Journal of Engineering Physics and Thermophysics, Vol. 76, No. 2, 2003

INVESTIGATION OF PARAMETERS OF THE ION BEAM FORMED IN CROSSED ELECTRIC AND MAGNETIC FIELDS

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The results of experimental investigations of the characteristics of the positive ion beam formed in an ion-plasma system with discharge generation in crossed electric and magnetic fields are presented. The conditions for the discharge formation and the specific features of the developed configuration of the discharge unit are described. It is shown that such discharge systems are capable of forming broad low-energy ion beams and can be used successfully in various fields of thin-film technology.

Introduction. Modern trends in the development of the technology of applying thin-film coatings for the needs of optics, micro- and optoelectronics, and machine-building presuppose the provision of possibilities of on-line control of the structure, stoichiometry, and the phase composition of deposited films by means of independent check of the energy flux and the flow of matter arriving at the substrate.

For production processes, it is also important to provide a high uniformity of treatment of the whole surface and the generation of an ionic current comparable in intensity to flows of sputtered or evaporated materials.

One effective method for the formation and on-line control of energy fluxes is intensive bombardment of the surface by low-energy particles. Ions with energies in the 10–100-eV range produce a determining effect on the processes of nucleation and growth of thin-film coatings [1, 2], and in the 100–500-eV range they make it possible to carry out effectively the processes of surface activation and cleaning [1–3].

In this connection, the development and investigation of systems generating directed low-temperature gas-discharge plasma streams with a widened range of treating energies capable of forming high-intensity ion beams from various gases at low pressures seem promising [2]. This will make it possible to realize, in one vacuum cycle, the processes of ionic cleaning and activation of the surface, direct deposition from an ion beam, and ion-assisted deposition.

Conditions for Charge Formation. To initiate and maintain the processes of ion generation and acceleration in Hall current devices, it is necessary to provide an electron flow directed to the ionization zone. The density of such an axial electron current can be determined, proceeding from the Bohm diffusion for the potential gradient and the concentration gradient [4]:

$$\mathbf{J}_{\mathrm{e}} = \frac{en}{16\mathbf{B}}\frac{dU}{dx} - \frac{eT_{\mathrm{e}}}{16\mathbf{B}}\frac{dn}{dx} . \tag{1}$$

Assuming that the plasma is quasi-neutral throughout the acceleration region, we integrate expression (1) along the x-axis:

$$\frac{\mathbf{J}_{\mathrm{e}}}{en_0U_0}\int \mathbf{B}\times d\mathbf{x} = f\,(U/U_0, x) , \tag{2}$$

where $f(U/U_0, x)$ is the function showing the character of the change in the electron temperature; $\mathbf{B} \times d\mathbf{x}$ is the vector product taking into account the field orientation with respect to the x-axis.

The metal walls of the acceleration channel in Hall current devices are under a negative potential with respect to the anode. Therefore, electrons move towards the anode, as a rule, and are reflected from them even in the case of only the radial component of the magnetic field in the channel [4]. To obtain a given ion current at a lowered anode

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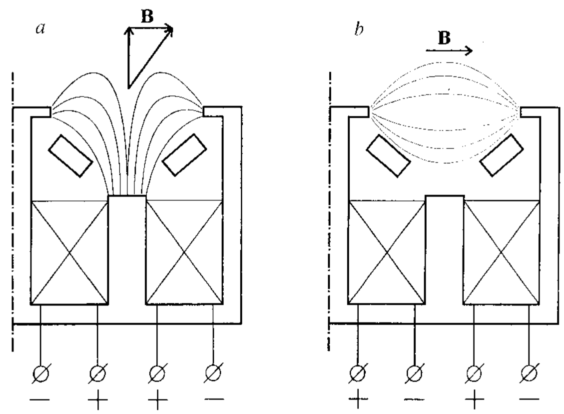


Fig. 1. Form of the magnetic field in the discharge at "counter" (a) or "forward" (b) switch-on of electromagnet voltage.

potential, a relatively higher value of the reverse electron current is required. At the same time, the conditions determining the formation of an electron flow towards the anode are hardened because of the continued expenditure of energy in ionization. From expression (2) it follows that the reverse electron flow and, accordingly, the ion current of the beam can be increased by decreasing the value of the magnetic integral. However, a decrease in the magnetic field leads to a decrease in the probability of ionization of neutral atoms and, as a result, to a limitation of the ion current density.

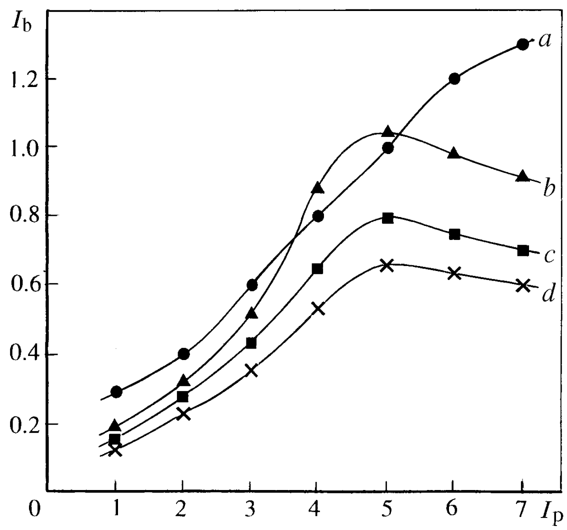
H. R. Kaufman et al. [5] found a solution: they separated the mechanical trajectories of electrons and ions by changing the geometry of the discharge zone. They oriented the acceleration channel not in parallel to the axis of the device, but at a certain angle with it. The central pole tip was displaced inside of the device so that the radial component of the magnetic field along the direction of motion of the reverse flow of electrons was considerably decreased and a significant axial component was formed. In so doing, the magnetic field lines remained parallel to the anode working surface. In such a case, at a constant value of the magnetic field the magnetic integral decreases without a change in the conditions for the proceeding of the process of ion formation, which, in the final analysis, leads to a decrease in the value of anode voltage at higher values of the generated ion current. However, such devices have a narrow energy range of formed ions (30 to 120 eV) and a low energy homogeneity of the beam, which limits the possibilities of their use in thin-film technology.

Proceeding from the foregoing, on the basis of the anode-layer accelerator [6–8] and the Hall end accelerator [5] an accelerating system with a discharge in $\mathbf{E} \times \mathbf{H}$ fields [9] for forming intensive ion flows in a wide low-energy range was designed and made.

Features of the Discharge System. It seems possible to extend the energy range and improve the characteristics of the energy homogeneity of an ion beam formed by creating conditions for flexible and on-line control of the vector value of the magnetic integral in the discharge region. This can be realized by transforming the spherical discharge region into a circular one. Since the extension of the energy spectrum to the region of higher energy of ions is only possible as a result of an increase in the magnetic integral associated with the work on transporting electrons into the discharge region (2), the most effective solution in this case seems to be control of the ion energy by changing the form of the magnetic field. The realization of such a configuration presupposes the existence of a three-pole magnetic system with two independent field sources and the possibility of their reverse switch-on, which permits controlling the axial and radial components of the magnetic field.

As a magnetic field source, we used two electromagnets arranged coaxially inside the magnetic circuit. Each of them is connected to an energy-independent power supply with the possibility of reverse switching of voltages. Between the electromagnets, a circular pole tip, which simultaneously serves as a gas distributor, is located. The system of accelerating electrodes consists of two concentrically arranged anodes, between which ionization and acceleration of ions occur. In the direction of ion extraction outside the accelerating system, a cathode-neutralizer is fixed [9].

Depending on the mode of operation of the ion-plasma system, the electromagnets switch on in the "counter" (Fig. 1a) or "forward" (Fig. 1b) direction of electric current in the windings, which permits controlling the magnetic field shape in the region of ionization and acceleration of ions.



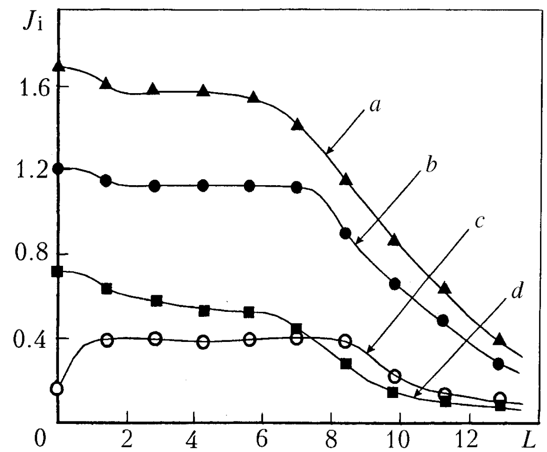


Fig. 2. Graphs of the beam ion current versus discharge current at various values of the current-ratio coefficient of solenoids: a) K_s = 1; b) 1.5; c) 4; d) 0.5.

Fig. 3. Ion current density distribution from the center to the periphery of the discharge device for the following parameters: a) I_d = 6 A; U_a = 280 V, and K_s = 1.5; b) 6.5, 200, and 1; c) 7, 40, and 3; d) I_d = 0.5 A and U_a = 800 V.

In the case of "counter" switching of electromagnet voltages, a magnetic field with a significant axial component is formed and the source generates a low-energy ion beam (300–450 eV). If it is necessary to form an ion beam with higher energies (up to 1 keV), "forward" current is applied to the electromagnets and in the discharge region a radial magnetic field is formed.

Results of the Investigations. In the process of the experiments, it has been established that the parameters of the discharge and the ion beam formed in the "counter" direction of electric current in the windings are strongly dependent on the current-ratio coefficient of solenoids K_s:

$$K_s = I_1/I_2 \,. \tag{3}$$

In different combinations of the working-gas flow rate and values of the current-ratio coefficient of solenoid and compensator currents, the discharge "ignition" potential varies from 20 to 400 V. As the anode potential is increased further, the discharge current increases considerably, up to a few amperes. An increase in the electron flow at a constant power input into the discharge also leads to an increase in the discharge current I_d and, as a consequence, a decrease in the anode voltage U_a. Such a situation is observed at certain values of K_s up to some critical value of reverse electric current after which the discharge parameters remain practically unchanged.

The results of the investigations given below have been obtained for a working pressure in the chamber of $4 \cdot 10^{-2}$ Pa.

The total current of the ion beam was determined by means of a target-current collector of area more than 500 cm^2, representing an insulated screen covering the whole region of ion propagation. Figure 2 shows the beam current–discharge current diagrams for various values of the current ratio coefficient of solenoids in the regime of low-energy ion formation. It is seen that in the general case the ion-beam current I_b is proportional to the discharge current I_d. However, at different values of K_s the character of the dependence changes, and this is especially noticeable when the power is increased, which is due to the change in the configuration of the magnetic fields and, accordingly, in the conditions for ion-beam formation. For some values of the current-ratio coefficient of solenoids an increase in the I_b/I_d ratio with increasing value of the magnetic field was also apparent. As a result of these investigations, it has been established that the formation of discharges of power more than 1.5 kW and a beam current of more than 1 A is most reasonable at values of $K_s \sim 1$.

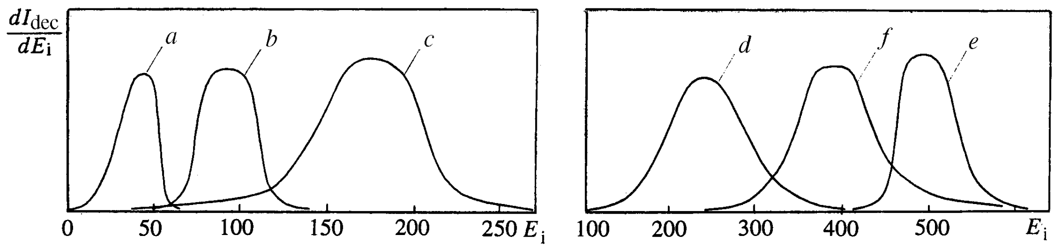


Fig. 4. Energy spectra obtained by differentiating the dependences of the ion-beam retardation for the following parameters: in the low-energy regime — a) I_d = 5 A, U_a = 55 V, and K_s = 1; b) 3, 120, and 1; c) 1, 280, and 1.5; d) 4, 310, and 1.5; e) 0.5, 570, and 1; in the high-energy regime — f) I_d = 0.9 A, U_a = 590 V.

To investigate the spatial characteristics of the beam, we used a multielectrode probe. It had 10 round cells of area 1 cm^2 each. The probe was fixed in parallel with the end of the ion-plasma device so that the first cell was on the symmetry axis of the discharge system and the other cells were located at regular intervals in the direction from the center to the periphery of the source. A small negative bias of the order of ~50 V was applied to the probe to exclude the action of the electronic component. Figure 3 shows the dependences of the ion current density distribution in the regimes of generation of low- and high-energy ions. In the regime of generation of a low-energy ion beam, the value of K_s was also varied.

The investigations have shown that the presented ion-plasma device in the regime of generation of low-energy ions (Fig. 3a–c) forms a broad beam over the substrate surface. Depending on the intensity ratio coefficients of solenoids, it is possible to control its geometry. The plot also shows that in the near-axis region a maximum is formed. This effect is associated with the radial convergence of the peripheral part of the ion beam and the increase in the ion density in the vicinity of the mutual intersection of their trajectories at the center.

In the case of the formation of high-energy ions, the appearance of a dip on the curve of the current density distribution along the symmetry axis of the device (Fig. 3d) is observed, which points to the tubular geometry of the beam. In such regimes, the beam current was relatively smaller than in the regimes with a low energy of ions, which is due to the low plasma conductivity across the magnetic field lines.

In both regimes, it was also possible to control the ion-beam geometry directly in the process of operation by connecting the anodes to independent power supplies.

It has been found that in the general case the ion current density of the beam, depending on the regime, varies between 0.01 and 2.5 mA/cm^2 at different values of the anode voltage. For uniform bombardment of the surface area in the treatment zone, the optimum distance to the substrate from 100 to 200 mm has been determined. When it is shorter than 80 mm, the beam takes on the tubular form in the treatment zone.

The investigation of the ion energy in the beam was carried out on the cylindrical axis between the two anodes of the device by means of a multigrid probe. Figure 4 depicts the beam spectra obtained by differentiating the delay curves taken for various values of the anode voltage. Spectra *a–e* correspond to the regime of generation of low-energy ions, and spectrum *f* — high-energy ions.

As is seen from the plots, the maximum number of ions have an energy of (0.65–0.85)U_a in the low-energy regime and (0.4–0.6)U_a in the high-energy regime. It is noteworthy that in the beam ions with an energy above U_a are present. This can be explained by the presence in the beam of multicharge ions or the development of oscillations in the discharge.

The decrease in the value of the mean energy of ions with increasing power (Fig. 4c and d) applied to the anode is, in all probability, due to the extension of the ion formation zone in the direction of ion acceleration. Moreover, it has been established that in the general case the energy homogeneity of the beam is the higher, the larger the electron emission from the cathode-neutralizer (Fig. 4a and b), which is caused by the increase in the probability of working-gas ionization at the entrance to the acceleration channel or by the operation of the ion-plasma device with a higher anode voltage without additional injection of electrons (Fig. 4e).

CONCLUSIONS

On the basis of the results of the investigations made, it has been concluded that the proposed model ion-plasma system with a double anode layer is capable of generating a broad (up to 180 cm^2) and current-homogeneous beam with a range of mean energies of ions from 30 to 100 eV and a discharge power from 50 W to 2 kW. This system is fairly flexible in operation and functions with various compositions of the gas fed.

The device is suitable for use in the technological processes of forming optical thin-film coatings and layers of materials with a higher density and hardness by the methods of ion-beam assisted deposition. The employment of this system as part of vacuum technological complexes will make it possible to perform, in one vacuum cycle, etching and cleaning of substrates and modification of the surface and gaseous synthesis of solid-state structures and also form directed energy fluxes for assisted deposition; it promotes an increase in the adhesion and packing density, the dominant orientation formation and control of the crystal lattice step of growing layers. The device is simple in design, and it is multifunctional and reliable.

NOTATION

e, electron charge, C; n, electron concentration, m^{-3}; n_0, ion concentration at the anode, m^{-3}; $\mathbf{B}$, magnetic induction, T; U, electric potential relative to the source housing, V; U_0, potential difference under whose action ions are accelerated, V; U_a, anode voltage, V; T_e, electron temperature, eV; x and $\mathbf{x}$, axial coordinate in the direction of the electron flow and its vector, m; I_1 and I_2, respectively, currents applied to the external and internal solenoids of the ion-plasma system, A; K_s, current-ratio coefficient of solenoids; $\mathbf{E}$, electric field strength, V/m; $\mathbf{H}$, magnetic field strength, A/m; I_b, ion-beam current, A; I_d, discharge current, A; E_i, ion energy, eV; dI_{dec}/dE_i, ratio between the decelerated beam current gain and the ion energy gain, rel. unit; I_{dec}, decelerated ion-beam current, μA; $\mathbf{J}_e$, reverse electron current density, mA/cm^2; J_i, ion flow density of the beam, mA/cm^2; L, distance from the ion beam center to the periphery, cm. Subscripts: a, anode; e, electron; d, discharge; i, ion; dec, decelerated; s, solenoid.

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