Expansion of the Gas Pressure Range and the Increase in the Lifetime of the Plasma Cathode Grid in Ion Sources

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Abstract – What is proposed is a gas-discharge system with a plasma-cathode for a bucket-type gas ions source. Electron emission from the wide anodic part of the constricted hollow-cathode glow discharge, which is bounded by a grid electrode, is used in this ion source. The modification of the electrode scheme of the ion source allowed increasing the surface area and the size of apertures of the plasma cathode grid. As a result, the ion emission of the plasma was stable and constant over a wide interval of gas pressures and the lifetime of the grid was one order of magnitude longer. Specific features of the plasma cathode operation in regimes of the free and forced electron emission were analyzed and the energy efficiency of the ion generation in the gas-discharge system was evaluated.

1. Introduction

Specific features of the operation of a glow-discharge based gridded plasma cathode in a two-stage ion source were considered in [1]. The plasma cathode grid, which was an anode electrode of the glow discharge, was placed near the outlet aperture of the glow-discharge hollow cathode. Surface area of the grid was determined by the cross-sectional area of the cathode aperture. A bipolar diode with an adjustable voltage drop was formed on the anode side of the grid. The diode had counter flows of electrons and ions extracted from the cathode and anode plasmas respectively. The anode plasma was generated by electrons, which were accelerated in the bipolar diode, in the volume bounded by a peripheral magnetic field and the screen electrode of the ion optical system used for the beam formation.

The optimal surface area of the grid S_g in this gas-discharge system is determined by the relation $S_g \sim S_c(m_e/M_i)^{1/2}$ [2], where S_c is the surface area of the hollow cathode, while m_e and M_i denote the electron and ion masses respectively. The small size of the grid, which is necessary to provide reasonable dimensions of the electrode system, determines the high current density in the bipolar diode. The high pressure of the gas leaked into the cathode cavity ensures an efficient resonance charge exchange of ions from the anode plasma. As a result, the working range of pressures, at which the plasma cathode provides the maximum efficient extraction of electrons with an insignificant rise of the cathode plasma potential, proves to be narrow. For the ion source to operate with a wider interval of gas pressures and discharge currents, it is necessary to use fine-structure grids having a high geometrical transparency, but their lifetime is insufficient in conditions of intensive ion sputtering.

A considerable increase in the surface area of the plasma cathode with relatively small dimensions of the electrode system can be achieved if electrons are extracted from the wide anodic part of the constricted glow discharge. This approach is used in arc plasma-cathode sources of electrons [3]. The ratio between the surface area of the anode and that of the plasma emitter of electrons in these systems is determined by the parameter G, which is approximately equal to the ratio of the density of the chaotic electron current in the plasma and the electron current to the anode when electrons are not extracted [4]. The parameter G is equal to 2–20. Therefore, the surface area of the plasma cathode grid can be increased by one order of magnitude and, correspondingly, the density of the electron and ion currents in the bipolar diode can be decreased. As a result, the grid apertures can be made larger. The plasma cathode grid can be made as large as the screen grid of the ion optical system of the beam formation. The large surface area of the plasma cathode grid with a high geometrical transparency will allow decreasing the gas pressure in the anode cavity by 1–2 orders of magnitude as compared to the cathode cavity, adding to stability of the plasma cathode [5].

In this study we analyzed how the size of apertures of the plasma cathode grid influenced the distribution of the plasma potential and currents over electrodes of the gas-discharge system, which included a hollow cathode and a hollow anode of a constricted glow discharge and an outlet stage in a peripheral magnetic field. The lifetime of the plasma cathode grid and the energy efficiency of the ion generation in the gas-discharge system under study were evaluated.

2. Experimental

Electrode schemes of the ion source are shown in Fig. 1. In the initial variant of the ion source [6] (Fig. 1, *a*) the plasma cathode grid 1 of diameter 20 mm was placed opposite to the exit aperture of the hollow cathode 2. Linear rows of permanent magnets 4, which formed the peripheral magnetic field, were installed on the external surface of the main hollow anode 3. The screen electrode of the ion optical system was replaced by the ion collector 5 in experiments. The modified ion source (Fig. 1, *b*) additionally had the glow-discharge hollow anode 6, which was covered with the perforated electrode 1. The plasma emitter of electrons was formed in the plane of the electrode. The diameter and the length of the hollow cathode 2, the hollow anode 6, and the cylindrical portion of the main anode 3 were 130×100 mm. The diameter of the exit aperture of the hollow cathode in the variant "b" was 10 mm, while the diameter of the perforated surface area of the electrode 1 was 80 mm. The size of apertures was adjusted at 0.6–4 mm. The geometrical transparency of the perforated part of the electrode was 2/3.

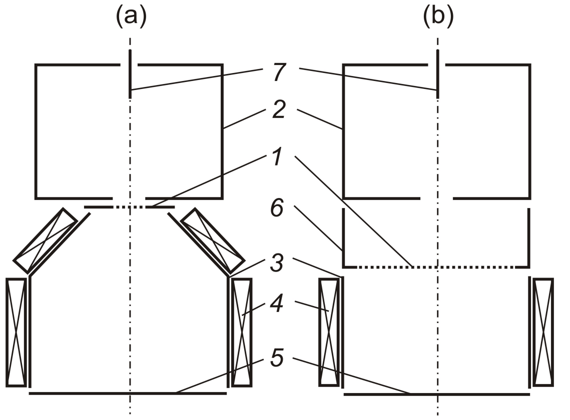

Fig. 1. Electrode schemes of the ion sources: 1 – grid; 2 – hollow cathode, 3 – main hollow anode; 4 – magnets; 5 – collector; 6 – glow-discharge hollow anode; 7 – igniting electrode

The glow discharge current was adjusted at 0.2–0.6 A. The voltage U_2 applied across the second-stage discharge gap was 50, 100 or 150 V. The argon pressure was measured in the vacuum chamber and was varied over the interval of $1.3 \cdot 10^{-2}$–0.13 Pa. Currents were measured in circuits of the hollow cathode, the glow-discharge anode, the main anode, the cathode grid and the ion collector. The potential difference of plasmas on both sides of the plasma cathode grid was measured using a double probe, which was screened from fluxes of fast charged particles. The voltage U_1 between electrodes of the first stage was measured too.

The measured ion current in the collector circuit of the system "a" with a 20-mm grid having meshes 1.2 mm in size is shown in Fig. 2. Pressure dependences of the current exhibited a nonmonotonic trend with the current maximum at a pressure of about $2.7 \cdot 10^{-2}$ Pa. According to [1], this behavior of the dependences is due to the better efficiency of the electron extraction at low pressures and the decrease in the voltage across the bipolar diode at high pressures.

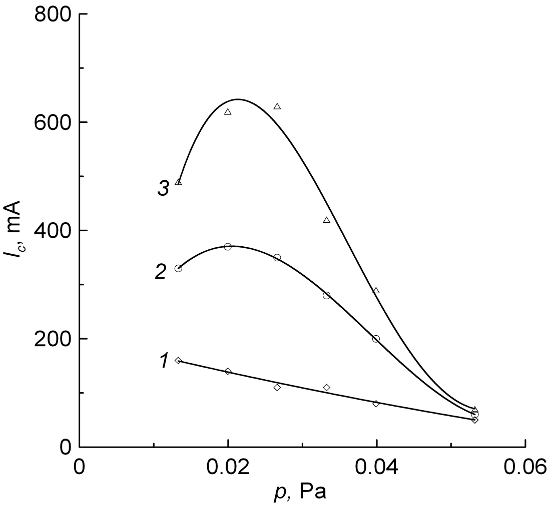

Fig. 2. Dependences of the current in the collector circuit on the gas pressure. The grid diameter was 20 mm. The mesh was 1.2 mm in size. The second-stage voltage U_2: 1 – 50, 2 – 100, 3 – 150 V. The discharge current was 0.6 A

Fig. 3 presents pressure dependences of the ion current in the system "b" when electrons were extracted from the plasma of the wide anodic part of the discharge through the electrode of diameter 80 mm with different grid steps (0.6, 1.2, 2 and 4 mm). If the mesh size was small, the ion current increased monotonically over the whole pressure interval. As the mesh size increased, the current growth rate accelerated with the pressure and the current reached a maximum. The dependences flattened out in the case of coarse grids. The coarser was the grid, the smaller was the saturation current value.

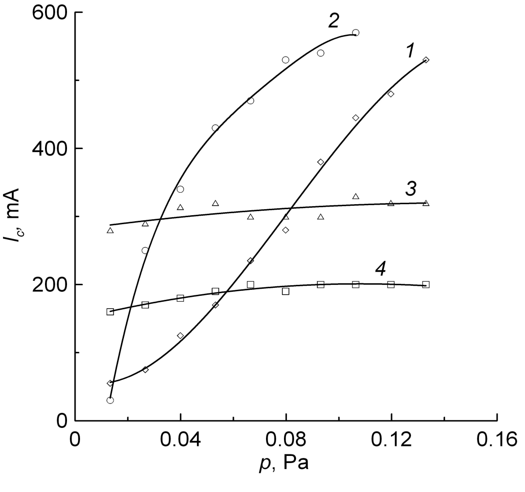

Fig. 3. Dependences of the current in the collector circuit on the gas pressure. The grid diameter was 80 mm. The mesh size: 1 – 0.6, 2 – 1.2, 3 – 2, 4 – 4 mm. The second-stage voltage was 150 V. The discharge current was 0.4 A

The second-stage voltage was 150 V. The discharge current was 0.6 A.

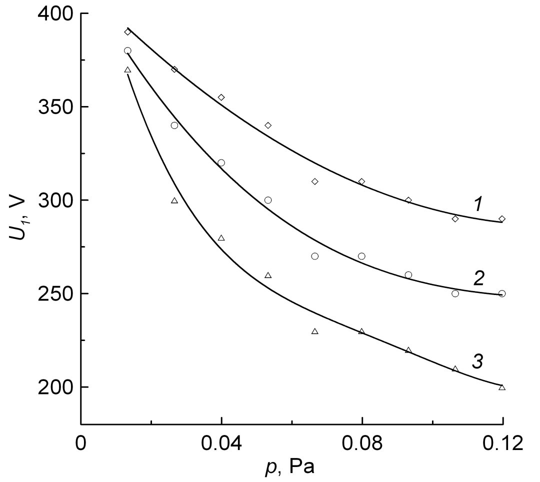

Fig. 4. Dependences of the voltage between the first-stage electrodes on the gas pressure. The grid mesh was 4 mm in size. The second-stage voltage U_2: 1 — 50, 2 — 100, 3 — 150 V. The discharge current was 0.6 A

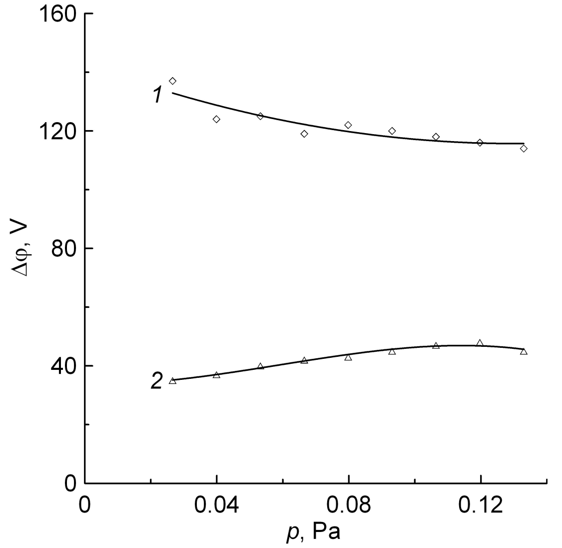

Fig. 5. Dependences of the potential difference between plasmas in the first and second stages on the gas pressure. The grid mesh: 1 — 1.2; 2 — 4 mm

The change of the voltage between electrodes of the first stage, which was necessary to maintain the discharge current constant at different pressures in the second stage, is shown in Fig. 4. If the potential difference of the electrodes in the second stage was increased by 50 V at the maximum gas pressure, it was necessary to decrease the voltage in the first stage nearly by 40 V. The measured difference of the plasma potential on both sides of the plasma cathode grid at different sizes of the apertures is given in Fig. 5. If the size of the apertures increased, the potential drop at the bipolar diode sharply decreased. Since the plasma potential in the outlet stage, which was measured by the probe method, approached the potential of the main anode and increased from +2 to +5 V with the dropping pressure, then it followed that the potential of the electron-emitting plasma sharply increased with the growing size of the apertures. As the voltage at the second stage was 150 V and the grid apertures were 3 mm in size, the voltage drop across the bipolar diode decreased by 100 V. The influence of the discharge current on the voltage drop at the bipolar diode is shown in Fig. 6.

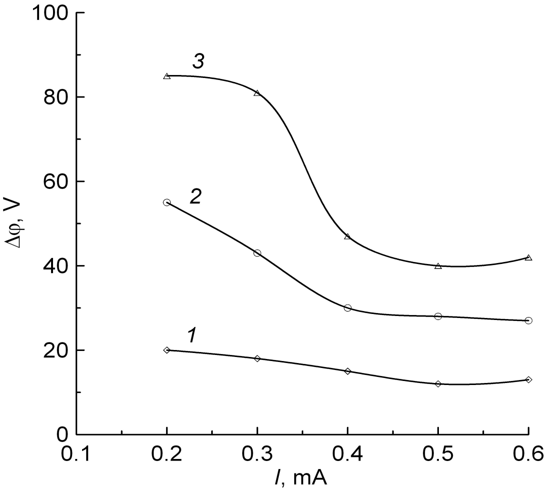

Fig. 6. Dependences of the potential difference between plasmas in the first and second stages on the discharge current. The grid mesh was 4 mm in size. The second-stage voltage U_2: 1 — 50, 2 — 100, 3 — 150 V. The gas pressure was 6.7 10 2 Pa

Separate measurements of the current in circuits of the glow-discharge hollow anode and the plasma cathode grid revealed that the current in the anode circuit reversed sign and became ionic with the growing pressure. The density of the ion current to the anode was 1—2 orders of magnitude smaller than to the grid.

3. Discussion

Different emission regimes of the plasma cathode in the ion source were realized by changing the size of the grid apertures and the gas pressure. When the size of the grid meshes was small and the gas pressure was low, the current of extracted electrons was determined by the capacity of the bipolar diode. That is, in accordance with the Langmuir criterion, the density of the electron current changed in proportion to the density of the reverse ion current $j_e \sim j_i (M_i/m_e)^{1/2}$ [7]. The potential difference at the bipolar diode was nearly equal to the voltage between electrodes of the second stage. This emission regime, which was limited by the space charge, corresponded to the free emission of a thermoionic cathode in the case of the discharge in a gas-filled diode.

As the gas pressure or the voltage in the second stage increased, the saturation current of ions from the anode plasma and the bipolar diode conductivity increased, leading to the regime when the electron emission current was equal to the glow-discharge current or when electrons were extracted from the plasma most efficiently. Since the discharge current was constant, the emission electron current was stabilized too, despite the increase in the density of the reverse ion current from the anode plasma. Put another way, by analogy with a thermoionic cathode, the plasma cathode changed to the forced emission regime. Similarly to the electron sources [8], the emission current of the plasma cathode was stabilized thanks to the growth of the cathode plasma potential, the increase in the ion sheath thickness, the decrease in the surface area of the electron emitting plasma, and the rise of the emission current density in accordance with the change of the density of the reverse ion current. Unlike the case of the thermoionic cathode, the electric field intensity was zero on the surface of the plasma cathode in the stationary state. It may me conjectured therefore that the cathode plasma received just a small portion of the ion current, which ensured stability of the double sheath in the grid apertures. The rest of the ion current, which was comparable in its magnitude with the electron emission current, closed to the plasma cathode grid.

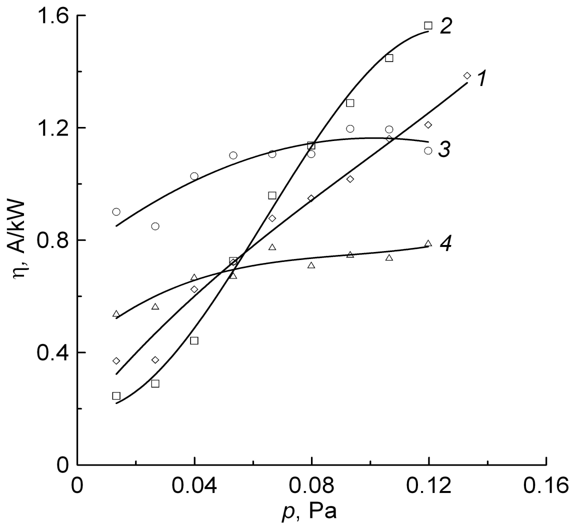

Fig. 7. Dependences of the energy efficiency of the ion generation on the gas pressure. The grid mesh: 1, 2 – 0.6; 3, 4 – 4 mm. The discharge current: 1, 3 – 0.2; 2, 4 – 0.6 A. The second-stage voltage was 150 V

Because the electrode scheme of the ion source was altered and electrons were extracted from the plasma in the wide anodic part of the hollow-cathode glow discharge, it was possible to increase the diameter of the plasma cathode grid to 80 mm and replace mesh grids by a solid perforated electrode with apertures having a larger diameter. As a result, in addition to the decrease of the current density in the bipolar diode, the total current to the grid increased thanks to its larger surface area. In our experiments the surface area of the grid increased ~16 times and the total current to the grid became ~4 times larger at the same discharge current. Consequently, the density of the ion current to the grid decreased ~4 times. The perforated electrode was 0.5 mm thick as compared to the grid wire 0.3 mm thick. So, if we proceed from the condition that the grid should not be less than 0.15 mm thick, the lifetime of the plasma cathode grid increased by nearly one order of magnitude. It should be noted however that in this case of large grid surface area the number of sputtered species should increase in proportion to the ion current, that is, by several (~4) times.

The energy efficiency of the ion generation in the anode plasma of the ion source with extraction of electrons through a perforated electrode can be given by the relationship $\eta = I_{i1}/[I_1(U_1+U_2)+I_{i12}U_2]$. Here I_{i1} is the ion current to the collector, I_{i12} is the sum of ion currents to the grid and the collector, and I_1 is the discharge current in the first stage. Because the ion loss to the plasma cathode grid increased and the electron energy diminished (and, hence, the ionization frequency decreased), the efficiency was impaired, but was partially compensated by the decrease in the total voltage (U_1+U_2) at the gas-discharge system with growing pressure. Calculated efficiencies for the grid with a large surface area (50 cm^2) at different apertures and discharge currents are shown in Fig. 7. The rapid growth of the efficiency with the gas pressure and meshes 0.6 mm in size was due to the better extraction of electrons while the plasma potential of the electron emitter changed little. When the grid had openings 4 mm in size, the plasma cathode operated in the regime of the forced direct-current emission. A small improvement of the efficiency in this regime could be explained by the increase in the gas ionization frequency in the second stage with growing pressure. The maximum energy efficiency was 1.6 A/kW and 1.1 A/kW for grids with meshes 0.6 mm and 4 mm in size respectively. In the source with a small-size grid (Fig. 1, *a*) the energy efficiency at the point corresponding to the maximum pressure dependence of the ion current (Fig. 2) was 1.4, 2.2 and 2.6 A/kW at the discharge current of 0.2, 0.4 and 0.6 A respectively. The better efficiency was due to a little loss of the ion current to the grid having a small surface area.

4. Conclusions

1. The use of a gridded plasma cathode with extraction of electrons from the plasma in the wide anodic part of the hollow-cathode glow discharge in a bucket-type ion source provided operation of the plasma cathode in the forced emission regime with a maximum efficiency of the electron extraction and a nearly constant ion emission current over a wide interval of gas pressures.
2. The forced emission of the grid plasma cathode in the ion source was ensured by the grid stabilization mechanism when the adjustment of the potential of the electron emitting plasma changed

the size of the near-anode ion sheath, the surface area of the electron plasma emitter and the electron current density such that the condition of stability of the double sheath in the grid apertures was fulfilled. The surplus ion current from the anode plasma was closed to the plasma cathode grid.

3. If the plasma cathode grid size was made larger, the loss of the ion current to the grid increased. As a result, the flow of sputtered species increased and the energy efficiency of the ion source was impaired. Nevertheless, the lifetime of the grid, which is the most critical unit of ion sources of this type, can be extended, according to estimates, by one order of magnitude.

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