Formation of beam-produced plasma by a forevacuum plasma-cathode source of a pulsed large-radius electron beam

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Abstract. The research of formation of beam-produced plasma by a pulsed low-energy (up to 7 keV) large-radius electron beam, generated by a forevacuum plasma-cathode electron source based on a cathodic arc, is presented. Density of the beam-produced plasma depends nonmonotonically on accelerating voltage. A certain threshold voltage, which depends on the gas pressure and a distance from the extractor of the electron beam source, provides maximal plasma density. At a voltage higher than the threshold voltage, a further increase in the accelerating voltage leads to a decrease in the density of the beam-produced plasma, and the plasma density increases as the distance from the extractor of the electron source increases. These dependencies of plasma density are caused by change in the electron-impact ionization cross sections of gas. Plasma density increases with increasing electron beam current and increasing gas pressure. For the used forevacuum plasma-cathode source of the large-radius electron beam and experimental conditions, varying parameters of the electron beam provides formation of beam-produced plasma with cross-section radius up to 4–5 cm and plasma density up to $10^{17} – 10^{18}$ m$^{-3}$ at distance from the extractor up to 19 cm.

1. Introduction

Low-temperature plasmas are widely used in various fields of science and technology, as well as for medical application [1–6]. In particular, the low-temperature plasmas are used for modification of materials, plasma-chemical technology, etching, sterilization of medical devices and instruments, etc. Various types of gas discharges are usually used to form the low-temperature plasma [1–3]. Generation of plasma by a certain type of gas discharge may have some limitations and disadvantages due to the physical characteristics of the used discharge (for example, a narrow range of operating gas pressure and/or a narrow range of discharge currents at which the discharge operates stably). One of the other ways to generate the low-temperature plasma is by injection of an accelerated electron beam into gas [7–10]. The electron beams can provide generation of beam-produced plasmas with rather high ion density (as high as $10^{11}$ cm$^{-3}$ or more), and the ion density of this plasma can be controlled by beam current [9, 10]. The plasma generated by electron beam has some parameters, which cannot be obtained in plasmas generated by conventional gas discharge systems. One of the features of the beam-produced plasma is the lower electron temperature (about 0.3–1 eV) in comparison with the plasma generated by gas discharges [8–10]. The electron temperature determines the potential of the plasma and, therefore, determines the minimum energy of the ions extracted from the plasma. Lower ion energy provides to
decrease the spread of ion energies in a stream of accelerated ions (or in an ion beam) extracted from the plasma. This is important for precision treatment of materials, in particular, in the production of semiconductor devices [11]. The beam-produced plasma is also used for processing sensitive materials and for controlled etching [12].

Density of the beam-generated plasma is highly dependent on gas pressure. Therefore, an increase in gas pressure leads to higher density of the beam-produced plasma due to an increase in the number of ionization acts of gas particles by accelerated electrons. Forevacuum plasma-cathode electron sources provide generation of electron beams in the pressure range from several pascals to tens of pascals (forevacuum pressure range) [13–15], which is higher in comparison with operation pressure range of conventional plasma-cathode electron sources (10^{-4}–10^{-1} Pa). In the forevacuum pressure range, the electron beams generate the beam-produced plasma with rather high ion density. The beam-produced plasma provides direct treatment of dielectric materials by the electron beam in the forevacuum pressure range (the negative potential brought by the electron beam to the surface of the dielectric is compensated by the ion flow from the beam-produced plasma) [16]. This beam-produced plasma can also be used for treatment of materials and plasma-chemical processes. In the forevacuum pressure range, the generation of the beam-produced plasma by continuous electron beams with current of up to hundreds of mA, as well as by pulsed electron beams with energy up to 3 keV in a strong magnetic field (up to 100 G) has been studied well [8–10]. However, detail research of the generation of the beam-produced plasma by a pulsed large-radius electron beam with current form several amperes to tens of amperes and electron energy of more than 3 keV in the absence of an external magnetic field has not been carried out in the forevacuum pressure range. Therefore, the research of the generation of the beam-produced plasma under these conditions is essential for the development of plasma technology. The purpose of this work is to investigate the formation of the beam-produced plasma by the pulsed low-energy (up to several keV) large-radius electron beam with current up to tens of amperes in the forevacuum pressure range.

2. Experimental setup and techniques

A schematic of experimental setup is presented in Figure 1. A forevacuum pulsed plasma-cathode electron source based on a cathodic arc (an arc discharge with cathode spots), described in detail elsewhere [15], is used to generate a pulsed low-energy large-radius electron beam. The forevacuum plasma-cathode electron source is mounted on a flange of a vacuum chamber, which is pump out by mechanical vacuum pump. The vacuum chamber is preliminarily evacuated to a base pressure of 2.5 Pa, then the operating pressure $p = 3$–15 Pa is controlled by the rate of gas flow to the vacuum chamber (the pumping speed is constant). Nitrogen (N$_2$) is used as working gas. The plasma-cathode electron source is powered and controlled by a power supply unit. The pulsed electron beam is generated by a combination of DC accelerating voltage $U_a$ and pulsed operation of the arc discharge forming emission plasma. In the experiments pulsed arc discharge current $I_d$ is varied from 10 to 40 A, pulse duration is 500 μs, pulse repletion rate 1 Hz, and accelerating voltage $U_a$ is up to 7 kV. The electron beam propagates in the vacuum chamber and is collected by a grounded collector located at a distance of 25 cm from the extractor (accelerating electrode) of the forevacuum electron source. Emission current $I_e = 5$–30 A (and, consequently, electron beam current $I_b$) is controlled by varying arc current $I_d$. The beam current $I_b$ is 30% less than the emission current $I_e$ for the used pressure range $p = 3$–15 Pa [17]. The arc current $I_d$ and emission current $I_e$ are measured by current monitors (current transformers), the accelerating voltage $U_a$ is measured by a high-voltage oscilloscope probe.

Investigations of the ion density $n$ of the beam-produced plasma are carried out using a single flat probe with a grounded guard ring. The working part of the probe (thin rod) with a diameter of 5 mm is made of stainless steel. An annular ceramic insulator covers the side surface of the stainless-steel rod, and the flat end of rod is the working (collecting) surface of the probe. The guard ring is made of stainless steel and protrudes 1 mm above the flat collecting surface of the probe, which prevented the electron beam from hitting the collecting surface of the probe. To measure distribution of the plasma density $n$, the probe is mounted on a manipulator. The radial distance $r$ is measured from the symmetry axis of the electron beam, and longitudinal distance $L$ is measured from the accelerating electrode (extractor) of the
forevacuum plasma-cathode electron source. The plasma density \( n \) is estimated from the saturation current \( I_i \) of ion branch of the current-voltage characteristic of the probe. A negative DC voltage bias \( U_{bias} = -100 \) V is applied to the probe using a DC voltage source to provide ion current saturation. The current \( I_i \) is determined by measuring the voltage \( U_p \) across a non-inductive resistance \( R_p (1000 \Omega) \). The voltage \( U_p \) is measured using an oscilloscope voltage probe.

![Diagram of experimental setup](image)

**Figure 1.** Scheme of the experimental setup.

3. Experimental results and discussion

An increase in the emission current \( I_e \), and, accordingly, in the electron beam current \( I_b \), as expected, leads to an increase in the plasma density \( n \). Density \( n \) of the beam-produced plasma depends nonmonotonically on the accelerating voltage \( U_a \). At a certain threshold value of the accelerating voltage \( U_{a-th} \), which depends on the gas pressure \( p \) and the distance \( L \) from the extractor, the maximal density of the plasma is provided. For example, at a distance \( L = 19 \) cm, gas pressure \( p = 8 \) Pa and an emission current \( I_e \) of up to 15 A, the maximum plasma density is provided at accelerating voltage \( U_a \) of about 2 kV (Figure 2). In the case of \( U_a < U_{a-th} \), a decrease in the plasma density, occurring as voltage \( U_a \) decreases, is mainly due to a decrease in the distance \( L \) over which the electron beam propagates with minimal losses. At \( U_a < U_{a-th} \), losses of beam current are caused by ionization processes of gas by electron beam and by beam scattering on gas molecules. A decrease in voltage \( U_a \) and an increase in gas pressure \( p \) result in the shorter distance of beam propagation occurring with minimal losses. In the case of \( U_a > U_{a-th} \), an increase in the accelerating voltage \( U_a \) leads to a decrease in the density \( n \) of the beam-produced plasma (Figure 2). This decrease of density \( n \) is due to a decrease in the electron-impact ionization cross section of gas by accelerated beam’s electrons. For the used voltage \( U_a \), the energies of the accelerated electrons are several kilo-electron volts, and these energies correspond to the right (falling) branch of the dependence of the total ionization cross section of gas on the electron energy [18].
Figure 2. Dependence of the density $n$ of the beam-produced plasma on the accelerating voltage $U_a$, $I_e = 16$ A, $L = 19$ cm, $p = 8$ Pa, $r = 0$ cm.

The radial distributions of ion density $n$ of the beam-produced plasma at different distances $L$ from the accelerating electrode are presented in Figure 3(a). At $U_a > U_{a, th}$, the plasma density $n$ increases as the distance $L$ increases. The observed increase in the plasma density $n$ with increasing distance $L$ is probably caused by an increase in the electron-impact ionization cross section of gas due to a decrease in the electron energy occurring as the beam propagates through the gas. Figure 3(b) shows the radial distributions of the plasma density $n$ at different gas pressures $p$. An increase in the gas pressure $p$ leads to an increase in the density $n$ of the beam-produced plasma due to the growth of number of ionization acts of gas particles by accelerated electrons.

Figure 3. Radial distributions of density $n$ of the beam-produced plasma (a) at different distances $L$ from the extractor and (b) at different gas pressure $p$, $I_e = 13$ A: (a) $-U_a = 5$ kV, $p = 8$ Pa; $b)-U_a = 3$ kV, $L = 19$ cm; 1 – $L = 10$ cm; 2 – $L = 15$ cm; 3 – $L = 19$ cm; 4 – $p = 8$ Pa; 5 – $p = 10$ Pa.

At an emission current $I_e$ of up to 15 A and accelerating voltage $U_a > U_{a, th}$ the shape of radial density distribution of the beam-produced plasma changes insignificantly, and the nonuniformity of the beam plasma distribution does not exceed 10–15 % at distances $L$ up to 19 cm (Figure 3). At longer distances $L$ from the extractor, depending on the gas pressure $p$, accelerating voltage $U_a$ and emission current $I_e$ (beam current $I_b$), a cross-section radius $r_p$ of the area, where the beam-produced plasma is formed, can noticeably decrease. The radius $r_p$ of plasma formation area is considered at the half of the height of the
plasma density distribution. At emission current \( I_e > 15 \) A, an increase in the current \( I_e \) leads to a decrease in the radius \( r_p \) at a distance \( L > 10 \) cm from the extractor. The observed decrease in the radius \( r_p \) of the plasma formation area is caused by a decrease in a radius of the electron beam. The radius of electron beam decreases due to compression of the beam by its own magnetic field and by the interaction of the electron beam with the beam-produced plasma [19]. The compression of the electron beam leads to an increase in the beam current density, which causes corresponding increase in the beam-produced plasma density \( n \). This enhances the increase in the plasma density \( n \) with increasing distance \( L \) at \( I_e > 15 \) A. Since the current density of the electron beam increases greater near the symmetry axis of the beam, compression of electron beam also leads to decrease in uniformity of plasma density distribution \( n(r) \) as distance \( L \) increases.

The required density \( n \) of the beam-produced plasma can be obtained by varying the emission current \( I_e \) (electron beam current \( I_b \)), accelerating voltage \( U_a \) and gas pressure \( p \). The choice of the parameters of the electron beam (energy and current) provides to form the beam-produced plasma with cross-section radius \( r_p \) about 4–5 cm and with density \( n \) up to \( 10^{17}–10^{18} \) m\(^{-3}\).

4. Conclusion
We have investigated the formation of the beam-produced plasma by the pulsed low-energy large-radius electron beam with current up to tens of amperes in the forevacuum pressure range. Plasma density depends nonmonotonically on the accelerating voltage. A certain threshold voltage provides the maximal plasma density. This threshold accelerating voltage depends on the gas pressure and the distance from the extractor. At a voltage higher than the threshold voltage, a further increase in the accelerating voltage leads to a decrease in the density of the beam-produced plasma due to a decrease in the electron-impact ionization cross section of gas. Density of the beam-produced plasma increases with increasing electron beam current and increasing gas pressure. The plasma density increases as the distance from the extractor of the electron source increases. For the used forevacuum plasma-cathode electron source and experimental conditions, the beam-produced plasma with cross-section radius about 4–5 cm and with density up to \( 10^{17}–10^{18} \) m\(^{-3}\) has been formed by the pulsed electron beam.

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