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Ionization mechanism of beam plasma generated by an electron beam in medium vacuum

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We present the results of the measurements of the ionic composition of plasma generated by an accelerated electron beam at medium vacuum (fore-vacuum) pressures. Calculations of the contribution of plasma electrons and beam electrons to the mechanism of ionization are presented. Comparison of the calculated with the experimental data led us to the conclusion about the dominating contribution of beam electrons and to the ionization process.

Keywords: beam plasma, fore-vacuum, electron beam, plasma-cathode electron source.

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Dense beam plasma with an electron temperature of several electronvolts [1], which features a number of unique parameters and properties, is generated in the process of transport of kiloelectronvolt electron beams in a gas atmosphere within the range of medium vacuum pressures (1−100 Pa). The high efficiency of dissociation of molecules, ionization of their decomposition products in beam plasma [2], and a positive potential of plasma relative to grounded walls of the vacuum chamber [3] make such plasma viable for application in ion-plasma material modification processes [4,5].

The process of electron-beam evaporation of high-temperature ceramic materials and metals with subsequent ionization of the evaporated material and synthesis of dielectric coatings [6,7] is of practical relevance. The ion composition of beam plasma in electron-beam evaporation affects the process of formation and parameters of such coatings, since their properties may be adjusted by applying a negative or bipolar bias to the substrate. This is the reason why accurate measurements of the mass-to-charge composition of ions and the identification of key physical mechanisms governing ionization processes in beam plasma are essential. These topics are in the focus of the present study.

The idea of the experiment was to introduce a pair of inert gases (argon−helium) into a vacuum chamber and form a gas mixture with equal partial pressures at the level of 1 and 1.5 Pa. Two separate gas lines for two working gases were used for the purpose. Argon was the first gas to be introduced into the chamber evacuated to a residual pressure. When the needed argon pressure, which was measured with a VIT-2 vacuum gauge, was reached, the flow of helium (its partial pressure was monitored as an increment of the total pressure in the chamber) was turned on. Inert gases were chosen for this study, since it was needed to exclude the influence of dissociation processes. A mixture of argon and helium, which are gases with widely different values of the ionization potential and cross section, was used to reveal clearly the ionization mechanism.

The mass spectrum of ions was measured in the process of generation of beam plasma, and the ratio of ion components of the working mixture was monitored. This ratio was compared to theoretical estimates of the ratio of probabilities of ionization for the indicated pair of gases by plasma electrons and beam electrons. The energy distribution function for plasma electrons was assumed to be Maxwellian, and their temperature was assumed to be equal to 1.5 eV [1]. Beam electrons are virtually monoenergetic, and their energy is much higher than the one corresponding to the maximum ionization cross section. The relation between the probabilities of ionization by an electron beam is then specified by the ratio of ionization cross sections of each gas at a fixed electron energy.

The schematic of the experiment is shown in Fig. 1. A forevacuum plasma source of electrons, which was based on a hollow-cathode discharge and operated in the continuous mode, was used to generate beam plasma [8]. The electron beam current was kept at 50 mA. A significant difference between the energies of plasma electrons and beam electrons was maintained in experiments by setting an accelerating voltage at the level of 10 kV. An ultimate vacuum of 0.027 Pa was achieved using a nEXT300D turbomolecular pump with an evacuation rate of 300 l/s.

An upgraded quadrupole mass spectrometer of an RGA-300 residual gas analyzer was used to analyze the mass-to-charge composition of plasma. The operating principle and changes in the design of the stock mass spectrometer were detailed in [8].

Let us use the well-known expression for ionization yield v_i at electron energies close to the ionization energy to estimate the contribution of plasma electrons to the process of formation of beam plasma in the chosen pair of gases. This expression was derived under the assumption of a Maxwellian energy distribution of electrons and with a

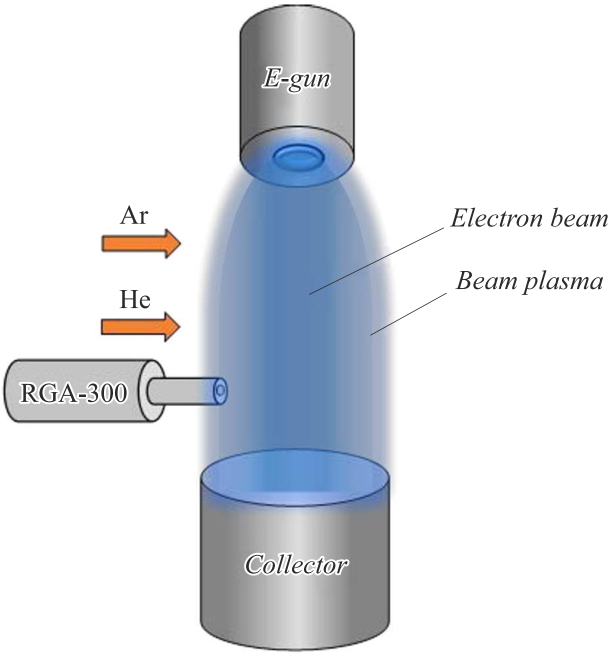

Figure 1. Schematic of the experiment.

linear approximation of the dependence of the electron-impact ionization cross section on electron energy [9]:

$$v_i = n_e n_a C_i \left(\frac{8kT_e}{\pi m_e}\right)(eU_i + 2kT_e)\exp\left(-\frac{eU_i}{kT_e}\right), \qquad (1)$$

where C_i is a constant in the linear dependence of the ionization cross section on temperature, n_a is the density of gas molecules, n_e is the density of plasma electrons, and U_i is the ionization potential.

With equal partial pressures of gas components in the mixture, the comparison of probabilities of ionization of these gases P_{Ar} and P_{He} comes down to calculating the ratio of the rates of their ionization:

$$\frac{P_{\mathrm{Ar}}}{P_{\mathrm{He}}} = \frac{v_{i\mathrm{Ar}}}{v_{i\mathrm{He}}} = \frac{C_{i\mathrm{Ar}}}{C_{i\mathrm{He}}}\left(\frac{eU_{i\mathrm{Ar}} + 2kT_e}{eU_{i\mathrm{He}} + 2kT_e}\right) \times \exp\left(\frac{eU_{i\mathrm{He}} - eU_{i\mathrm{Ar}}}{kT_e}\right). \qquad (2)$$

With the ratio of constants $C_{i\mathrm{Ar}}/C_{i\mathrm{He}} = 2.0/0.13$ in the linear dependence of the ionization cross section on temperature taken into account, the ratio of ionization probabilities was found to be $P_{\mathrm{Ar}}/P_{\mathrm{He}} = 3677$.

Let us the approximation proposed by Lotz [10] for the cross section of ionization of atoms from the ground state:

$$\sigma(E) = \sum_{i=1}^{N} a_i q_i \frac{\ln\frac{E}{U_a}}{EU_a}\left\{1 - b_i \exp\left(-c_i\left(\frac{E}{U_a} - 1\right)\right)\right\}, \qquad (3)$$

where a, b, and c are constants of an empirical formula [10]; q_i is the number of equivalent electrons on a shell; E is the electron energy; and U_a is the ionization potential. Formula (3) characterizes single ionization of atoms, and the dominance of single-charged ions is typical of beam plasma of a medium vacuum.

Figure 2 shows the results of this approximation. It can be seen that the ratio of ionization cross section of argon and helium atoms is 5.5. If gas is ionized by beam electrons, the ratio of their ionization probabilities is the same: $P_{\mathrm{Ar}}/P_{\mathrm{He}} = 5.5$.

It follows from the above estimates that the ratio of probabilities of ionization of argon and helium by plasma electrons (3677) differs greatly from the corresponding ratio calculated for beam electrons (5.5). Thus, having measured this ratio experimentally, one may then determine which of the calculated values is closer to the obtained value and identify the dominant mechanism of ionization (i.e., by plasma or beam electrons) in medium-vacuum beam plasma.

Figure 3 presents the results of examination of the mass-to-charge composition of ions of beam plasma in a mixture of argon and helium gases at two partial pressures. The mass spectra were found to be almost identical; the only difference is in the absolute amplitudes of peaks recorded at different partial pressures. A reduction in the amplitude of peaks is associated with scattering of a part of the ion flux induced by an increase in the total pressure in the chamber and the corresponding increase in the number of collision of ions with neutrals in the working mixture and the residual atmosphere.

The ratio of the number of argon ions to the number of helium ions (i.e., the ratio of areas under the corresponding peaks) was 5.1 (Fig. 3, *a*) and 5.8 (Fig. 3, *b*) at a partial pressure of 1 and 1.5 Pa, respectively.

Thus, the results of calculations and experiments suggest that beam electrons produce the dominant contribution to ionization of atoms. When beam plasma is ionized by

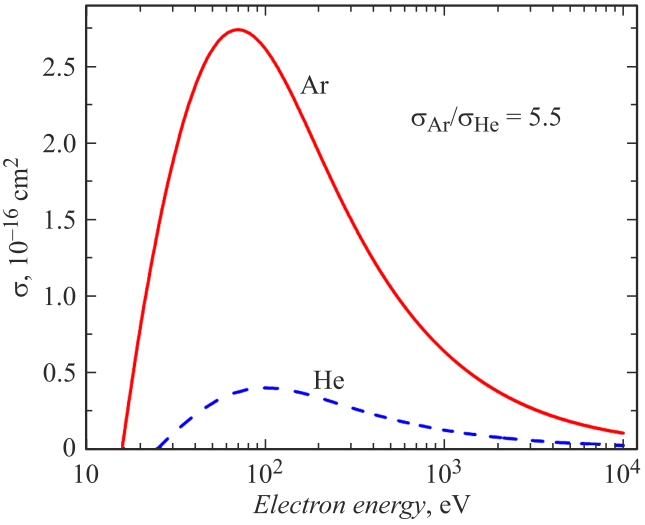

Figure 2. Approximations for the ionization cross sections of argon and helium atoms.

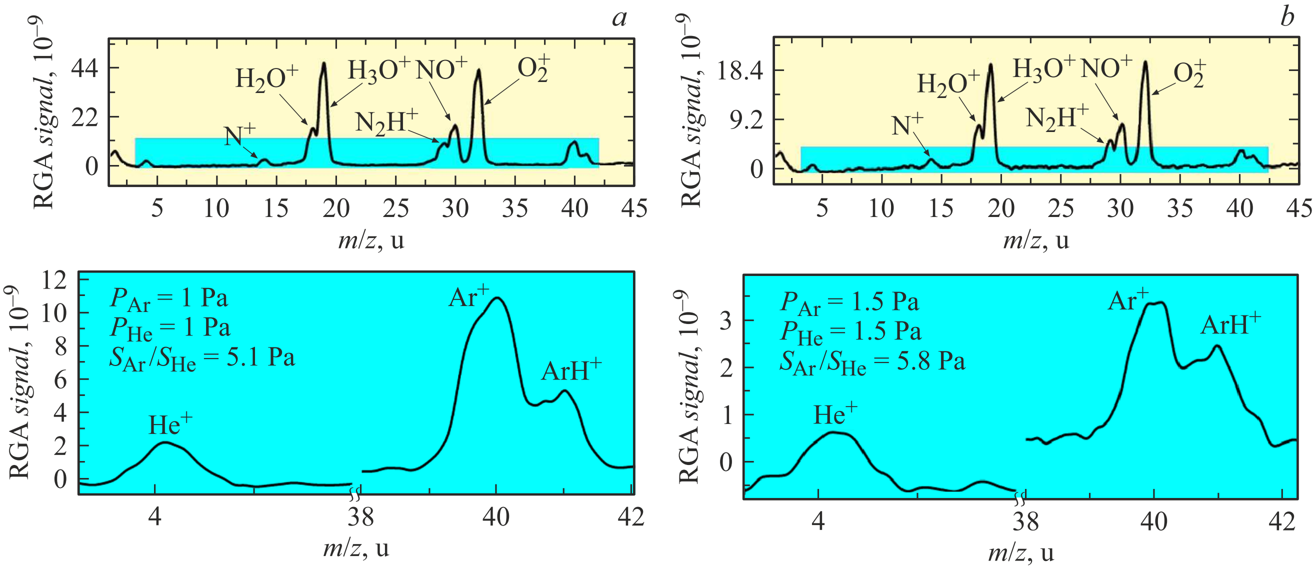

Figure 3. Results of mass spectrometry at a partial gas pressure of 1 (*a*) and 1.5 Pa (*b*).

plasma electrons, the ratio of ionization probabilities for the pair of working gases differs by several orders of magnitude from the corresponding ratio for electron-beam ionization. The obtained experimental ratios of the numbers of argon and helium ions were 5.1 and 5.8 at a partial pressure of 1 and 1.5 Pa, respectively. This fact suggests that beam electrons produce the dominant contribution to ionization of beam plasma. A slight discrepancy between the experimental and theoretical data is attributable to inaccuracies in approximation of the ionization cross section and probable experimental errors. The data reported above should help interpret the results of mass-spectrometric studies of beam plasma and find the optimum parameters for surface modification by an ion flux.

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Conflict of interest

The authors declare that they have no conflict of interest.

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