Formation of emission plasma by a constricted arc discharge in a pulsed forevacuum plasma-cathode electron source

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Abstract. The research of generation of emission plasma by a constricted arc discharge in the discharge system of a pulsed forevacuum plasma-cathode electron source is presented. Formation of emission plasma by the constricted arc discharge in the forevacuum electron source has provided elimination of penetration of the cathode material into the hollow anode, i.e. into region of emission plasma formation. As compared to plasma-cathode electron sources generating electron beams in pressure range $10^{-3}$–$10^{-1}$ Pa, for the forevacuum plasma-cathode source higher operation pressure in the hollow anode (7–21 Pa) has caused strong dependence of emission plasma density on gas pressure. In particular, an increase of the gas pressure has led to a decrease of the plasma density at distance from the constricting channel.

1. Introduction

Plasma-cathode electron sources of pulsed electron beams are used for surface modification of different materials [1-3], pumping of gas lasers [4, 5], and for some other applications [6, 7]. In particular, electron beam sources generating the low-energy (usually up to 25–30 keV) pulsed electron beams in the standard gas pressure range $10^{-3}$–$10^{-1}$ Pa are used mainly for surface modification of metals and other conductive materials [2, 3]. Forevacuum plasma-cathode sources generating electron beams in the pressure range 3–100 Pa (forevacuum pressure range) [8, 9] provide to treat various dielectric materials (ceramics, glasses and polymers) [10, 11]. The possibility of direct treatment of dielectrics by the electron beams in the forevacuum pressure range is provided due to the negative charge, brought by the e-beam to the dielectric surface, is compensated by ions from a beam-produced plasma and by a non-self-sustained discharge arising between the charged dielectric surface and grounded walls of the vacuum chamber (or other grounded parts) [10].

The characteristics of the plasma-cathode sources of electron beams are dependent on the parameters of the emission plasma, from which electrons forming e-beam are extracted [12, 13]. To generate emission plasma in the pulsed plasma-cathode sources, an arc discharge with (“open”) cathode spots is often used [12, 13]. This type of arc discharge has some advantages, for example, the relative simplicity of the discharge system, high discharge current, and long pulse duration of the discharge current. At the same time, the use of the arc discharge with open cathode spots has disadvantages associated with the operation of the cathode spots [13]. In particular, the chaotic movement of the cathode spot can significantly affect the plasma homogeneity, and the flows of macroparticles and vapors of the cathode material, which are formed during the operation of the
cathode spots, can penetrate into the acceleration gap of the electron source and into beam propagation region. To reduce these disadvantages associated with the operation of the cathode spots, a constricted arc discharge is used [13–15]. The constricted arc discharge is realized by compression (constriction) of the positive column of the arc discharge by a narrow channel in the intermediate (constricting) electrode installed between the cathode and the anode of the discharge system [13–15]. In the plasma-cathode sources, this intermediate electrode is usually made of metal and it has a floating potential.

The operation features and parameters of the constricted arc discharge and features of emission plasma formed by this type of discharge have been well studied for the plasma-cathode sources generating electron beams in the standard gas pressure range of $10^{-3}$–$10^{-3}$ Pa [13-15]. However, the use of the constricted arc discharge for generation of the emission plasma in the forevacuum pulsed electron source has not been investigated previously. Therefore, the aim of this work is to research generation of emission plasma by the pulsed constricted arc discharge in the discharge system of the forevacuum plasma-cathode electron source.

2. Experimental setup and techniques
A scheme of an experimental setup for research of the emission plasma formed by the constricted arc discharge in a pulsed forevacuum plasma-cathode source of electron beam is presented on Figure 1. The cathode assembly of the source consists of a cylindrical copper cathode (diameter of 6 mm), a ceramic insulator, an igniter electrode, and a current lead. The current lead and the ignition electrode are made of stainless steel. The cathode assembly is mounted in polyamide insulator. Constriction of the positive column of arc discharge is carried out by a narrow channel in an intermediate electrode (constricting electrode). The intermediate electrode is made of two stainless-steel insulated plates of 1 mm thick each, and has floating potential. Coaxial holes with a diameter of 3 mm are made in these plates. The distance between the plates is 1 mm, which provided the constricting channel of 3 mm long. The cathode and the constricting holes in the intermediate electrode (plates) are aligned with axis of symmetry of the discharge system. The current of the constricted arc discharge on the one hand is limited by the current cutoff (current drop to 0 A) followed by the extinction of the discharge, on the other hand, by the transition to the cascade mode of the arc discharge operation [13-15]. Both of these cases are not working modes. In particular, in case of arc “switching” to the cascade mode of discharge operation, cathode spots appear on the intermediate electrode, which negates all the advantages of the constricted arc discharge. The transition to the cascade mode can occur both after the interruption of the discharge current (current drop to 0 A) and without interruption of the arc current. Therefore, as in the monograph [13], to detect the transition of the arc discharge to the cascade mode of operation the constricting plates are connected by a conductor, and the current $I_c$ between these constricting plates is measured with using a current transformer. In case of transition of arc to the cascade mode, the current $I_c$ appears between the constricting plates, and the value of $I_c$ can reach a value closed to or equal to the discharge current $I_d$. A cylindrical hollow anode is made of stainless steel. The inner diameter of the anode is 114 mm, and the height is 100 mm. The hollow anode on the upper end has opening with diameter of 4 cm. An emission aperture (opening in the bottom end of the hollow anode with diameter of 114 mm) is covered by fine stainless-steel mesh (cell sizes are $0.3 \times 0.3$ mm²). The isolation of the constricting electrode from the anode is provided by a polyamide insulator. The discharge system is installed on an insulator. To introduce the probes into the discharge system, the accelerating electrode (extractor) has been removed and small openings (diameter of 8 mm) in the anode mesh have been made.

The plasma-cathode electron source is mounted on a flange of a vacuum chamber. The vacuum chamber is pumped out by a mechanical forevacuum pump. The pump provides a minimum pressure of 2.5 Pa, and the operating pressure $p$ is controlled by flow rate of working gas directly to the vacuum chamber (at constant rate of pumping out). Argon (Ar) has been used as a working gas in this work. The constricted arc discharge is powered by a pulsed power supply unit. In the experiments arc discharge current $I_d$ has been up to 50 A, the pulse duration has been 120 μs, and the pulse repetition rate has been 1 pps (pulse per second).
The discharge current $I_d$ has been measured by a current transformer. Plasma density $n$ has been measured using a single Langmuir probe. The plasma density $n$ has been estimated from the saturation current $I_i$ on the ion branch of the probe current-voltage characteristic. The negative bias potential of the probe has been set using a DC voltage $U_b$ power supply. The probe current $I_i$ has been determined by measuring the voltage $U_p$ across a non-inductive resistance $R_p$ (1.5 kΩ). The voltage $U_p$ has been measured by compensated oscilloscope voltage probe. To measure the plasma density $n$ on different distances $L$ from the constricting channel the Langmuir probe has been mounted on a movable manipulator platform (not shown in the Figure 1). Investigations of the optical emission spectra of the constricted arc plasma formed in the hollow anode have been carried out using the spectrometer Ocean Optics HR4000CG-UV-NIR. This spectrometer provides registration of optical radiation in the wave range of 200–1100 nm. To output the optical radiation from the plasma, a special "optical probe" has been used. This vacuum-tight "optical probe" consists of a quartz window (with a wide bandwidth) and stainless-steel tube inside which an optical fiber has been located. The plasma radiation is transmitted through this fiber to the spectrometer. The input aperture of the optical fiber has been directed parallel to the axis of symmetry of the discharge system. To prevent the registration of bright radiation appearing directly from the cathode spots operating on the copper cathode, the input aperture of the optical fiber has been shifted in the radial direction at a distance of 8 mm from the axis of symmetry. The emission lines observed in the experiment have been identified according to [16-18].

3. Experimental results and discussion

Figure 2 shows a typical radiation spectrum of the plasma formed in the hollow anode by the constricted arc discharge. The optical emission spectra of the plasma generated in argon include the emission lines of excited argon atoms Ar in the 700–850 nm region. The most intense lines of the excited argon atoms are wavelengths of 811.5 nm, 763 nm, and 750.4 nm, corresponding to the transitions (2p$^2$) → (1s$^2$), (2p$^6$) → (1s$^5$), (2p$^1$) → (1s$^2$), respectively. The emission spectrum contains several lines of argon ions Ar$^+$ in the 440–1100 nm region, but intensity of argon ions lines are weaker than the intensity of excited Ar atoms. The most intense spectral lines of argon ions are wavelengths 427.7 nm ($^2$P$^0_{3/2}$ → $^2$D$^0_{5/2}$), 460.8 nm ($^2$P$^1_{1/2}$ → $^2$D$^0_{5/2}$), 476.48 nm ($^2$P$^1_{3/2}$ → $^2$D$^0_{5/2}$), and 487.98 nm ($^2$P$^1_{3/2}$ → $^2$P$^0_{1/2}$). Spectral lines of the excited OH* molecule (observation region 305–320 nm) corresponding to the transitions (A$^2Σ^+$) → (X$^2Π_1$), lines of excited atomic oxygen O* (777.4 nm)
corresponding to the transition \((4s(3D)4d) \rightarrow (4p(3P^o))\), and the lines of an excited hydrogen atom from the Balmer series \(\text{H}_\alpha\) (656.2 nm) and \(\text{H}_\beta\) (486.3 nm) have been also observed. The presence of spectral lines of excited \(\text{OH}^*\), \(\text{O}^*\), \(\text{H}_\alpha\) and \(\text{H}_\beta\) is due to residual atmosphere in the vacuum chamber. In the investigated discharge system, the spectral lines corresponding to \(\text{Cu}\) atoms and \(\text{Cu}^+\) ions of the cathode material in the radiation of the plasma formed by the constricted arc discharge has not been observed. Thus, the spectral analysis of the plasma in the hollow anode indicates an insignificant penetration of the cathode material into the hollow anode. At the same time, in case of the transition of arc to the cascade mode of operation, spectral lines of excited \(\text{Fe}\) atoms have appeared in the plasma emission spectra (Fe is the main component of stainless-steel intermediate electrode).

An increase in the discharge current \(I_d\) has led, as expected, to an increase in the intensities \(I\) of the spectral emission lines of argon (Figure 3), which indicates an increase in the density of the plasma formed in the hollow anode. The increase in the plasma density \(n\) with increasing current \(I_d\) has also confirmed by the Langmuir probe measurements. Figure 4 presents the dependence of the plasma density \(n\) on the distance \(L\) from the constricting channel. As the distance \(L\) increases, the plasma density \(n\) sharply decreases.

In plasma-cathode electron sources based on the constricted arc discharge, generating electron beams in the standard gas pressure range of \(10^{-3}–10^{-1}\) Pa, the working gas is puffed into the cathode region, and the gas enters to the hollow anode (or expander) through the constricting channel [13–15]. Therefore, for these electron sources the pressure in the cathode region may reach values about 10 Pa, but pressure in the hollow anode (or expander) does not exceed 0.1 Pa. Forevacuum plasma-cathode electron sources operate in the isobaric mode, i.e. the pressure in the vacuum chamber and pressure in the source are the same, and working gas enters to the source from the vacuum chamber. Therefore, under our experimental conditions, the gas pressure in the hollow anode is 2–3 orders of magnitude higher than in Refs. [13-15]. The higher pressure in the hollow anode of the forevacuum electron source determines the features of formation of emission plasma by the constricted arc discharge. Analysis of the optical radiation of the plasma has demonstrated that increase of gas pressure \(p\) causes first increase in the intensity of the plasma radiation, but when a certain value of \(p\) is reached, a further increase in pressure leads to a decrease in the intensity (Figure 5). This change of intensities \(I\) indicates corresponding change in plasma density \(n\) in the hollow anode. Probe measurements and visual observations of plasma glow in the discharge system have showed that with increasing pressure, the region of “effective” plasma formation moves closer to the constricting channel. In particular, at distance \(L > 30\) mm an increase in the gas pressure \(p\) has led only to a decrease in the plasma density \(n\) (Figure 6). This decrease in plasma density with increase of gas pressure has not observed in plasma-cathode sources operating in the standard pressure range \(10^{-3}–10^{-1}\) Pa. Moreover, in the pulsed
forevacuum electron source based on an arc discharge with (“open”) cathode spots, an increase in gas pressure has led only to an increase in the plasma density \( n \) at distance from the cathode [9].

![Figure 3](image3.png)  
**Figure 3.** Dependences of the intensities \( I \) of argon lines on arc current \( I_d \), \( p = 8 \) Pa: 1 – 750.4 nm; 2 – 763.5 nm; 3 – 811.5 nm.  

![Figure 4](image4.png)  
**Figure 4.** Dependence of the plasma density \( n \) on the distance \( L \) from the constricting channel, \( p = 8 \) Pa, \( I_d = 14 \) A.

![Figure 5](image5.png)  
**Figure 5.** Dependences of the intensities \( I \) of argon lines on gas pressure \( p \), \( I_d = 12 \) Pa: 1 – 750.4 nm; 2 – 763.5 nm; 3 – 811.5 nm.  

![Figure 6](image6.png)  
**Figure 6.** Dependences of the plasma density \( n \) on gas pressure \( p \), \( I_d = 13 \) A.

For the constricted arc discharge formation of plasma in the hollow anode is provided by electrons accelerated in double electrostatic layer existing near the intermediate electrode. In the present work, the observed changes in the plasma density with increasing pressure of the working gas are apparently caused by significant change in the mean free path of accelerated electrons in the hollow anode. Since these accelerated electrons provide formation of plasma in the hollow anode, the mean free path determines the region of “effective” plasma formation. For our experimental conditions, the mean free path of electrons is of the order of several centimeters, and decreases with increasing pressure.

4. Conclusion

We have investigated the generation of emission plasma by the pulsed constricted arc discharge in the discharge system of the forevacuum plasma–cathode electron source. The use of the constricted arc discharge in the pulsed forevacuum electron source has eliminated penetration of the cathode material into the hollow anode, i.e. region of emission plasma formation. The higher pressure in the hollow anode (7–21 Pa) of the forevacuum electron source has caused strong dependence of plasma density
on gas pressure, as compared to the plasma-cathode electron source generating electron beams in pressure range $10^{-3}$–$10^{-1}$ Pa. In particular, at some distance from the constricting channel increase in the gas pressure has led to a decrease in the plasma density.

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