The Features of Gridded Plasma Cathode Operation at Ion Sources [1]

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Abstract – Characteristics of glow discharge and plasma parameters in the electrode system of a two-stage ion source with a grid plasma cathode and a magnetic trap in the anode region of the system have been studied. It was shown that the increase in the gas pressure and, hence, the rise of the ion current in the bipolar diode, which was formed between cathodic and anodic plasmas, led to the growth of the cathodic plasma potential and transition of the plasma cathode to operation mode corresponding to electron emission from the open plasma boundary. It was found that the decrease in the voltage across the diode gap and shrinkage of the gap with growing pressure were followed by breakage of the space charge layer and transition of the discharge to the constricted regime of operation, in which the current of ions extracted from the anodic plasma decreased several times.

Introduction

A bipolar diode, in which the ratio of electron and ion currents depends on the gas pressure, is formed between the grid and the anodic plasma in an ion source with a gridded plasma cathode (GPC) [1]. When the energy of injected electrons nearly equals the maximum cross-section of gas ionization and an efficient energy relaxation of electrons is provided, a positive space charge in the diode may dominate over the electron charge. Ions, which came from the beam plasma or the accelerating gap, increased the density of the emitting plasma, leading to the rise in the electron emission current [2]. Studies of GPC [3, 4] demonstrated that an efficient extraction of electrons resulted in growth of the emitting plasma potential, but the effect of the reverse ion current on processes in GPC was not analyzed in those studies. Since the value and the sign of the anodic potential drop in the discharge are determined by conditions of generation and disappearance of positive ions near the anode [5], one may think that an intensive reverse current of ions has a considerable effect on plasma parameters and GPC emission in the ion source. The importance of the study of processes, which determine emission of a plasma cathode, is also due to the fact that the grid in an ion source with GPC represents the principal element limiting the lifetime of the source and the maximum current of the plasma ion emission.

The interrelationship of processes in cathodic and anodic plasmas and the dependence of the cathodic plasma parameters on discharge conditions were analyzed in this study in order to optimize the operating regime of the plasma cathode in ion sources.

1. Experiment

The schematic diagram of an ion source with a two-stage electrode system [6] is shown in Fig. 1. The plasma cathode was formed in the cathodic stage of the source with the use of a glow discharge. Homogeneous plasma was generated with fast electrons in the magnetic field free region of the anodic stage. The metal grid 1 with the mesh size $h = 0.2–2$ mm was installed between the 20-mm outlet aperture of the cathode 2 and the anode 3. The hollow electrodes had the same length and diameter equal to 150 mm. For measurement of the resulting current of charged particles from the cathodic and anodic plasmas to the grid, the grid holder was covered with the shield 4. The measured values of the shield current were used to estimate the density of the ion current from the anodic plasma. Permanent magnets 5 created linear multipole magnetic fields at the surface of the hollow cathode and anode.

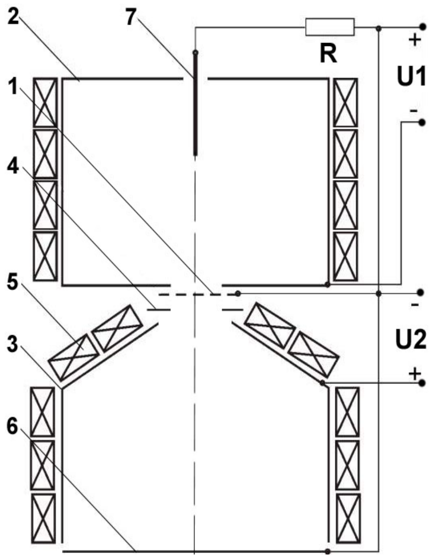

Fig. 1. A schematic view of the ion source

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A gas (argon) was leaked into the cathode chamber. A magnetic multipole in the cathodic stage served to decrease the working gas pressure. The given values of the gas pressure were measured in the vacuum chamber. The estimated average pressure of the anodic and cathodic stages was nearly two times and ~25 times higher than the measured pressure respectively. The cathodic stage was powered from a supply unit with a controlled current $I_d = (0.2–1)$ A. The output voltage U_2 of the supply unit of the second stage was adjustable within 0 to 300 V. The ion collector 6 had a potential equal to the grid 1 potential. A rod electrode 7 facilitates the discharge igniting.

The increase in the gas pressure led to the growth of the ion current in the collector circuit and the anodic current of the second stage, while the electron current in the grid circuit dropped (Fig. 2). When the voltage U_2 was high, the anodic current and the ion current to the collector first increased at a slower rate and then began to decrease. The current to the grid changed its sign and transformed to the ion current.

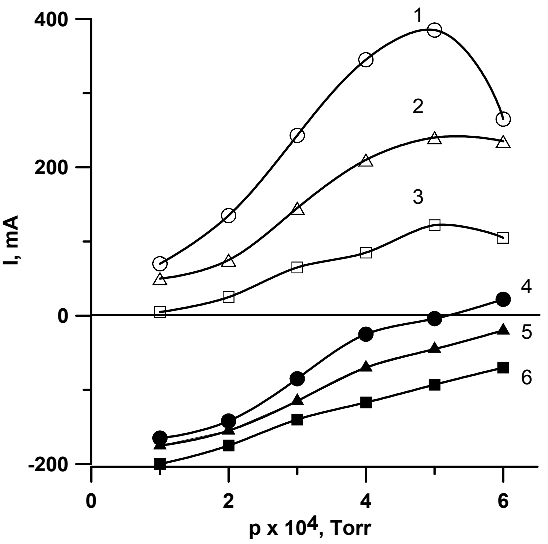

Fig. 2. Collector ion current (1–3) and grid current (4–6) as a function of gas pressure (argon). $I_d = 0.4$ A; $U_2 = 50$ (3, 6), 100 (2, 5), 200 V (1, 4)

When the grid mesh was $h = 0.6$ mm or smaller, currents to the collector and the anode did not decrease. To keep the glow discharge current constant the difference of potentials U_1 between the hollow cathode and the grid decreased with growing gas pressure, the voltage U_2 and the grid mesh (Fig. 3).

Plasma parameters were measured using Langmuir probes and gridded energy analyzer with a retarding electric field.

If the voltage was not applied to the second stage ($U_2 = 0$), the potential of the cathodic plasma was negative (–12…–8 V) and slightly rises with gas pressure. When the second stage was turned on, the plasma potential increased. In this case, the larger were the values of h, p, U_2 and I_d, the greater was the plasma potential. If the gas pressure increased, volt-ammetric characteristics of the Langmuir collecting probe in the plasma (Fig. 4) were shifted. At high pressures the dependences transformed to straight lines. When a potential of 30–40 V was reached, the probe changed abruptly to the anode regime. Plasma electrons had a temperature of 1.5–3 eV at low gas pressures.

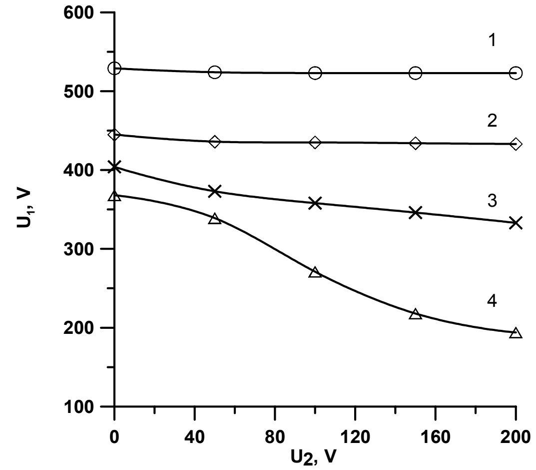

Fig. 3. Dependencies of first stage voltage upon second stage voltage. $I_d = 0{,}4$ A. Grid mesh size $h = 1.4$ mm. Gas pressure (Ar): $1{\cdot}10^{-4}$ (1); $2{\cdot}10^{-4}$ (2); $4{\cdot}10^{-4}$ (3); $6{\cdot}10^{-4}$ Torr (4)

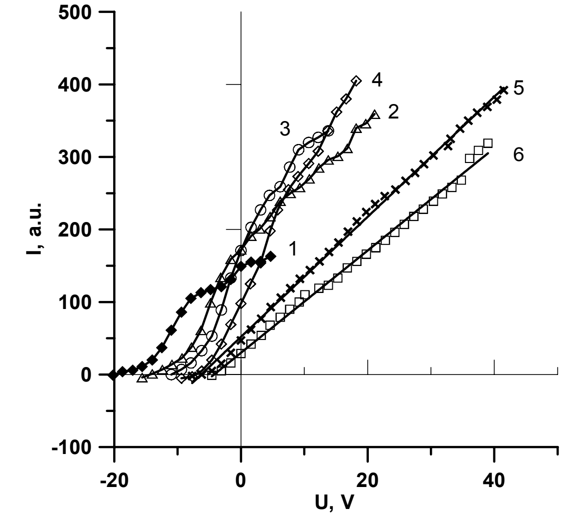

Fig. 4. Probe characteristics for the cathode plasma. $I_d = 0{,}4$ A. $U_2 = 200$ V. Gas pressure (Ar): $1{\cdot}10^{-4}$ (1); $2{\cdot}10^{-4}$ (2); $3{\cdot}10^{-4}$ (3); $4{\cdot}10^{-4}$ (4); $5{\cdot}10^{-4}$ (4); $6{\cdot}10^{-4}$ Torr (6)

Operation of the discharge in the system with the grid mesh of the size $h = 1.4$ mm was unstable at a pressure $p \sim (5–6){\cdot}10^{-2}$ Pa, but then stabilized as the pressure increased further. A constriction of the discharge near the grid was observed visually in this regime. The diameter of the plasma filament approached the size of the grid mesh (1–2 mm). In this regime, the floating potential of the probe was 30–40 V. The probe changed to the anode regime at a voltage of 80–100 V relative to the grid.

Figure 5 presents the retarding curves for the electron current from the anodic plasma. These curves were recorded with an electrostatic analyzer, whose inlet grid had a potential 50 V lower than the anode potential. The curve 1, which was obtained at a low gas pressure, suggested the presence of a large number of high-energy electrons in the plasma. However, the peak of electrons having an energy corresponding to the diode voltage could not be resolved even if methods of preliminary collimation of the electron flow and acceleration-deceleration of electrons were used. The reason could be a curvature of the plasma boundary in each grid mesh, which caused considerable angular scattering of fast electrons, and also efficient relaxation of fast electrons thanks to their interaction with the plasma. The curve 2 in Fig. 5, which was recorded for the constricted discharge, was characterized by much smaller values of the fast electrons current, which obviously appeared as a result of the ion-electron emission of the shield.

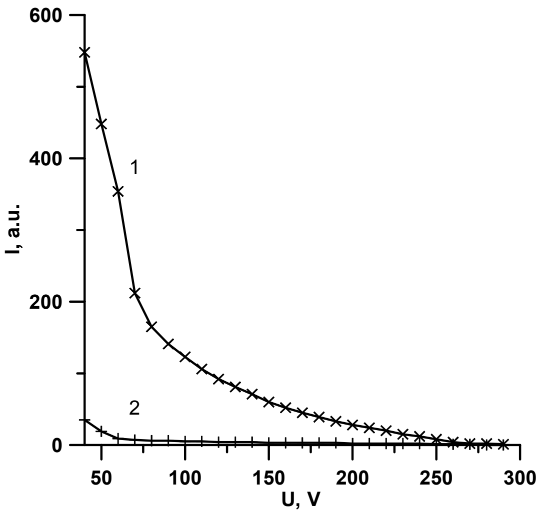

Fig. 5. Retarding curves for electrons from anodic plasma. $I_d = 0{,}4$ A. $U_2 = 200$ V. Gas pressure (Ar): $4 \cdot 10^{-4}$ (1); $6{\cdot}10^{-4}$ Torr (2).

Retarding curves of the ion current from the cathodic plasma are shown in Fig. 6. As the pressure increased, the ion current decreased at potentials smaller than the grid potential and the potential, at which the current in the collector circuit became the anodic current, increased. When the pressure was large, the retarding curve shifted to the region of potentials, which were positive relative to the grid. With growing pressure and increasing resonance charge exchange, the energy spectrum of the cathodic plasma ions was widen. Ions of the anodic plasma were responsible for the signal at potentials more positive than the grid potential. Charge exchange of these ions in the retarding field of the analyzer led to ion bombardment of the grid and appearance of the secondary electrons, which compensated the ion current. The shift of the retarding curve to the region of positive potentials at large pressures could be explained by the increase in the cathodic plasma potential.

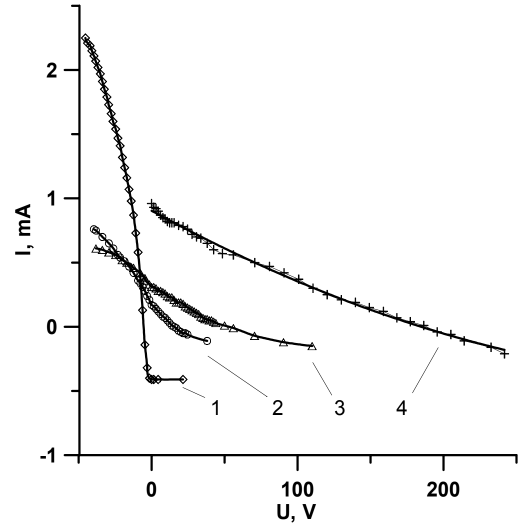

Fig. 6. Retarding curves for ions from cathodic plasma. $I_d = 0{,}4$ A. $U_2 = 200$ V. Gas pressure (Ar): $3{\cdot}10^{-4}$ (1); $6{\cdot}10^{-4}$ (2); $8{\cdot}10^{-4}$ (3); $2{\cdot}10^{-3}$ Torr (4).

2. Discussion

As the first approximation, the energy of electrons, which were accelerated in the bipolar diode, was determined by the value of voltage U_2. For a precise determination of the electron energy, it was necessary to take into account the potential drop across the anode sheath in the first and second stages. Measurements of the anodic plasma potential φ_2 showed that the plasma potential was always positive relative to the anode ($\varphi_2 = 1$–10 V). If the voltage $U_2 = 0$, the cathodic plasma potential φ_1 was always lower than the grid potential (see Fig. 4), although it increased with growing gas pressure. In experiments the sign of the plasma potential changed when the anode surface area increased by ~5 cm^2. Thus, if the second stage was turned off, the grid surface area and the concentration of ions near the grid were insufficient for feeding of the discharge current to the anode without formation of a positive anodic drop of the potential.

The cathodic plasma potential φ_1 increased when the second stage was turned on, but the potential φ_1 remained negative at low gas pressures p and low U_2 (see Fig. 4). As a result, preliminary acceleration of electrons in the anode sheath was realized. In this regime the emission current depended on the transparency of the grid. When the gas pressure was a minimum, a grid current, which was predominantly the electron current, reached ~1/4 of the glow discharge current. That is, electrons were extracted from the plasma with an efficiency of about 0.75 when the grid transparency was about 2/3. The increase in the pressure p and the voltage U_2 led to the growth of the ion current of the bipolar diode and the increase and sign reversal of the cathodic plasma potential.

The ratio between ion and electron currents in the diode could be roughly estimated as $I_i/I_e \sim$ $\sim en_o(\sigma_i v_e)V/V_{ext}$, where n_o is the concentration of neutrals, σ_i is the ionization cross-section, v_e is the electron velocity, V is the plasma volume, and V_{ext} is the volume, from which ions are supplied to the diode. If the full path of fast oscillating electrons in the plasma was much longer than the average ionization path, the ion current increased by a factor of $\sim e(\varphi_2 - \varphi_1)/w$. Here w is the average energy consumed for generation of an ion in the plasma taking into account the loss of energy for excitation of atoms. At the $I_d = 0.4$ A the average electron current density through the grid was 130 mA/cm^2, while the average ion current density was 3–4 mA/cm^2. At high values of gas pressure p and U_2 the ratio between ion and electron currents in the bipolar diode becomes much larger than $(m_e/M_i)^{1/2}$, resulting in domination of the ion space charge. As a result, the gap length narrowed with growing ion current, leading to the increase in the intensity of the electric field in the diode.

If $\varphi_1 > 0$, a potential barrier, which impeded the escape of electrons to the anode, was formed between the plasma and the grid wires. Depending on the ratio between the size of the grid meshes and thickness of the anode sheath, emission of electrons through the potential barrier or from the open plasma surface could be realized [3, 4]. In the latter case, the electron extraction efficiency was a maximum. The increase in the size of h and the rise of the field intensity in the diode were accompanied by the increase in the area of the open emitting plasma surface, leading to the rise of the electron emission current which value may be as high as the discharge current value.

The increase in the potential of the electron emitting plasma in the ion source was caused by both a highly efficient extraction of electrons and the additional supply of ions from the anodic plasma, which charge exchanged resonantly on gas atoms in the cathode chamber. The escape of slow ions to the walls could be provided by an electric field in the plasma, which led to the experimentally observed growth of the electron temperature.

The rise of the potential φ_1 led to the decrease in the energy of fast electrons $e(\varphi_2 - \varphi_1)$ in the anodic plasma. As a result, the ion current and the anode current, which were equal to the sum of currents of injected and secondary plasma electrons, dropped.

At high pressures the increase in the ion current and the decrease in the diode voltage caused shrinkage of the diode gap to the value, which was comparable with the mesh size. This led, in the final analysis, to breakage of the space charge layer and to a constriction of the discharge.

When the size of the cathode aperture increased, the ion current density dropped, making the space charge layer thicker. Therefore, it was possible to increase the size of the grid meshes and, correspondingly, thickness of the grid wires, which determined the lifetime of the grid.

3. Conclusion

The experiments, which were performed at the emission current of the plasma cathode of up to 1 A, the bipolar diode voltage of up to 300 V and the argon pressure of the anodic stage equal to 0.02–0.1 Pa, led to the following conclusions:

1) The ion charge of the diode dominated when the gas pressure and the voltage increased. Growth of the ion current led to the increase in the cathodic plasma potential and transition to the electron extraction from the open plasma boundary with the emission current approached the glow discharge current value.

2) When the cathodic plasma potential increased, the bipolar diode voltage dropped, the voltage between the electrodes of the first stage necessary to keep the discharge current constant decreased, and the electron temperature elevated.

3) If the gas pressure in the system with grid mesh size 1.4 mm increased up to ~0.1 Pa, the bipolar diode failed and the discharge changed to the constricted operation regime. The cathodic plasma potential relative to the grid increased up to ~100 V.

References

[1] N.V. Gavrilov and A.S. Kamenetskikh, Physics Doklady **49**, 19 (2004).

[2] M.A. Zavjalov, Yu.E. Kreindel, A.A. Novikov, and L.P. Shanturin, *Plasma processes at technological electron guns*, Moscow, Energoatomizdat, 1989, pp. 86–93.

[3] A.V. Zharinov, Yu.A. Kovalenko, I.S. Roganov, and P.M. Turukanov, Rus. J. Tech. Physics **56**, 66 (1986).

[4] V.L. Galanskiy, Yu.E. Kreindel, E.M. Oks, and A.G. Ripp, Rus. J. Tech. Physics **57**, 1518 (1987).

[5] B.N. Klarfeld, N.A. Neretina, Rus. J. Tech. Physics **28**, 296 (1958).

[6] N.V. Gavrilov and A.S. Kamenetskikh, Rev. Sci. Instrum. **75**, No. 5 (2004).