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PLASMA

Parameters of the Beam Plasma Formed by a Forevacuum Plasma Source of a Ribbon Beam in Zero-Field Transportation System

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Abstract—We have studied the generation of the beam plasma formed by a forevacuum plasma source of a ribbon electron beam in the conditions of its transportation without an accompanying magnetic field. The ignition conditions in the beam transportation region of the beam–plasma discharge producing a plasma formation of the plasma sheet type with a plasma concentration of $\sim 10^{16}$ m^{-3} and an electron temperature of 1–2.5 eV have been determined. The attained values of parameters and the sizes of the plasma formation make it possible to use it in technologies of the surface modification of planar extended articles.

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INTRODUCTION

The beam plasma formed during the interaction of an accelerated electron beam with a residual gas can be used in plasmachemical processes [1], for etching and cleaning the surfaces of various materials, in the synthesis of protecting and functional coatings [2, 3], for sterilizing the inner surfaces of hollow articles [4], and in a number of other applications. The optimal range of pressures for the formation of a beam plasma is 1–40 Pa [5].

Forevacuum plasma sources of electrons [6] mark a trend in modern development of electron sources with a plasma cathode [7]. These sources produce electron beams directly in the high-pressure regions of the forevacuum range, which are close to optimal pressured for synthesis of beam plasmas. The ribbon electron beams produce a beam plasma of the plasma sheet type with an area on the order of 100 cm^2 [8]. The results of analyzing the parameters and characteristics of beam plasma formed by a forevacuum plasma source of a ribbon electron beam were reported in our earlier publication [9]. In the experiments described in [9], an electron beam was transported in a weak longitudinal magnetic field. However, the presence of a magnetic field is undesirable and even inadmissible in some applications. In addition, the possible penetration of a scattered magnetic field from the transportation region into the accelerating gap may reduce its electric strength.

These circumstances stimulated special investigations aimed at analysis of the features of generation of extended plasma formations produced by a forevacuum plasma source of a ribbon electron beam in the beam transportation region free of magnetic field. The results of these investigations are described in this article.

1. EXPERIMENTAL THECHNIQUE

The experiments were carried out on the ELU-1A vacuum setup including a rectangular vacuum chamber of size 0.4 × 0.7 × 0.4 m^3 with a mechanical evacuation system (Fig. 1). A continuous ribbon electron beam was formed by a forevacuum plasma electron source based on a hollow-cathode discharge [10]. Hollow cathode *1* of the discharge cell of the electron source had the shape of a right parallelepiped open at the lower end with a cross section of 120 × 75 mm^2 and a depth of 40 mm. Plane anode *2* was separated from cathode *1* by a distance of 5 mm. The anode had an emission window of size 100 × 10 mm^2, which was covered by fine tungsten grid *3*. The unit cell of the grid had a size of 0.6 × 0.6 mm^2 and a geometrical transparency of 80%. The extraction of electrons from the discharge plasma and the formation of a ribbon electron beam with an initially rectangular cross section of 100 × 10 mm^2 were carried out by supplying an accelerating voltage between anode *2* and extractor *3*. The shape of the accelerating gap for forevacuum

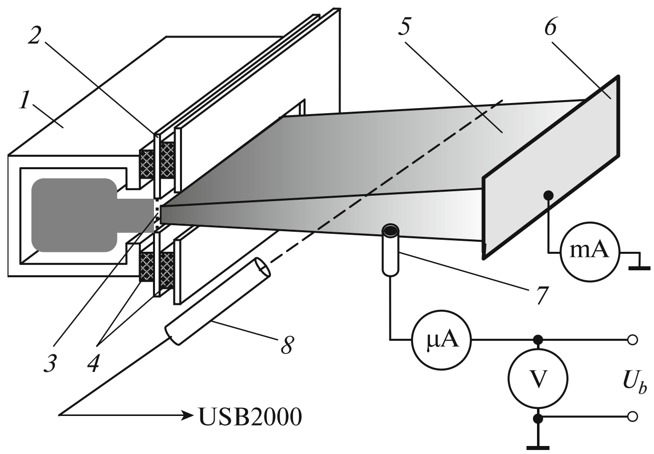

Fig. 1. Schematic diagram of experimental setup: (*1*) extended hollow cathode; (*2*) anode; (*3*) extractor; (*4*) insulators; (*5*) electron beam; (*6*) collector; (*7*) single probe; and (*8*) spectrometer.

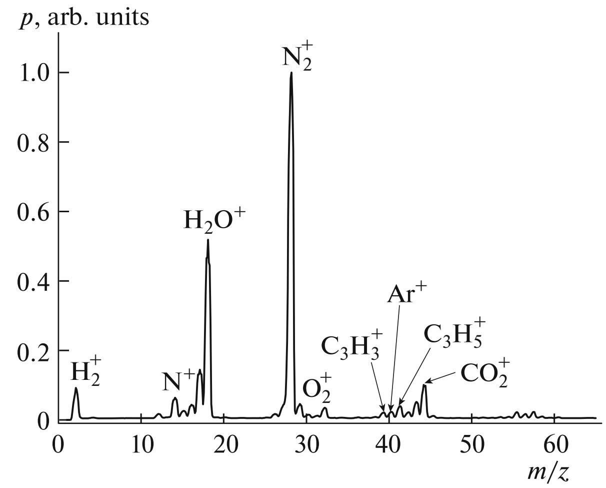

Fig. 2. Composition of residual atmosphere in the electron beam transportation region.

plasma electron sources for accelerating electrons in the region under investigation was traditionally [11] chosen so as to prevent the initiation of a discharge along long paths. Electrical insulation of the electrodes in the electron source was ensured by kaprolon insulators *4*.

In our experiments, the beam current was varied from 100 to 500 mA at a constant accelerating voltage of 2 kV. Electron beam *5* formed by the plasma source was transported over a distance of 50 cm, then fed to collector *6*. The electron concentration in the beam plasma was measured using a single-plane Langmuir probe *7* with a guard ring. The collecting surface of the probe was the open surface of a copper disk of diameter 4 mm. This region was additionally covered by a metal screen to prevent the ingress of beam electrons. The probe was located in the electron beam transportation region at a distance of 20 cm from the extractor. The plasma parameters were determined using the standard technique of analyzing the current–voltage characteristics of the probe [12]. The plasma glow was investigated using the Ocean Optics USB2000 spectrometer (with a spectral sensitivity range of 200–800 nm and a half-width of the instrumental function of about 0.3 nm). The beam electron energy distribution function was measured by the method of retarding potential using a special collector located in the displacement device. Therefore, the electron distribution function could be determined depending on the distance from the electron source.

The residual gas pressure in the vacuum chamber was maintained at a level of 5–10 Pa using a mechanical forevacuum pump BocEdwards 80. The composition of the residual gas in the chamber was monitored using the RGA-100 quadrupole mass analyzer.

2. EXPERIMENTAL RESULTS

The experiments were carried out in an atmosphere of a residual gas that, according to the results of measurements (Fig. 2), contains molecules of air components, as well as molecules of water and hydrocarbons. For relatively small currents (150–200 mA), the propagation of the electron beam in the transportation region is characterized by uniform violet glow of the beam plasma. The most intense lines in the radiation spectrum of the plasma under these conditions correspond to the first negative (1–) system of nitrogen with wavelengths of 391.4 and 427.8 nm, transition $(B^2\Sigma_u^+) \to (X^2\Sigma_g^+)$ (Fig. 3c). This is probably due to the fact that for an electron beam energy of 2 keV used in our experiment, cross section σ_i of ionization of nitrogen molecules by a direct electron impact from the ground state of the molecule with population of the $B^2\Sigma_u^+$ state of the molecular nitrogen ion considerably exceeds the cross section σ_{exc} of the excitation of state $C^3\Pi_u$ of the nitrogen molecule by the direct electron impact from the ground state of the molecule [13]. For this reason, the ionization rate constant k_i of nitrogen molecules (and, hence, the rate of impact ionization by beam electrons from the ground state of the molecule) considerably exceeds the rate constant k_{exc} and the rate of excitation of nitrogen molecules in the same process as follows:

$$k_i = \int \sigma_i(v) v f(v) dv \approx \sigma_i(v_b) v_b,$$
$$k_{\text{exc}} = \int \sigma_{\text{exc}}(v) v f(v) dv \approx \sigma_{\text{exc}}(v_b) v_b. \quad (1)$$

In these relations, $f(v)$, v, and v_b are the beam electron velocity distribution function, the electron velocity, and the velocity of beam electrons, respectively. The radiation spectrum also displays low-intensity

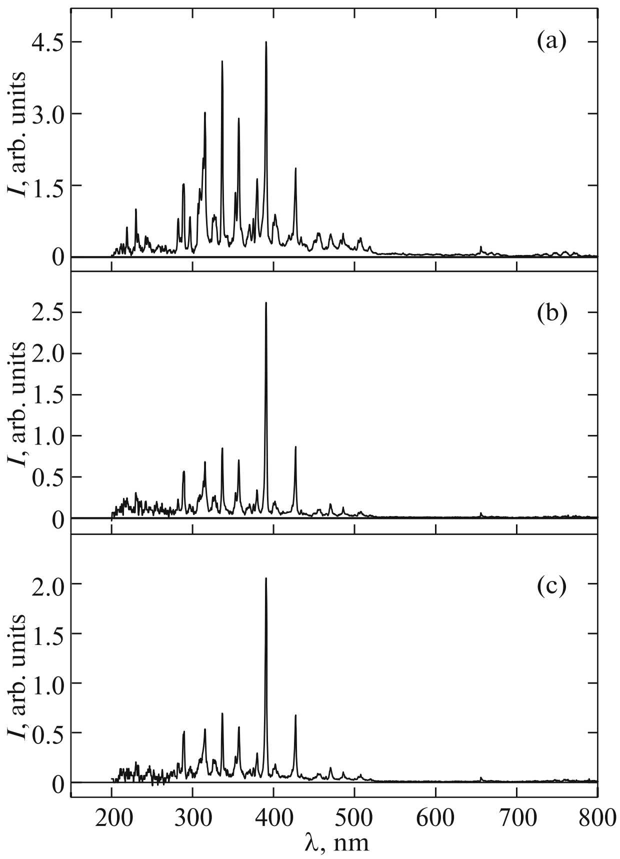

Fig. 3. Radiation spectra of the plasma for beam currents of (a) 400, (b) 200, and (c) 160 mA. The pressure is 7 Pa.

bands of the first positive (1+) and second positive (2+) nitrogen systems, transitions $B^3\Pi_g \rightarrow A^3\Sigma_u^+$ and $C^3\Pi_u \rightarrow B^3\Pi_g$, respectively [14].

When the beam current exceeds a certain threshold value at a constant pressure at a distance of about 10 cm from the extractor, and the violet glow of the beam plasma changes to a bright-pink glow. In this case, the intensity of the (1+) and (2+) bands of the nitrogen system in the radiation spectrum of the plasma, as well as of the continuum in the spectral range from approximately 300–800 nm, increases (Figs. 3a, 3b).

The dependence of the intensity of the glow of the band at 391.4 nm on the beam current exhibits an inflection and can be represented by two linear segments differing in the slope to the abscissa axis (Fig. 4).

The intensity of the (2+) bands of the nitrogen system with wavelength of 337.1 and 357.7 nm in the plasma glow varies nonmonotonically in the electron beam transportation region (Fig. 5), attaining its maximum at a certain optimal distance from the exit section of the extractor.

Probe measurements of the electron concentration and temperature of the beam plasma (Fig. 6) show that

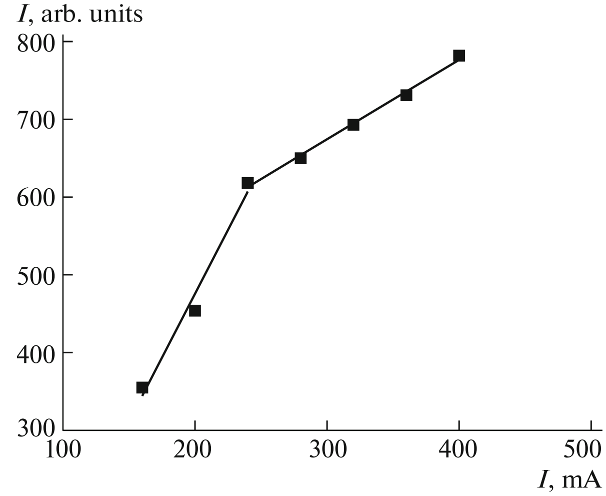

Fig. 4. Dependence of luminous intensity of the 391.4 nm line on the beam current; the pressure is 7 Pa.

a relatively small increase in the plasma electron concentration and temperature for beam currents in the interval 50–180 mA (Fig. 6, region I) changes to a sharp increase when the beam current exceeds values of 180–200 mA (Fig. 6, region II).

The energy distribution function for accelerated electrons measured in the beam transportation region is shown in Fig. 7. It can be seen that the energy spectrum of beam electrons is noticeably deformed upon the electron beam propagation.

The variations in the gas pressure in the above limits did not noticeably change the experimental dependences, but affected the threshold values of the beam current at which the characteristic transitions were observed in these dependences. The threshold value of the current varied in proportion to the pressure. An analogous tendency was observed for relatively small variations of the accelerating voltage.

3. DISCUSSION

The results of our experiments indicate the existence of conditions in which the form of the interaction of beam electrons with the beam plasma changes sharply. The ratio of the radiation power in the wavelength range from 200 to 874 nm (see Fig. 3) for beam currents of 400, 200, and 160 mA is 4.1 : 1.2 : 1, respectively, which indicates a qualitative change in the plasma parameters when the beam current exceed a value of 200 mA at constant accelerating voltage and pressure. The threshold nature of these changes suggests the emergence of beam instability and, as a consequence, the ignition of a beam–plasma discharge [15]. This assumption is justified by the increase in the temperature and concentrations of electrons in the plasma, as well as the changes in the emission spectrum of the beam plasma, which can be associated

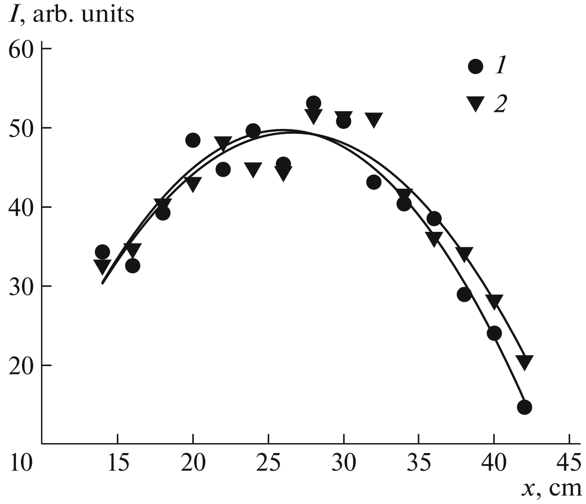

Fig. 5. Dependence of the luminous intensity of the beam plasma on the distance x from the plane of injection of the electron beam: (*1*) 337.1 and (*2*) 357.7 nm. The beam current is 200 mA, the pressure is 7 Pa.

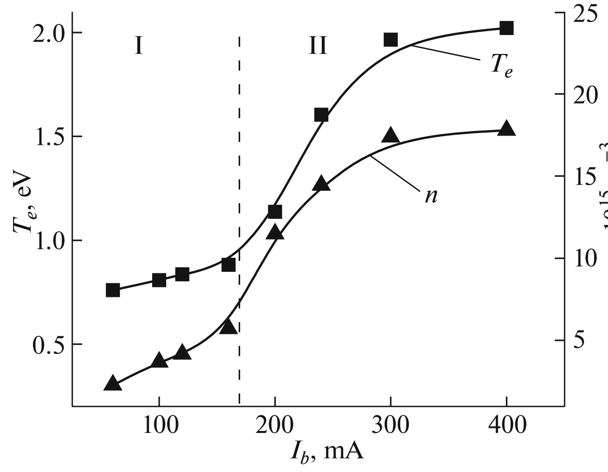

Fig. 6. Dependence of electron temperature T_e and concentration n of the beam plasma on the beam current. The pressure is 7 Pa.

with the difference in the rates of excitation of nitrogen neutral molecules and molecular ions. The excitation of emitting particles can occur in collisions with beam electrons as well as with plasma electrons.

The detected increase in the plasma electron density and temperature upon an increase in the beam current (Fig. 6) leads to a substantial increase in the rate of excitation of emitting particles by plasma electrons, which explains the observed change in the emission spectrum of the plasma.

It is well known that the following condition must be satisfied for effective energy transfer from the beam electrons to the plasma electrons [15]:

$$\omega_{pe}\left(\frac{n_e}{N_i}\right)^{\frac{1}{3}} > 5\nu_{en}, \tag{2}$$

where $\omega_{pe} = 5 \times 10^4\sqrt{N_i}$ is the Langmuir electron frequency of the plasma,

$$n_e = \frac{j_e}{e}\sqrt{\frac{m}{2eU_a}}$$

is the concentration of electrons in the beam (j_e is the beam current density, m and e are the electron mass and charge, respectively, and U_a is the accelerating voltage), N_i is the concentration of the plasma, and $\nu_{en} = \sigma_{en}v_{ep}N_a$ is the frequency of collisions of electrons with neutral atoms (σ_{en} is the cross section of collisions of electrons with gas molecules and v_{ep} is the velocity of plasma electrons).

Our estimates show that, in our case, relation (2) holds for beam current density $j_b = 0.1$–0.5 mA/mm^2, accelerating voltage $U_a = 2$ kV, beam plasma concentration $N_i = (0.2$–$2.0) \times 10^{16}$ m^{-3}, and pressure $p = 7$ Pa, which were observed in our experiment; this indirectly confirms the existence of the beam–plasma discharge (BPD) in our experimental conditions.

One of the criteria for BPD ignition is a noticeable deformation of the beam electron spectrum [16]. The beam energy relaxation length can be determined using the Bethe nonrelativistic formula [17] (in CGS units), which describes the rate of energy loss for a beam that propagate through a gas as follows:

$$\frac{dE}{dx} = -2\pi N_{\mathrm{mol}}Z_{\mathrm{mol}}e^4\frac{1}{E_b}\ln\frac{E}{E_0}, \tag{3}$$

where E_b is the beam energy in electronvolts; x is the distance traversed by the beam in the gas; N_{mol} is the concentration of gas molecules; Z_{mol} is the charge

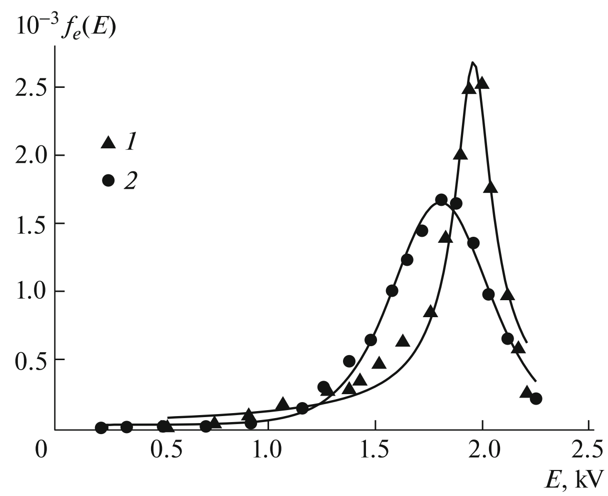

Fig. 7. Electron energy distribution function for various distances from the electron source extractor: (*1*) 20 and (*2*) 45 cm. The beam current is 200 mA and the pressure is 7 Pa.

number of gas atoms; e is the electron charge; and $E_0 \sim$ 100 eV is the mean energy of excitation of a single molecule, which is approximately the same for most gases. Expression (3) holds for $E \gg E_0$. Disregarding the dependence of quantity E on coordinate x in the logarithm and integrating, we obtain the energy relaxation length of beam R_b as follows:

$$R_b = \frac{E^2}{4\pi N_{\rm mol} Z_{\rm mol} e^4}\left(\ln\frac{E}{E_0}\right)^{-1}. \quad (4)$$

For an electron-beam energy of 2 keV and a gas (nitrogen) pressure of 7 Pa, the relaxation length is about 100 cm; in this case, the energy loss over a length of 40 cm calculated by formula (4) is about 50%.

The experimental electron-energy distribution functions (Fig. 7) measured in the region of electron-beam transportation at various distances from the electron source extractor also indicate the possibility of BPD initiation. In the vicinity of the electron source, no beam relaxation is observed, and the form of the distribution function in this case (Fig. 7, curve *1*) indicates that almost all beam electrons move with an initial energy of about 2 keV, participating only in pair collisions. With increasing distance from the plane of electron beam injection to the gas, noticeable broadening of the energy spectrum is observed (Fig. 7, curve *2*), which indicates the partial relaxation of the beam.

The possibility of the initiation of a BPD in zero magnetic field was indicated in [18]. However, the range of pressures in which BPD ignition was observed in those experiments was considerably lower.

CONCLUSIONS

The results of our experiments indicate the possibility of initiation of a BPD in the transportation region of a ribbon beam formed by a forevacuum plasma electron source even in the absence of a transporting magnetic field in this region. In the plasma formation of the plasma sheet type generated in this case, the plasma concentration and electron temperature are $\sim 10^{16}$ m^{-3} and 1.0–2.5 eV, respectively. The attained values of the parameters and the size of the plasma make it possible to use it in technologies of surface modification of various articles with a planar extended shape.

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