Generation of beam plasma near a dielectric target irradiated by a pulsed large-radius electron beam in the forevacuum pressure range

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Abstract. We have investigated generation of beam plasma near a dielectric (ceramic) target irradiated by a pulsed large-radius electron beam in the forevacuum pressure range 3–15 Pa. The electron beam was accelerated with voltage up to 8 kV. Under a certain threshold accelerating voltage increase in the plasma density was observed near the dielectric target as compared with beam plasma density without the target. A decrease in gas pressure leads to smaller value of this threshold voltage. The observed dependencies are apparently caused by two factors: secondary electrons being emitted from the ceramic target and charging of surface of the ceramic target by the e-beam. The secondary electrons, emitted from the ceramic target, provide “additional” ionization of the gas. The charge on the dielectric target surface creates a field that accelerates the slow secondary electrons, which provides an increase in plasma density near the ceramic target. The negative charge on the target slows down the beam electrons, and thus increases total ionization cross section of gas by electron impact. The value of negative charge on the dielectric surface increases with decreasing gas pressure.

1. Introduction
Low-temperature plasmas are widely used in science and various industries [1, 2]. The low-temperature plasma is generated with pulsed and continues gas discharges, and microwave gas discharges [1], as well as by injection of accelerated particles into gas [3–5]. The plasma formed by the injection of accelerated particles into a gas is called beam plasma. In particular, the beam plasma can be formed by an electron beam (“e-beam”) propagating through working gas [5]. The beam plasma can have parameters that cannot be provided with conventional gas-discharge plasma systems. For example, the electron temperature in beam plasma may have values of about 0.3–1 eV [5], which is lower as compared to plasma generated with conventional gas discharges. Since the electron temperature determines the ion energy in plasmas, the beam plasma provides formation of ions with lower energy. The lower ion energy makes it possible to form an ion beam or an ion flux with narrow spread in ion energy, which is crucial for precision processing of different materials, for example, in manufacturing of semiconductor components [6] and surface activation of brittle polymer substrates [7].

Forevacuum plasma-cathode electron-beam sources operate at higher gas pressure from about 3 Pa to 100 pascals (“forevacuum pressure range” or “forevacuum”) [8, 9] as compared to conventional e-
beam sources with hot cathodes (thermionic cathodes) and plasma cathodes, which generate electron beams at $10^{-4}$–$10^{-1}$ Pa. Therefore, the forevacuum e-beam sources are attractive for the formation of beam plasma due to the higher density of neutral gas atoms and molecules as compared with conventional pressures ($10^{-4}$–$10^{-1}$ Pa). Also, such sources can provide treatment of dielectric materials by electron beams due to compensation of the negative charge, which arises on the dielectric surface under e-beam irradiation, with ion flow from the beam plasma [10]. The generation of the beam plasma can be used to obtain atomic and molecular ions, which are difficult to obtain by other methods. For example, the forevacuum sources of a continuous electron beam can be used for evaporation of a ceramic target and ionization of target material vapors [11]. The features of beam plasma generated with continuous electron beams have been well studied in the forevacuum pressure range [11, 12]. The aim of this work has been to investigate generation of beam plasma near a dielectric target irradiated by the pulsed large-radius electron beam in the forevacuum.

2. Experimental setup and techniques

A beam plasma was generated by a pulsed large-radius (about 2.5–3 cm) electron beam at pressure 3–15 Pa. The pulsed electron beam was generated by a forevacuum plasma-cathode electron source based on an arc discharge. The design and operation features of this e-beam source are presented in [9]. The electron-beam source was mounted on a vacuum chamber (Fig. 1). At first, the vacuum chamber and electron source were evacuated by a forevacuum pump to pressure 2.5 Pa, and this pressure was kept about 1 hour. Then, at invariable pumping out rate of vacuum chamber, working gas was supplied to the vacuum chamber, and the required operating pressure $p$ was regulated by the gas flow rate into the chamber. Nitrogen ($\text{N}_2$) was used as the working gas. A power unit provided power supply and controlled the forevacuum plasma-cathode e-beam source. The electron beam propagated in the vacuum chamber and ionized the working gas, which provided formation of the beam plasma. A dielectric target was plane plate made of a high-temperature alumina ($\text{Al}_2\text{O}_3$) ceramic and it had sizes of $50 \times 50 \times 8 \text{ mm}^3$. This ceramic target was positioned on the propagation way of the pulsed electron beam. The distance between the electron beam source and the ceramic target was 25 cm. The ceramic target was mounted on a manipulator, which provided the target movement in a vacuum chamber. It provided to compare the generation of the beam plasma by the pulsed e-beam in two cases: 1 – the ceramic target irradiated by the electron beam; 2 – “free” propagation of electron beam in the vacuum chamber. A stainless-steel holder, which provided attachment of the ceramic target to the manipulator, was designed to minimize a “leak” of beam current through the metallic parts of the holder and the manipulator. To generate the beam-produced plasma in case of presence of the dielectric target along the propagation path of the electron beam, the ceramic target was positioned by the manipulator so that the center of the target coincided with the symmetry axis of the electron beam. To provide “free” propagation of the e-beam in the vacuum chamber, the ceramic target was moved with the manipulator outside the region of beam propagation. A grounded, massive stainless-steel collector was installed at the bottom end of the vacuum chamber (the distance between the e-beam source and the collector was 50 cm) to collect the electron beam (in conditions without the ceramic target).

The emission current $I_e$ was controlled by varying the current $I_d$ of the arc discharge, which formed the emission plasma in the plasma-cathode of the e-beam source. Pulse duration was 500 μs, and pulse repetition rate was 1 Hz. The operating voltage $U_a$ on acceleration gap of the e-beam source was changed in the range from 2 kV to 8 kV. Current transformers were used to measure the currents $I_d$ and $I_e$. A high-voltage probe was used to measure voltage $U_a$ on the accelerating gap. We chose the parameters of the electron beam at which noticeable evaporation and sputtering of the target were not occur. The investigation of the parameters of the beam plasma was fulfilled with a single flat probe. The collecting (working) surface of the probe had radius of 2.5 mm. The collecting surface of the probe was made of stainless steel and was insulated with a ceramic insulator. An annular stainless-steel protective shield was installed on the ceramic insulator. This protective shield protruded on 0.5 mm relative to the working surface of the probe to prevent beam’s electrons reaching the probe surface. The collecting surface of the probe was positioned parallel to the symmetry axis of the
electron beam. The probe was mounted on a manipulator, which provided to change distance \(L\) between the extractor and the probe, and thus distance \(L_c\) between the ceramic surface and the probe. Distance between the probe and the symmetry axis of the electron beam was 2.5 cm. The density \(n_i\) of ions in the beam plasma was investigated by measuring the saturation ion current \(I_i\) to the probe. To provide the saturation of current \(I_i\), a DC power supply unit was used to apply negative bias voltage \(U_b = -100\) V to the probe. The current \(I_i\) was estimated by measuring the voltage \(U_R\) across a non-inductive resistance \(R_p = 1.4\) k\(\Omega\). This voltage \(U_R\) was measured with a voltage probe.

![Figure 1. Scheme of the experimental setup.](image)

3. **Experimental results and discussion**

Figure 2 shows shapes of the discharge current \(I_d\) pulse, the emission current \(I_e\) pulse, and the signal from the probe converted to the ion current \(I_i\). The signal from the probe \(I_i\) has a shape close to the shape of \(I_e\). In case of “free” propagation of the e-beam, the density \(n_i\) of the beam plasma rises with increasing of the distance \(L\) from the electron beam source, but when a certain “boundary” distance \(L_b\) is reached, longer the distances \(L (L > L_b)\) results in lower plasma density \(n_i\) (Fig. 3, curve 2 and 4). This distance \(L_b\) is longer at higher accelerating voltage \(U_a\) and at lower pressure \(p\). The “boundary” distance \(L_b\), at which the maximum density of the beam plasma is reached, is determined by the mean free path of beam’s electrons in the gas. The electrons’ mean free paths increase with increasing kinetic energy of electrons (i.e., increasing voltage \(U_a\)) and decreasing \(p\) [13]. For the used range of the accelerating voltage \(U_a\), the energy of the beam electrons is several keV, which corresponds to the decreasing curve of the dependence of the total ionization cross section \(\sigma\) of nitrogen by electron impact on the electron energy [14]. Therefore, at \(L < L_b\), the beam plasma density \(n_i\) rises with increasing distance \(L\) probably due to a rise in \(\sigma\), because of the beam’s electrons lose the kinetic energy. These losses of kinetic energy occur mainly due to the scattering of the beam’s electrons on gas molecules and also due to electron impact ionization of gas lying in the path of the beam propagation to the considered distance \(L\).
In case of the dielectric target placed on the way of propagation of the e-beam, the saturation ion current $I_i$ (Fig. 2, curve 4), and, consequently, the beam-produced plasma density $n_i$ is higher as compared to generation of the beam plasma without the target (Fig. 3, curves 1 and 3). Difference in the plasma density $\Delta n_i$ for beam plasmas, generated with and without the ceramic target, depends on $L$, $U_a$ and $p$. As the distance $L$ increases, the beam-plasma density $n_i$ increases more strongly in the presence of the ceramic target, i.e., the difference in plasma density $\Delta n_i$ increases (Fig. 3). At distances $L$ up to 19 cm an increase in $L$ results in an almost monotonic rise in $\Delta n_i$. However, at distances $L > 19$ cm, i.e., near the ceramic target (at a distance of less than 6 cm from the ceramic target), a sharp increase in the plasma density $n_i$ is observed as $U_a$ reaches some threshold accelerating voltage $U_{a-th}$. This threshold voltage $U_{a-th}$ depends on gas pressure $p$.

Due to the operation features of the used pulsed plasma-cathode electron-beam source, at voltage $U_a < 3.5$ kV the emission current $I_e$ and the e-beam current density may strongly depend on $U_a$ at $p > 5$ Pa [9]. In addition, it is not always possible to maintain invariable emission current $I_e$ at different $U_a$ under these conditions ($U_a < 3.5$ kV). Therefore, in the Figure 4 we have shown dependences of the beam plasma density normalized to the emission current $n_i/I_e$ on $U_a$. In the case of “free” propagation of the e-beam (without the ceramic target), the normalized plasma density $n_i/I_e$ depends non-monotonically on $U_a$ at distances from the e-beam source $L > 15$ cm (Fig. 4, curve 1). At distance $L > 15$ cm, normalized density $n_i/I_e$ increases with increasing in $U_a$, but reaching some optimal value of the voltage $U_{a-opt}$, a further increase in voltage $U_a$ leads to lower normalizes density $n_i/I_e$. This optimal value $U_{a-opt}$ at which the maximum density $n_{i-max}$ (and $n_{i-max}/I_e$) of the beam plasma is provided, depends on $p$ and $L$. For example, at pressures $p = 8–10$ Pa and $L = 20$ cm, the maximum normalized plasma density $n_{i-max}/I_e$ is reached at voltage $U_{a-opt} \approx 3$ kV. The observed non-monotonic dependence of $n_i/I_e$ on $U_a$ is due to mean free path of beam electrons increases with increasing $U_a$, but $\sigma_i$ decreases with increasing $U_a$.

In case of $U_a > U_{a-opt}$, a decrease in cross section $\sigma_i$, occurs with increasing $U_a$, affects more significantly on generation of the beam plasma and causes lower normalized plasma density $n_i/I_e$ (Fig. 4, curve 1). At distances less than 6 cm from the ceramic target (i.e., $L > 19$ cm) and $U_a > U_{a-opt}$, a increase in the normalized plasma density $n_i/I_e$ is observed when the accelerating voltage reaches some threshold value $U_{a-th}$. A decrease in pressure $p$ leads to a lower threshold voltage $U_{a-th}$ and a larger difference $\Delta n_i$ (Fig. 4). However, without the ceramic target (Fig. 4, curve 1) and at distances more than 6 cm from the ceramic target (i.e., $L < 19$ cm) a decrease in $p$ leads to a lower plasma density $n_i$. 

**Figure 2.** Shapes of the discharge current $I_d$ pulse, the emission current $I_e$ pulse, and the signal from the probe converted to the ion current $I_i$: 1 – $I_d$, 2 – $I_e$, 3 – $I_i$ (without the target), 4 – $I_i$ (with the dielectric target).

**Figure 3.** Dependence of beam plasma density $n_i$ on distance $L$, $U_a = 5$ kV: 1 and 3 – with the ceramic target; 2 and 4 – without the ceramic target; 1 and 2 – $p = 8$ Pa, $I_e = 20$ A; 3 and 4 – $p = 11$ Pa, $I_e = 15$ A.
The observed increase in the beam plasma density $n_i$ near the ceramic target is probably caused by secondary electron emission, which occurs from a ceramic target under electron beam irradiation, and by negative charge created by the e-beam on the ceramic target surface. The negative charge creates an electric field, which accelerates the secondary electrons. These secondary electrons provide “additional” ionization of the gas. On the other hand, the negative charge on the ceramic target slows down the beam electrons and partially reflects slow electrons in the opposite direction of beam propagation. Deceleration of electrons provides an increase in $\sigma$, that also provides increase in plasma density $n_e$, and the reflected electrons additionally ionize the gas. Moreover, for the alumina ceramic at energy of beam’s electrons more than 1 keV, further increasing of electron energy leads to decreasing of the yield of secondary electron emission [15]. The value of negative potential on the dielectric surface depends on value of working gas pressure $p$ [10]. For example, for alumina ceramic, irradiated by pulsed electron beam, the negative potential may reach 800–1000 V at $p = 8$ Pa and 3000–3500 V at $p = 4$ Pa [10]. A decrease in pressure $p$ also provides a longer mean free path of the secondary electrons, which being emitted from the ceramic target. These processes lead to lower threshold voltage $U_{\text{a-th}}$ at lower gas pressure. Thus, the secondary electrons and the negative potential on the ceramic surface provide higher density $n_i$ of the beam plasma formed near the dielectric target.

![Figure 4](image.png)

**Figure 4.** The normalized beam plasma density $n_i/I_e$ versus accelerating voltage $U_a$ at pressure $p = 8$ Pa (a) and $p = 10$ Pa (b), distance $L = 20$ cm: 1 – without the ceramic target; 2 – with the ceramic target.

4. Conclusion

Special features of generation of beam plasma near a dielectric (ceramic) target irradiated with a large-radius pulsed electron beam in the pressure range 3–15 Pa have been investigated. Near the dielectric target (at a distance of less than 6 cm from the target), a sharp increase in the plasma density is observed as certain threshold accelerating voltage is reached. The value of this threshold voltage decreases with decreasing in pressure of gas. The observed dependences are apparently due to secondary electron emission from the target and negative charge, arises on the ceramic surface under the e-beam irradiation. The secondary electrons, appearing from the ceramic target under e-beam irradiation, provide “additional” ionization of gas. Electric field, created by the negative charge, slows down the beam electrons, which increases total ionization cross section of gas by electron impact and the yield of secondary electron emission, and accelerates secondary electrons. The negative potential on the ceramic surface increases with decreasing of pressure. Thus, the secondary electrons, which emitted under irradiation of the target by the e-beam, and the negative potential on the dielectric surface provide higher density of the beam plasma near the dielectric target.
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