of modern architecture are discussed. It was shown that the magnetic flux can be expelled from the volume filled by the plasma due to the plasma-beam interaction. The dynamics of the magnetic field cavity formation depending on the characteristics of the ion beam and the background plasma is investigated. The comparison of the computer simulation results and the analytical assessments [3] has been done.

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A NEW TYPE OF NON-THERMAL ATMOSPHERIC PRESSURE PLASMAS SOURCE.

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The unique applications of Non-Thermal Atmospheric pressure Plasmas (NTAP) are associated with its enormous potential for providing technological capabilities for new products and technologies. In such plasmas, most of the electrical energy is deposited in the electron component of the plasma, while plasma ions and neutral components remain at or near room temperature, this allows the use of such a “cold” plasma for low-temperature plasma chemistry and for treating heat-sensitive materials, including polymers and biological tissues [1, 2]. Typical examples of NTAP sources are: corona discharge, glow discharge, dielectric barrier discharge (DBD) and non-thermal plasma jet (NTPJ).

DBD is a sequence of fast-flowing micro-discharges in a gas with a duration of several to tens of nanoseconds, when at least one of the electrodes is separated from the gas by a dielectric barrier made of glass, quartz, ceramic or polymeric materials. A distinctive feature of NTPJ sources is their ability to launch a thin jet of non-thermal plasma (based on discharge in argon or in helium) up to several centimeters in the external environment, where the electric field can be very low.

Figure 1 on the left shows the NTAP source, which combines the attributes of DBD (by discharge configuration) and NTPJ (by plasma jet formation).

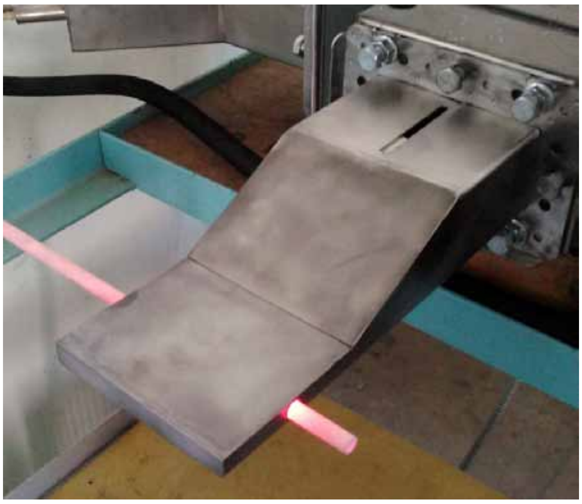

Fig. 1. Waveguide source NTAP with a ceramic discharge tube (left).
The moment of testing the non-temperature properties of an Argon plasma jet formed in a glass tube (right).

This device is a segment of a rectangular waveguide, short-circuited at the end and diaphragmed at the beginning, operating on the basic type of oscillations H_{01} [3]. The length of the segment is chosen close to the resonance. In the nearest to the short-range maximum field across the waveguide is placed discharge tube so that its axis is perpendicular to the electric field vector (DBD configuration). In this zone, the height of the waveguide is reduced to increase the E-field strength. Quartz, ceramics and glass were tested as the material of the discharge tube.

The advantage of the proposed device in comparison with DBD is the possibility of forming a stable long and thin plasma jet (Fig. 1 right). And unlike NTPJ, where the power consumed by the discharge is only a few tens of watts, in our device the microwave power supplied to the discharge can reach several kW.

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IMPROVING THE PERFORMANCE OF N_2 LASER WITH LONGITUDINAL DISCHARGE*

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The results of a study of an electric-discharge N2 laser pumped by a longitudinal discharge are presented. The discharge tube consisted of two sections 200 mm long and had a diameter of 18 mm into which nitrogen was blown at a pressure of 6-18 Torr. As a pump generator, an LC - inverter with a shock capacity of 4 nF was used, which was connected to a discharge tube through a coaxial cable, in parallel to which a peaking capacitance of 3.8 nF was placed. As a high-voltage switch, a TPI 10k / 20 brand tiratron was used. The charging voltage was 22-24 kV.

The main problems that arise in such lasers are to collapse the diffuse discharge with increasing discharge current density, which limits the amount of specific pump power and, accordingly, the output radiation energy. The use of various types of current interrupters providing an increase in the charging voltage to ~70 kV on the electrodes [1] or the installation of additional spark gaps for UV-preionisation of the discharge region [2] did not significantly increase the generation energy of the nitrogen laser, which was within 0.1-0.3 mJ, at a pulse duration of ~ 5 ns.

In our experiments to improve the stability of the diffuse discharge at higher values of the specific pumping power, a beam of runaway electrons was used both for preionizing the discharge volume and for the formation of the diffuse discharge. The generation of runaway electrons in the gas gap occurred when a high voltage (~ 25 kV) was applied to electrodes in the form of rings that had a sharply inhomogeneous electric field near their surface. The forming electron beam in the near-cathode region provided a good degree and homogeneity of pre-ionization, which allowed at the initial field strength on the gas tube E = 1.25 kV/cm, to realize in the diffuse discharge the maximum current density of 2-3 kA/cm^2, with a maximum specific pumping power of ~ 3 MW/cm^3.

The laser generation duration was equal to the pump pulse duration. At a wavelength of ~ 337.1 nm, radiation pulses with an energy of up to 3 mJ and a duration of up to 20 ns (FWHM) were obtained. Stability of discharge characteristics and generated radiation was maintained during laser operation at a frequency of up to 30 Hz [3].

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SPECTRAL CHARACTERISTICS OF ATMOSPHERIC PLASMA RF DISCHARGE AND LASER RADIATION PHILAMENT*

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Experimental studies of the spectral characteristics of plasma in the air of an RF discharge and in a filament of femtosecond laser radiation are presented. The ignition voltage of the high-frequency discharge had a sinusoidal shape with an amplitude of 10 kV, a discharge current amplitude of 2 mA, an oscillation frequency of 30 kHz. A filament in air arose during self-focusing of a 50-fs laser pulse with an intensity maximum at a wavelength of 950 nm.

In the emission spectrum of a plasma ignited by an RF discharge, emission bands of excited molecular nitrogen I, II of the positive system and N_2^+ I ions of the negative system are recorded. In the spectral range 200–280 nm, the fluorescence of $NO(A^2\Sigma^+–X^2\Pi, \nu_A=0)$ molecules is observed. In this type of discharge, the presence of excited neutral molecules $N_2(C^3\Pi_u, B^3\Pi_g)$ and ions of molecules $N_2^+(B^2\Sigma^+)$ is due to associative reactions of molecules $N_2(A^3\Sigma^+_u)$. Metastable states of $N_2(A^3\Sigma^+_u)$ molecules are formed in the afterglow in reactions between vibrationally excited ground state molecules $N_2(X^1\Sigma^+_g, \nu>39)$ and $N(^4S)$ atoms [1].

$N_2(X^1\Sigma^+_g, \nu>38) + N(^4S) \rightarrow N_2(A^3\Sigma^+_u, a'^1\Sigma^-_u) + N(^2D)$ $\quad k=10^{-11}\ cm^3s^{-1}$

$N_2(A^3\Sigma^+_u) + N_2(A^3\Sigma^+_u) \rightarrow N_2(C^3\Pi_u, B^3\Pi_g) + N_2(X^1\Sigma^+_g)$ $\quad k=1.5x10^{-10}\ cm^3s^{-1}$

$N_2(A^3\Sigma^+_u) + N_2(a'^1\Sigma^-_u) \rightarrow N_2^+(X^2\Sigma^+) + N_2(X^1\Sigma^+_g) + e$ $\quad k=0.1x10^{-11}\ cm^3s^{-1}$

The formation of nitric oxide $NO(X^2\Pi)$ in the atmospheric plasma of a high-frequency discharge is due to the presence of a high gas temperature, according to the Zeldovich mechanism. Due to the intermolecular interaction of the ground state molecules $NO(X^2\Pi)$ with molecules $N_2(A^3\Sigma^+_u)$, the formation of $NO(A^2\Sigma^+)$ molecules occurs.

$N_2(A^3\Sigma^+_u) + NO(X^2\Pi) \rightarrow NO(A^2\Sigma^+) + N_2(X^1\Sigma^+_g)$ $\quad k=7.0x10^{-11}\ cm^3s^{-1}$

On the plasma emission spectrum of fs laser radiation arising in the filament, neutral excited molecules $N_2(C^3\Pi_u, B^3\Pi_g)$ and ions of the molecules $N_2^+(B^2\Sigma^+)$ are recorded. The presence of excited molecules and ions of molecular nitrogen is due to the processes of multiphoton absorption and recombination with electrons. $NO(X^2\Pi)$ molecules are formed in the reactions of interaction between excited $N(^4S)$ atoms and O_2 molecules. The formation of $NO(A^2\Sigma^+)$ molecules occurs during the lifetime of the filament plasma due to inelastic collisions of $NO(X^2\Pi)$ molecules with electrons having an energy of ~ 5.5 eV [2].

$N_2(X^1\Sigma^+_g) + n\times h\nu \rightarrow N_2^+(B^2\Sigma^+)$; $N_2^+(B^2\Sigma^+) + N_2(X^1\Sigma^+_g) \rightarrow N_4^+$;

$N_4^+ + e \rightarrow N_2(A^3\Sigma^+_u, C^3\Pi_u, B^3\Pi_g) + N_2(X^1\Sigma^+_g)$

$N_2(A^3\Sigma^+_u) + O(^3P) \rightarrow NO(X^2\Pi) + N(^2D)$ $\quad k=7.0x10^{-12}\ cm^3s^{-1}$

$N(^2D) + O_2 \rightarrow NO(X^2\Pi) + O(^1D)$ $\quad k=6.0x10^{-12}\ cm^3s^{-1}$

$NO(X^2\Pi) + e \rightarrow NO(A^2\Sigma^+)$ $\quad \Delta E=5,5$ эВ

Consequently, the existing mechanisms for the formation of $NO(A^2\Sigma^+)$ molecules in the filament plasma are less efficient than in the RF discharge plasma, which is also confirmed by a significantly lower luminescence intensity of the molecule NO $(A^2\Sigma^+–X^2\Pi, \nu_A=0)$ in the filament.

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PLASMA SOURCES AND EQUIPMENT

LAUNCH OF LOWER HYBRID WAVES TO A DENSE PLASMA COLUMN IN A STRONG MAGNETIC FIELD

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Modern open magnetic facilities for fusion research confine hydrogen plasma with densities form 10^{19} to 10^{21} m^{-3} in magnetic fields from 0.1 to 10 Tesla. Usually start-up plasmas in these facilities are created using plasma guns. Alternative sources of plasma are electron guns and several types of in-chamber discharges [1]. A DC discharge with plasma contacted with walls has some disadvantages for fusion experiments. Indeed, plasma temperature is decreasing and wall material contaminate discharge by heavy elements when the plasma touching chamber. Electrodeless plasma sources does not have such weakness.

In other hand, helicon sources based on magnetized discharge are widely used as low temperature plasma sources in plasma technologies [2]. They produce highly ionized, pure plasmas in magnetic fields 10-100 Gauss, using 10-100 MHz electromagnetic waves. Densities of this plasmas can reach 10^{19} m^{-3} but usually lower densities are used for plasma deposition or etching.

Application of helicon sources for producing start-up plasma in modern open facilities is good way to improve quality of the plasma. Increasing magnetic field strength lead to increasing lower hybrid resonance frequency Ω_{LHR} (1), which is equal to 1.4 GHz for target plasma parameters – plasma density is 10^{20} m^{-3} and magnetic field 3 Tesla. If one construct plasma source based on low hybrid waves frequency of the source should be lifted from MHz to GHz band.

$$\Omega_{LHR} = \sqrt{{\Omega_i}^2 + \frac{(\omega_{\text{pi}} * \Omega_e)^2}{{\omega_{\text{pe}}}^2 + {\Omega_e}^2}} \tag{1}$$

Effective and respectively cheap industrial sources – magnetrons working on 2.45 GHz and 915 MHz are suitable for use in this band. Wavelengths of these waves make waveguides more suitable for power transportation.

New open facility GOL-NB is under construction in Budker Institute of Nuclear Physics. Main goal of the GOL-NB facility [3] is study of plasma confinement in axially-symmetric linear trap with multiple-mirror sections. The facility consist of central trap with 0.3 T magnetic field strength, two multiple-mirror sections with corrugated or uniform field with maximal strength 4.5 T and mirror ratio 1.5. Arc discharge plasma gun was chosen as start-up source for this machine. Alternative way for creating plasma is helicon discharge in multiple-mirror section.

Experimental study of coupling of low-frequency electromagnetic waves with plasma in strong magnetic field was done on GOL-3 facility in 2015-2017 [4]. RF source based on industrial 2,45 GHz magnetron and simple ring capacitor antenna were chosen for first stage. Plasma was created by external source – plasma gun. Different types of antennae with enveloping conductors were measured and it was found that efficiency of power coupling about 50%.

New system for launch electromagnetic waves in low hybrid range is based on simple waveguide design with slot antenna placed on front side of the waveguide. In the work we will present results of simulation of whole RF system and first experimental results of launching of microwave power to GOL-NB facility.

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STUDY OF IGNITION AND BURNING OF PARTIAL DISCHARGE AT LOW VOLTAGE IN THE PRESENCE OF ELECTROLYTES

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Fig. 1 shows an experimental setup, which is a spark plug which has been filled with electrolyte (1.5% NaCl in water solution) to a level of 4.

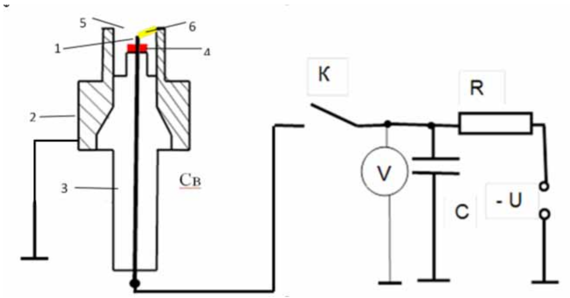

Figure 1. Scheme for generation of a partial discharge spark automotive: -U - constant voltage source 0 - 1000 V, R - resistance in the charging circuit, V - digital voltmeter, K – switch, Cв - automotive spark 1 - electrode 2 - electrode grounded, 3 - dielectric 4- place ignition incomplete PD, 5 - discharge gap, 6 - place ignition completed partial discharge.

The first stage PD - uncomplete discharge, shown in Fig. 2. It represents the current through the electrolyte surface, which heats and vaporizes a portion thereof, thereby initiating the formation of arcs which are further extended, covering the entire face. In fact, the incomplete discharge lasts about 10^{-1}s - capacitor discharge time constant. The discharge has a reddish color. Voltage of incomplete discharge ignition is about 600 V

Figure 2. The uncomplete partial discharge

Figure 3 Complete partial discharge

When the voltage reaches 730V, completed partial discharge occurs (Fig. 3), followed by bright white flash and a loud sound. Discharge time - less than 10^{-2} s. It seems that there has been a breakdown between the electrodes through the air. But 730V potential difference is insufficient to breakdown the interelectrode gap of 3 mm. In our opinion this is an incomplete discharge of its ultraviolet radiation initiates the breakdown in the air. Complete discharge current regulated ballast resistance Rb in the circuit automotive spark power.

Experiments with power rectified voltage from the voltage doubler circuit were also held. Figures 4 and 5 show the development of processes of incomplete and complete discharges, powered by the rectification circuit voltage doubler

Figure 4 (left). Incomplete partial discharge when supplied with rectified current. U = 600V, Rb >>100 ohm

Figure 5 (right). Complete partial discharge when supplied with rectified current. U = 600V, Rb <100 Ohm

MICROWAVE COMPLEX FOR OBTAINING LOW-TEMPERATURE PLASMA AT ATMOSPHERIC PRESSURE

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Over the past two decades, the scientific and technical community has made significant efforts to develop, maintain and use atmospheric non-thermal plasma (ANTP) in which ions and neutral components remain at or near room temperature [1,2]. The purpose of this work is to present a universal hardware complex, designed to generate both traditional low-temperature plasma and two types of ANTP in the R&D works on new materials and technologies, and also to intensify existing technological processes.

A hardware complex was designed and manufactured to produce low-temperature and/or non-thermal microwave plasma at atmospheric pressure. Non-thermal plasmas are generated by a diversity of microwave discharges such as dielectric barrier discharges (DBD), atmospheric pressure plasma jet (APPJ) and atmospheric pressure Argon streamer plasma. The equipment includes three types of applicators, waveguide/coax splitter, cable assembly and water load.

The hardware complex in the basic configuration consists of a microwave generator with HV power supply, a set of replaceable elements of the waveguide system, a water load, a 50 Ω cable assembly with N-connectors and one or several ANTP applicators (Fig. 1 left).

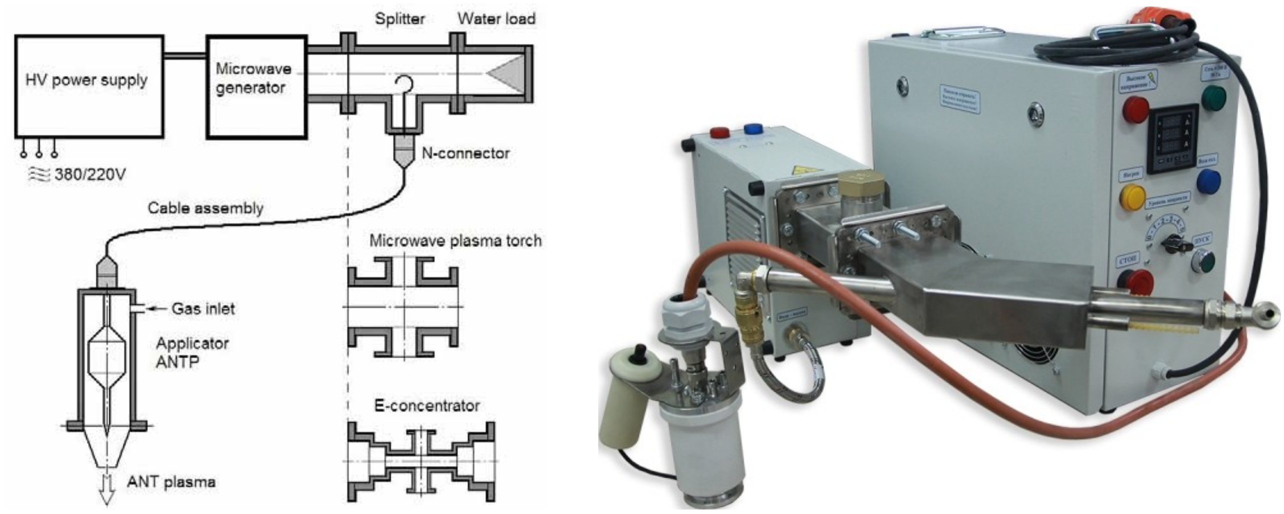

Fig. 1. Schematic diagram of components and blocks of the hardware complex (left).
The general view of universal hardware complex for obtaining of low-temperature and ANT plasma (right).

The basis of the presented hardware complex is a low-budget the 2.45 GHz magnetron microwave oscillator with a high-voltage power unit built on the magnetrons, transformers and capacitors used in microwave ovens for domestic and industrial use [3]. Between the output of the microwave generator and the load, the waveguide path elements from the next set can be placed. The microwave plasma torch on the main type H01 oscillations [4], E-field concentrator and an inductive-type splitter. ANTP applicator is connected to the splitter using a cable assembly.

The general view of the universal hardware complex of variable configuration for generation low-temperature microwave plasma at atmospheric pressure is shown in Fig. 1 (right). It is designed for both laboratory and industrial applications.

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SPECTRAL MEASUREMENTS IN THE PLASMA OF MICROWAVE AND MAGNETRON DISCHARGES

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1. The characteristics of Ar plasma emission of a low-pressure discharge (6-40 Pa) based on a household microwave (radiation frequency is 2.45 GHz, power is 800 W) oven are investigated. Spectrum measurements were performed using an AvaSpec 2048 fiber spectrometer in different sections of the working volume. It is shown that the intensity distribution of the Ar I and ArII lines is very non-uniform, namely, the maximum intensity is recorded near the chamber wall closest to the microwave emitter (position X_1 in Figure 1), the minimum is recorded in the middle section (position X_2) and the non-significant rise is recorded nearby the far wall (position X_3). Measurements of the degree of radiation coloration of LiF crystal samples placed in the plasma of this discharge at different distances from the microwave emitter showed that the staining profile correlates with spectral measurements. Consequently, the mechanism of coloration is due precisely to the bombardment of the crystal surface with plasma electron.

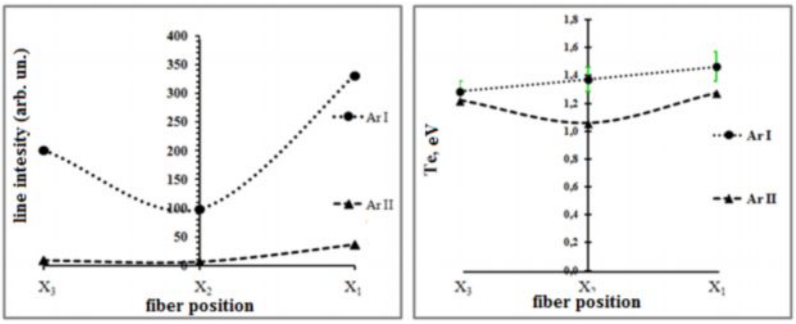

Figure 1. Distribution over the cross section of the working volume of intensity of the brightest spectral lines of argon (a) and the electron temperature determined from them (b). The coordinates xi correspond to the positions of the fiber shown in Fig. 3. P = 0.13 Torr

2. Similar spectral measurements were performed in a magnetron discharge plasma (current 250 mA, power 100 W). The dependence of the line intensity of the cathode materials (copper) and the buffer gas (argon) on the distance to the cathode-target is measured. It is shown that the intensity of the latter one drops significantly faster. This suggests that with a distance from the target, the concentration of atoms and argon ions also rapidly decreases, and their effect on the deposited film decreases, in particular, heating and defect formation. From the relative intensity of the lines, the excitation temperature of the plasma components was calculated in the framework of the model of local thermodynamic equilibrium (LTE) and the coronal model. It is shown that the temperature of all components () in the first case lies in the range of 0.6–1.2 eV; in the second case, it lies in the range of 0.7–1.4 eV and does not depend on the distance from the cathode. Thus, the LTE model can be used to estimate the plasma temperature in a given parameter range despite the violation of its applicability conditions for this case.

PLASMA EMISSION DURING COMBUSTION OF NI-AL POWDER MIXTURE

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The ionization ability of combustion reactions is well known and currently applied for magnetodynamic conversion of the energy of natural fuels. The formation of gas plasma in high-temperature combustion waves is caused by the volume thermo-and chemo-ionization of gaseous reaction products, as well as by the thermo-and chemo-stimulated emission of ions and electrons from the free surface of reacting condensed phases. The latter processes are the main source of gas ionization during the combustion of a number of heterogeneous systems (metal-metal powder mixtures, carbon, etc.) forming condensed products (intermetallic compounds, carbides, etc.).

In this case, substantially nonequilibrium states of the gas flowing from the reacting sample are observed: the excitation of the electron temperature up to 80000 K (Ti-Si system [1]) and energy spectrum of free electrons up to 60 eV (Ni-Al system [2]); second multiplicity ionization of metals (Ti-B, Zr-B systems [3]). Such systems are interesting as an autonomous chemical source of a concentrated stream of charged particles, for example, as a plasma cathode for gas discharge, however, their emission properties have not been fully studied.

In this work, plasma emission was studied during the combustion of a Ni + 31.5wt.% Al powder mixture. Reaction was conducted according to the scheme Ni + Al → NiAl + 117.7 kJ/mol under an argon atmosphere at a pressure of 10÷ 100 kPa. Nickel (PNC-UH1, with a purity of 99.85wt.% and a particle size not more than 20 μm) and aluminum (ASD-4, with a purity of 99.7wt.% and a particle size not more than 10 μm) were used as components of the mixture. The shape of the samples was as follows: cylinders 20 mm in height and 20 mm in diameter, with a porosity of 40%. An electric probe in the form of a tungsten wire with a diameter of 0.2 mm was placed at a distance of 1.5÷2.0 mm from the sample surface inside a special cavity. An alternating voltage with an amplitude of 1.5÷400 V and a frequency of 50÷1000 Hz was supplied through an electrical circuit with a reference 200 Ω and ballast 2 ÷ 74 kΩ resistances.

Combustion was initiated by the heated electrospiral and monitored by video recording. Electric current proportional to the degree of gas ionization appeared between the sample and the probe during the propagation of combustion in the circuit. The current signals in the circuit (i) and the probe voltage (V) were transmitted through a high-speed analog-to-digital converter (data acquisition frequency is 10 MHz) to the computer and processed as a set of current-voltage characteristics (CVC) of the probe for different times relative at the moment when the current appeared. The electron temperature of emission plasma (T_e) was determined by the Langmuir method [4]. For the positive steep part of the CVC with a voltage amplitude of 15V, the experimental data were interpolated by a linear function $\ln i = a + bV$. The electron temperature was calculated by the formula: $T_e = e(kb)^{-1}$, where e - electron charge, k - Boltzmann constant.

The experiments have shown that combustion propagates with a linear velocity of 4.6 cm/s. When the reaction wave passes by the probe for the time t <50 ms, the electron temperature of emission plasma increases to the level T_e = 14000 K. It is significantly higher than the equilibrium adiabatic combustion temperature of the mixture Ni + 31.5wt.% Al (T_c= 1911 K [5]). In the interval $t = t^* \approx 50 \div 500$ ms, the T_e value decreases and approaches T_c in the interval $t = t^*$> 500 ms. It can be concluded that the intervals t^*, t^{**} correspond to the modes of chemo-stimulated and thermal emission of charged particles. Analysis of the CVC shows that with increasing the voltage up to 400 V, the current reaches 0.2 A, while the gas discharge between the sample and the probe changes from non-self-sustaining to different forms of self-sustaining discharge: Townsend, abnormal glow, and spark. The first form takes place only with the support of chemo-stimulated emission of charged particles from the reacting sample (interval t^*).

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CALCULATION MODEL OF THE PLASMA LOAD MATCHING WITH THE CURRENT SOURCES BASED ON EXPLOSIVE MAGNETIC GENERATOR [*]

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The need for efficient energy supply of pulsed plasma loads imposes strict requirements on the front and amplitude of the current generated in the load [1]. Investigations of a pulsed current source based on an explosive generator (EMG) show its advantages over a capacitive storage device primarily due to the growing character of the power of this type of current source. The experiments presented in [2] confirm this fact. However, it should be noted that a correct engineering calculation of the parameters of the EMG and matching of its work with a variable plasma load are required for the implementation of these advantages in practice at the design stage of the system. The need for such models is especially great for explosive experiments with EMG, which are relatively expensive.

The use of electrical models for the analysis of linear circuits is impossible in this case because of the pulsed character of the sources, and nonlinear dynamics of current – voltage characteristics of the plasma load. The main nonlinearity is related to the change in space and time of the current shell shape of the plasma in the load, which is mainly inductive. At the same time, magneto hydrodynamic calculation for spatial geometry is complicated and provides extra information for engineering and design engineering. In this paper, the problem is considered for the matching scheme of EMG and pulsed plasma accelerator at the amplitudes of discharge current up to 2.5 MA. Experiments have shown that the dynamics of the inductance of the load is a critical parameter in this problem. Due to the self-consistency of the parameters of the system, which includes an explosive generator, switching elements and plasma load, the calculation of the pulse current in engineering models requires reliable assumptions. The main assumption taken as a basis in this model is the use of a time-dependent shell model with a concentrated mass. The specified simplification allows us to reduce the model of the motion of the current sheath to a one-dimensional model of the motion of the concentrated mass used, which greatly simplifies performing a series of calculations and optimization design of EMG under a specific load. The dynamics of the shell mass change is consistent with the experimental data.

The obtained data are compared with experimental data obtained in real experiments with the pulsed plasma accelerator powered from EMG. It is shown that the built model has sufficient accuracy for preliminary calculations of matching the operation of the EMG with the dynamics of the plasma accelerator.

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PLASMA SOURCES AND EQUIPMENT

INFLUENCE OF THE HOLES DIAMETER IN THE PERFORATED ELECTRODE ON THE PARAMETERS OF ELECTRON BEAM GENERATED BY FOREVACUUM PLASMA ELECTRON SOURCE

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Plasma technologies and sources of electrons based on a plasma cathode that are actively developing in recent times require continuous improvement of existing equipment. Forevacuum plasma electron sources, able to function in a pressure range of a unit and tens of pascals, allow electron-beam processing of both conductive materials and dielectrics without the use of additional means of compensation for the surface charge [1]. To stabilize the plasma emission boundary, they traditionally use either a grid of refractory material or a perforated electrode with a thickness of not more than 1 mm. The use of the grid allows to increase the efficiency of emission from the hollow cathode plasma, but at the same time the probability of its burnout at the breakdown of the accelerating gap is quite high. The use of a perforated electrode significantly increases the operating time of the electron source, even during the breakdown of the accelerating gap. However, when the electron source operates at maximum parameters, i.e. upon receipt of electron beams with a capacity of more than 5-6 kW, the thermal load on the perforated electrode increases, which ultimately also leads to its destruction. This paper presents the results of experiments to optimize the emission electrode in a plasma cathode electron source. The optimal thickness of the perforated electrode and the diameter of the emission hole are found. With this thickness, the maximum efficiency of electron extraction from the plasma in the range of operating pressures of the source is 10-30 Pa.

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THE EFFECT OF COMPRESSION PLASMA FLOWS ON THE METAL FILM-SUBSTRATE SYSTEM

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Surface engineering is a well-developed field of materials science. One of the surface engineering directions is high-energy surface treatment in order to modify its properties. Among the methods most developed are high-current electron and power ion beams processing [1], pulsed plasma flows [2], broadband [3] and laser radiation [4].

The report presents investigation results of the effect of compression plasma flow [5,6] on a metal film-substrate system in a pulsed-periodic mode. Critical modes of compression plasma flow influence to the surface were defined. The changes in the microhardness of the film and its adhesion were recorded. Also the changes of coating porosity and its microrelief were studied. The results have been discussing.

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THE ION BEAM GENERATION IN THE SELF-MAGNETICALLY INSULATED ION DIODE

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The studies of the plasma formation on the anode surface of the self-magnetically insulated ion diode were performed. The plasma formation is carried out by the voltage prepulse of negative polarity. The electrodes have a focusing geometry to provide ballistic focusing of ion beam. The anode was a graphite focusing electrode of rectangular cross-section. The diode cathode was designed in form of a grid from stainless steel. During the studies the anode and cathode configuration which provides uniform plasma formation was obtained. The experimental data of the current density and energy distribution over the ion beam cross section depending on the plasma formation conditions at the anode surface were obtained.

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Partial Discharge Analysis Through Lissajous Figure at Low Air Pressures

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the condition of electrical insulation is significant to the safety of electric power systems, especially to the More Electric Aircraft(MEA) that carries hundreds of people. The property of insulation will be reduced by aging and degradation which caused by partial discharge (PD). This has become a topic of extensive research and investigation.

This paper represents the PD detection in terms of Lissajous figures which is a composite of two orthogonal oscillations with integral proportional frequencies. It can be used to calculate the total charge of PD transferred per cycle and the total energy of PD per cycle, thus the average charge and energy of a single PD activity can be recognized accompany with the current pulse PD detection method based on IEC 60270.

Fig. 1.Typical Lissajous Figure of PD

The accumulated voltage value between the bottom and the top of the side on the right hand side that across the X axis can be taken as *ΔU*. There is a capacitor *C* connected in series with the testing sample, thus the discharge amount in a half cycle can be calculated with the formula below:

$$\Delta Q = \Delta U \times C \tag{1}$$

The total energy of a full cycle is the area of the parallelogram, which can be calculated trough the chequer grid circled by the parallelogram.

The calculated charge amount and energy reflect the condition of the insulation, which is helpful to the evaluation of the property of insulation.

DEVELOPMENT OF ELECTRON-BEAM EQUIPMENT AND TECHNOLOGY OF LAYER WELDING OF THE WIRE IN THE CONDITIONS OF ADDITIVE TECHNOLOGIES

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Currently, more and more often, a wide range of additive technologies (or 3D printing technologies) are used to solve problems of obtaining metal products of complex shape with anisotropic properties. If it is necessary to print thick-walled parts with less accuracy (a few millimeters) and greater productivity, the method of dimensional electron beam surfacing with wire is promising. In the period from 2015 to the present, the modular installation of electron beam fusion of powders and surfacing with wire was created and constantly modernized at NI TPU. At its core is a vacuum chamber with an electron-beam gun with a plasma emitter and modular manipulators, providing the possibility of layer-by-layer alloying of powders (EBM) or dimensional deposition with wire. The software provides the possibility of modular replacement and synchronized control of all installation organs, according to the task, using digital G - codes. Printing was carried out at an accelerating voltage of 30 kV and a beam current of 15 to 20 mA (depending on the distance from the substrate), thus, the input power varied from 450 to 600 watts. The focused beam (diameter 150 μm) moved in a circular scan 4 mm in diameter. The frequency of the beam on the scan of 1000 Hz. The wire was fed to the sweep area, and the sample geometry was achieved by moving the table along three axes. The distance between the tracks (hatching distance) was 4 mm, and the layer height was 0.8 mm, the movement in the horizontal plane was zigzag. The sample construction scheme is shown in Figure 1.

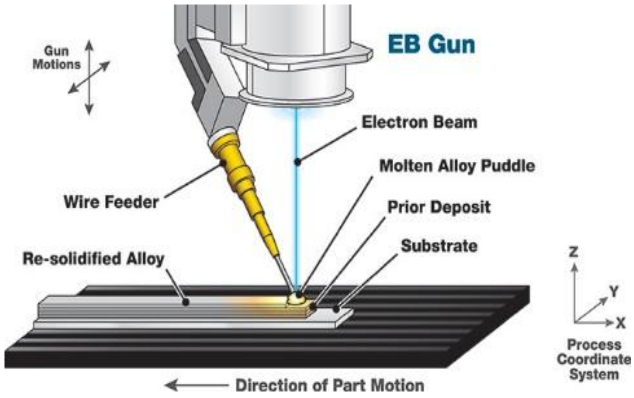

Fig.1.

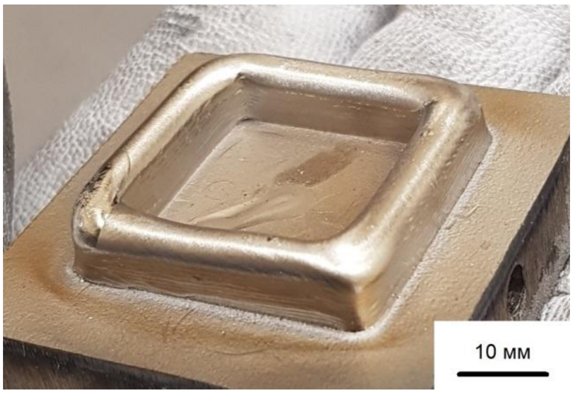

Fig.2

During the work, samples from wires of titanium alloy Ti-6Al-4V and steel AISI 304 were printed on an electron-beam 3D-printer. To study porosity and mechanical properties, a continuous sample of titanium alloy in the form of a cube and from steel in the form of a rectangle was obtained, fig.2. The study of the quality of the formed samples on the subject of porosity and structural heterogeneity, and hence the mechanical properties was carried out in the work of non-destructive testing methods using computed tomography and methods of mechanical testing and metallography. It is shown that the regulation of the modes of radiation exposure and modes of wire feeding and beam scanning allows obtaining titanium and steel products with high microstructural uniformity and satisfactory mechanical properties, but the problem of reducing macro porosity requires new approaches to optimize microstructural uniformity and porosity.

DEPOSITION RATES OF CU, CR, AND SI IN AN IMPULSE MAGNETRON DISCHARGE WITH HOT TARGET*

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Magnetron sputtering devices ensure deposition of thin films with outstanding physical properties and high quality. The constant demand for even better performance of coatings and their production processes stimulates the development of novel approaches in deposition techniques. One of the promising concepts is an impulse magnetron with hot (or liquid) target (IMHT, or IMLT, correspondingly [1].

We studied the deposition rates of Cu, Cr, and Si obtained in a magnetron device with thermally insulated target [2]. In each case, at first, the direct current discharge was initiated, and after the stabilization of parameters at a power level specific for the target material, the series of high-current impulses were applied to the target. The deposition rates were measured by weighing method. The prepared coatings were analyzed with scanning electron microscope.

The results demonstrate that the deposition rates in IMHT (IMLT) regimes are nearly the same as in the corresponding DC discharge modes. However, the structure of coatings becomes substantially denser that indicates the elevation of ion fraction in the impulse regimes and thus reveals their benefit of tailoring the coating properties.

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PLASMA SOURCES AND EQUIPMENT

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STUDY OF CHARACTERISTICS OF THE LOW-TEMPERATURE PLASMA SOURCE BASED ON THE PIEZOTRANSFORMER*

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Nowadays, it is of current interest to create and use devices for generating low-temperature non-equilibrium plasma at atmospheric pressure for treating various surfaces, including thermally unstable, as well as creating plasma-activated media (including biomedical) [1]. The most common sources of "cold" plasma have the disadvantage that is the difficulty of selecting operating modes. In addition, most of these sources have relatively large overall dimensions and can work only with noble gas pumping.

The proposed design of the source (generator) of low-temperature plasma [2] (Fig. 1) is compact and allows to use three different operation modes. The plasma source is a dielectric tube 4 fixed in a rigid case 5, forming an ionization chamber 3, inside which a piezotransformer 1 is installed. Piezotransformer configured to convert a low-amplitude alternating voltage from generator 6 into a high voltage at a discharge electrode 2 at the output end of the piezotransformer 1. This design of a low-temperature plasma generator contains a dielectric cap 9, which fits piezotransformer output end 1 tight and allows changing the thickness of the dielectric layer 10. This fact permits the source to operate in a mode of dielectric barrier discharge at a short distance from the outer dielectric 10 (1-3 mm). It is possible to create a direct piezo-discharge without a dielectric cap 9. The pumping of a noble gas through a dielectric tube allows obtaining a plasma jet with adjustable parameters of low-temperature plasma.

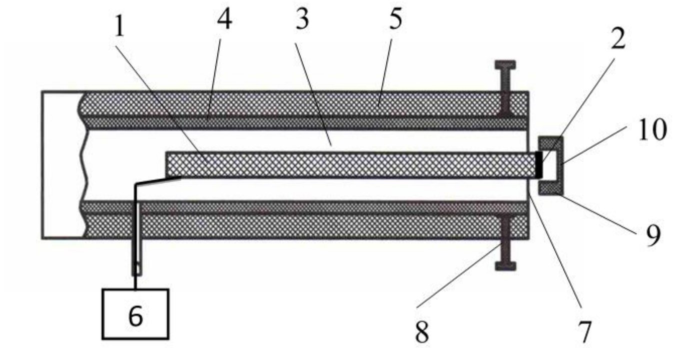

Рис. 1. The low-temperature plasma source based on the piezotransformer.

The rotational and oscillation temperatures of the electrons in the discharge were obtained from the emission spectra for all three operation modes of the low-temperature atmospheric pressure plasma source. The distribution of the electric field near the discharge gap was obtained using a probe operating on the Pockels effect. The possibility of treating biological objects by low-temperature plasma from this source was shown, as well as obtaining plasma-activated media used to study the mechanisms of multifactor effects on living tissue cells and to search for new possibilities of therapy of oncological formations with increasing efficiency of existing techniques.

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FEATURES OF LOW PRESSURE ARC DISCHARGE WITH THE COLD HOLLOW CATHODE IN A MAGNETIC FIELD[1]

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Low pressure arc discharge is widely used to solve scientific and applied problems [1]. In particular, on the basis of a low-pressure arc discharge, a plasma source with a cold hollow cathode is created, which allows generating plasma of inert and active gases [2]. Due to the low discharge voltage, this plasma source is advantageously used as a source of electrons for stable ignition and discharge of a high-current non-independent low-pressure glow discharge with a hollow cathode [3]. In [3], the operating pressure at which a non-independent glow discharge is stably functioning is limited to a minimum operating pressure of about 0.2 Pa, at which the arc discharge with a cold hollow cathode in crossed electric and magnetic fields is still stable. The purpose of the study was to identify the possibility of stable operation of the arc discharge with a cathode spot at lower operating pressure values. To this end, the maximum operating voltage applied to the discharge gap was increased from 55 V to 120 V at a fixed value of the axial magnetic field.

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PARAMETERS AFFECTING THE OPERATION OF ECR PLASMA SOURCE

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ECR (Electron Cyclotron Resonance) Plasma source was studied as apart of heating mechanism in the studies of beam plasma target interaction in plasma linear devices. Microwave of 2.45 GHz was launched radially with power ranging from 200 watts to 1400 watts. Plasma simulation was performed to study the effect of magnetic field intensity on the position of ECR layer. Hydrogen gas was fed to the chamber through flow meter with pressure ranging from 2×10^{-4} Torr to 8×10^{-3} Torr. Two identical magnetic coils were used with current ranging from 90 A to 160 A. Radial and axial Langmuir probes were installed for plasma profile measurements. Electron temperature was measured and ranging from 7 to 16 eV with electron plasma density range of 8×10^{15} m^{-3} to 6×10^{16} m^{-3}. Electron temperature groups were studied by means of EEDF. It was found that the shape of EEDF was affected by the applied magnetic field and gas pressure.