

Formation of emission plasma in a pulsed forevacuum-pressure plasma-cathode electron source based on a cathodic arc with redistributing electrode

I Yu Bakeev¹, A V Kazakov¹, A V Medovnik¹ and E M Oks^{1,2}

¹ Tomsk State University of Control Systems and Radioelectronics, 40 Lenina Ave., Tomsk 634050, Russia

² Institute of High Current Electronics SB RAS, 2/3 Akademichesky Ave., Tomsk 634055, Russia

E-mail: andrykazakov@gmail.com

Abstract. The paper describes the investigations of the influence of a redistributing electrode on the formation of emission plasma near the electron extraction region in a pulsed forevacuum-pressure plasma-cathode electron source utilizing a cathodic arc for generation of emission plasma. The authors show that the use of the redistributing electrode with optimal geometry in the discharge gap of the source provides a fairly uniform emission plasma density distribution. For the used discharge gap and pulse duration up to 5 ms, the use of the spherical stainless-steel redistributing electrode with radius of 6 mm provides rather uniform plasma density distribution near electron extraction region in the investigated gas pressure range 3–15 Pa. A model simulating the formation of plasma in the forevacuum pressure range has been developed. The model considers the scattering of ions of the arc plasma by gas atoms and the formation of gas ions by ionization of the operating gas by high-energy electrons. The calculated distributions of emission plasma density are consistent with the experimental data for different sizes of the redistributing electrode and for different gas pressures. The model and experiment show that the plasma density near the anode mesh increases with increasing gas pressure, for example, increase in gas pressure from 5 to 10 Pa leads to an 80% increase in density of emission plasma.

1. Introduction

Uniformity of the current density distribution over the beam cross section is an important parameter for large cross section electron beams [1–3]. For plasma-cathode electron-beam sources, the current density distribution uniformity is mainly determined by the distribution of plasma density in the electron extraction region [1–3]. Plasma-cathode sources based on an arc discharge provide generation of electron beams with high current and long pulse duration [4–6]. However, plasma-cathode electron sources based on an arc discharge with a single cathode are characterized by significant plasma distribution inhomogeneity [1]. A common approach to obtaining a more uniform plasma in such plasma-cathode sources operating at ordinary gas pressure (10^{-3} – 10^{-1} Pa) is to use expanders (hollow anodes) and special redistributing electrodes located in the discharge region (inside the expander) at some distance from the cathode [1, 2, 4, 5]. The redistributing electrode blocks part of the plasma streaming from the cathode and the plasma is more homogeneously distributed at the expander. The mechanism of the influence of the redistributing electrodes on the formation of uniform plasma in the



discharge gap has been researched quite well for plasma-cathode e-beam sources operating at pressures of 10^{-3} – 10^{-1} Pa [1, 2].

Forevacuum-pressure plasma-cathode electron sources, which generate low-energy (up to 30 keV) electron beams in the forevacuum pressure range 3–100 Pa both in continuous and pulsed modes [6–8] have been developed. Interest in developing this kind of electron source is due to their capability of treating insulating materials (ceramics, glasses, and polymers) by electron beam directly [10]. An arc discharge with cathode spots (a cathodic arc) is used to generate the plasma in pulsed forevacuum-pressure plasma-cathode electron sources to provide longer pulse duration and higher beam current, and therefore higher beam energy per pulse [6]. Generation of large-radius electron beams with homogeneous current density distribution requires optimizing the geometry of the discharge region with the redistributing electrode. However, the approaches used for sources operating at pressures of 10^{-3} – 10^{-1} Pa are not always appropriate for forevacuum-pressure electron beam sources. The most significant differences include the scattering of particle fluxes from the cathode by operating gas, as well as the significant effect of gas ions on the arc discharge operation [11].

Thus, the purpose of the work is to research the influence of the redistributing electrode on plasma formation near the electron extraction region in the pulsed forevacuum-pressure plasma-cathode electron source based on an arc discharge, and to develop a physical model of plasma generation in the discharge gap with redistributing electrode in the forevacuum pressure range.

2. Experimental setup and techniques

A schematic of the discharge gap (i.e., the emission plasma formation region) of the forevacuum-pressure plasma-cathode electron source based on the cathodic arc, along with the measurement system, is shown in Figure 1. The discharge gap consists of a copper rod cathode 1 of diameter 6 mm, a cylindrical ceramic insulator 2, and hollow stainless-steel anode 3 with inner diameter 114 mm. The cathode 1 and ceramic insulator 2 are mounted on a special current feedthrough 4 fixed in an insulator 5. The ceramic insulator 2 provides electrical insulation and limits the working surface of cathode 1. The emission window in the anode is covered by a fine stainless-steel mesh (anode mesh) 6. The arc discharge is initiated by an auxiliary discharge over the surface of the ceramic insulator between the cathode 1 and the ignitor electrode 7 in “triggerless” mode. To implement the “triggerless” mode, the ignitor electrode 7 is connected to the anode through a resistance of 500 Ω . A redistributing electrode 8 is installed within the discharge gap. In the experiments, we used spherical stainless-steel redistributing electrodes of different radii r_r . The arc discharge is powered by pulsed power supply unit 9 which provides a discharge current I_d up to 60 A with pulse duration up to 5 ms at a pulse repetition rate of 1 Hz.

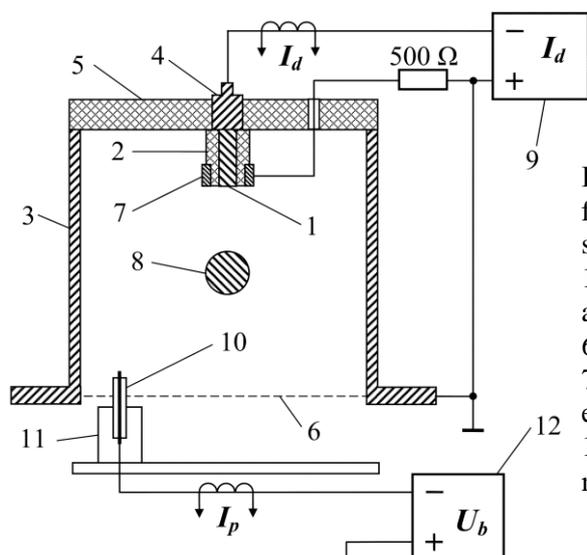


Figure 1. Schematic of the discharge gap of the forevacuum-pressure plasma-cathode electron source and the measurement system: 1 – cathode; 2 – ceramic insulator; 3 – hollow anode; 4 – current feedthrough; 5 – insulator; 6 – emission fine mesh (anode mesh); 7 – ignitor electrode; 8 – redistributing electrode; 9 – pulsed power supply unit; 10 – Langmuir probe; 11 – two-coordinate manipulator; 12 – DC power supply.

The discharge gap is mounted on a vacuum chamber that is pumped by a mechanical pump with base pressure 2.5 Pa. The operating pressure p is regulated via the flow rate of gas (nitrogen) into the vacuum chamber. Plasma density n is measured by a single Langmuir probe 10. To monitor the plasma density distribution, the probe was placed on a two-coordinate manipulator 11. A DC negative bias voltage $U_b = -100$ V, provided by power supply 12, was applied to the probe for measuring the ion saturation current, and the plasma density n was calculated from the ion saturation current I_p . The arc discharge current I_d and the probe current I_p were measured using current transformers.

3. Description of the model

Our model for describing the plasma formation process in the hollow anode near the emission surface of the plasma (i.e., near the electron extraction region) considers a two-dimensional plasma motion. The point of origin is placed at the center of the emitting surface of the cathode, the z axis is directed along the symmetry axis of the discharge gap, and the r axis is directed in the radial direction (Figure 2).

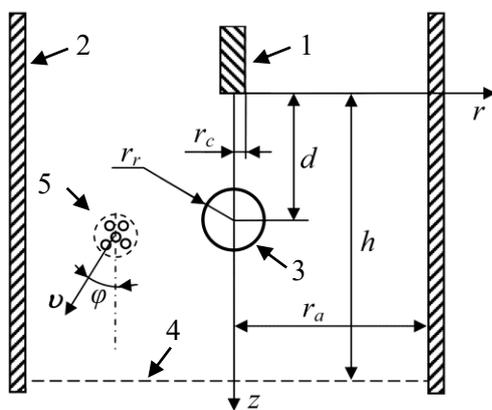


Figure 2. Schematic representation of the discharge system: 1 – cathode; 2 – anode; 3 – redistributing electrode; 4 – emission (anode) mesh; 5 – plasma group; r_c – cathode radius; r_a – radius of the hollow anode; r_r – radius of the redistributing electrode; h – distance between the cathode and the anode mesh; d – distance between the cathode and the centre of the redistributing electrode; v – plasma group velocity; φ – angle between velocity vector and z axis.

Since the plasma pulse duration $\tau_d = 70 - 5000$ μs is much longer than the discharge formation (initiation) time, we do not consider processes at the early stage of arc development [12]. Thus, the process of plasma propagation and distribution after initiation of the arc discharge is mainly due to the spread of the arc plasma from the cathode. To describe the plasma propagation process, a "large particle method" was used [13], in which we consider a finite (small) number of groups (a group is a large particle) characterized by common parameters: the coordinates (z , r); the absolute value of velocity v ; angle φ between the velocity vector and the z axis (see Figure 2); the number of particles in the group N ; the distance x traveled by the group, counted from the time the group was emitted from the cathode surface, or from the time the group particles scattered on gas molecules. Particles emitted from the cathode are divided into several plasma groups with different initial angles φ in the range of $-90 \div 90$ degrees, according to the distribution of plasma density near the cathode [14]. The groups are placed at the center of the cathode, and the velocity of groups is set as $v = 2 \cdot 10^4$ m/s (the velocity of the front of the expanding cathode plasma for copper electrodes [15]). Further propagation of plasma groups occurs according to the direction of the large particle velocity vector v . In addition to the initial directed velocity v , the plasma flow has a thermal velocity spread which causes expansion of plasma in the radial direction. Thus, the thermal velocity should be added to the radial component of velocity vector v_r . The expansion of plasma in the radial direction is taken into account by dividing groups into subgroups according to a Maxwellian velocity distribution:

$$\Delta N = N \cdot \sqrt{\frac{m}{2\pi \cdot k \cdot T_i}} \cdot \exp\left(-\frac{m \cdot v_r^2}{2 \cdot k \cdot T_i}\right) \cdot \Delta v_r, \quad (1)$$

where ΔN is the number of particles in the subgroup, m is the mass of the particle (ion), k is Boltzmann's constant, T_i is the plasma temperature, v_r is the average thermal velocity of ions in the group, and Δv_r is the speed interval in the group. The maximum possible thermal speed is taken as the speed corresponding to the value of the probability density function equal to 0.1% of the distribution maximum.

The geometry of the discharge gap of the plasma-cathode source, including the redistributing electrode and its size, is taken into account by removing the plasma groups falling on the cathode, anode and the redistributing electrode.

A characteristic of the plasma density distribution in the forevacuum pressure range is the scattering of plasma particles on operating gas molecules. Since the de Broglie wavelength of a copper atom is much smaller than the molecular size, scattering can be considered using classical mechanics. Thus, atoms and particles are represented as completely elastic balls [16, 17]. The scattering of groups of plasma particles is produced at each passage of the group with mean free path defined as [17]

$$\lambda = \frac{k \cdot T}{\sqrt{2} \cdot \sigma \cdot p}, \quad (2)$$

where $\sigma = \pi(r_1 + r_2)^2$ is the total scattering cross section (r_1 and r_2 are the radii of a moving copper atom and a stationary nitrogen atom, respectively), p is the operating gas pressure, and T is the gas temperature. Particles are deflected according to the differential scattering cross section $d\sigma$ in the center of inertia system of the considered inter-particle collision [18]:

$$d\sigma = \frac{\pi \cdot (r_1 + r_2)^2 \cdot \sin \theta \cdot d\theta}{2}, \quad (3)$$

where θ is the scattering angle in the center of inertia system. The absolute value of velocity in the center of inertia system v' does not change. To go to the "laboratory" reference frame, the velocity vector of the center of inertia v_c is added to the absolute value of the velocity in the center of inertia system v' .

The radial distribution of plasma density near the anode is determined by using the equation of particle balance in stationary mode, taking into account the formation of gas ions caused by ionization of operating gas by high-energy electrons from the cathode flare plasma:

$$\frac{dn_c}{dt} + z_i - D \cdot \frac{1}{r} \cdot \frac{d}{dr} \left(r \cdot \frac{d}{dr} \cdot n(r) \right) - z_{em} = 0, \quad (4)$$

where dn_c is the increase in plasma density due to the arrival of particles of plasma of the cathode flare, z_i is the yield of electron ionization of gas molecules by the cathode flare, D is the diffusion coefficient, and z_{em} is the number of ions per unit time that go to the anode.

The ionization yield z_i of gas molecules by high-energy electrons is determined by the equation [19]:

$$z_i = n_c \cdot n_0 \cdot \left(\frac{8k \cdot T_e}{\pi \cdot m} \right)^{3/2} \cdot \alpha_i \cdot \left(U_i + \frac{2k \cdot T_e}{e} \right) \cdot \exp \left(-\frac{e \cdot U_i}{k \cdot T_e} \right), \quad (5)$$

where k is Boltzmann's constant, n_0 is the density of gas molecules, e and m_e are the electronic charge and mass, T_e is the electron temperature, α_i is the proportionality coefficient [19], and U_i is the first ionization potential of a gas molecule.

The departure of plasma ions to the anode z_{em} is determined by the Bohm current:

$$z_{em} = \frac{1}{4} n(r) \cdot \sqrt{\frac{8 \cdot k \cdot T_e}{\pi \cdot m}} dh, \quad (6)$$

where dh is the width of the anode layer in which the distribution is calculated.

4. Results

The model developed allows optimizing the position (in the discharge gap) and radius of the redistributing electrode to obtain a uniform radial distribution of plasma density $n(r)$ near the anode mesh. Figure 3 shows the radial plasma density profiles near the anode mesh calculated for various redistributing electrode radii, together with the measured experimental data. For the case of a large diameter redistributing electrode, r_r (Figure 3, *a*), a significant part of the plasma flow from the cathode is blocked by the redistributing electrode, as a result of which the maximum of the distribution is near the walls of the hollow anode, while the use of the optimized radius r_r leads to a relatively uniform plasma density distribution near the anode mesh (Figure 2, *b*).

The calculated and experimental plasma density distributions for different gas pressures p are shown in Figure 4. These results show that the plasma density near the anode mesh increases with increasing gas pressure p , due to ionization of the operating gas. For example, a twofold increase in gas pressure from 5 to 10 Pa leads to an 80% increase in plasma density, and at the same time the shape of the density distribution changes little. The calculated plasma density distributions, both for different sizes of redistributing electrode and for different gas pressures p , are consistent with experimental results.

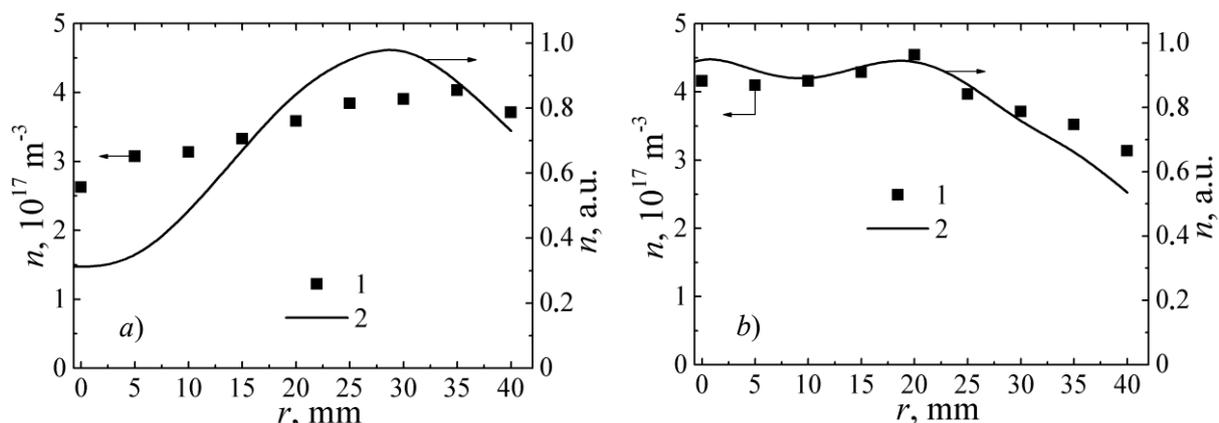


Figure 3. Radial distributions of plasma density n with a redistributing electrode of radius $r_r = 12$ mm (*a*), and $r_r = 6$ mm (*b*). 1 – experiment; 2 – calculation. Gas pressure $p = 4$ Pa.

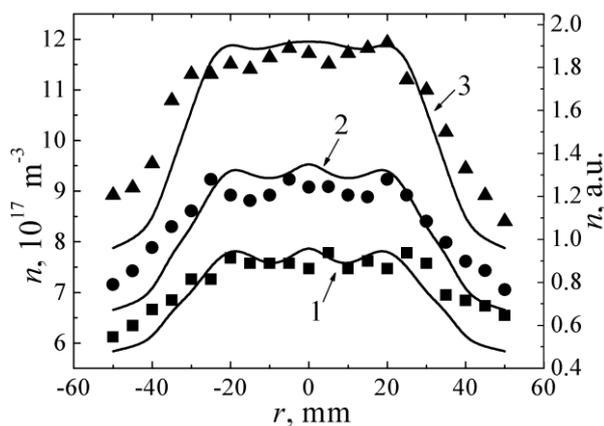


Figure 4. Distribution of plasma density n near the anode (emission) mesh for various gas pressures p ($r_r = 6$ mm): 1 – $p = 5$ Pa; 2 – $p = 7$ Pa; 3 – $p = 10$ Pa. Points – experimental data; curves – calculation.

5. Conclusion

The use of a redistributing electrode with optimized size and shape in the discharge gap of a plasma-cathode source provide significantly improved uniformity of the emission plasma. A model that elucidates the reasons and features leading to improved plasma density distribution uniformity near the electron extraction region (i.e., near the anode mesh) has been developed. In particular, the model includes mechanisms for the scattering of plasma ions by gas atoms and the formation of gas ions due to gaseous ionization by high-energy electrons. The calculated plasma density distributions are consistent with the experimental data for different sizes of the redistributing electrode and for different gas pressures.

Acknowledgements

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