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APPLIED PHYSICS

Plasma Generation upon Gas Ionization by Electronic Sources in the Pressure Range of 1–100 Pa (Review)

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Abstract—In this paper, we review recent advances in the generation and study of beam plasma produced upon gas ionization by a stationary low-energy electron beam in the forevacuum pressure range (1–100 Pa). The features of the interaction of a stationary electron beam with the produced plasma during its transportation in a large-volume vacuum chamber, as well as the results of a study of the parameters of the plasma generated by the injection of an electron beam into a vessel with dielectric walls, are presented. It is shown that depending on the parameters of the electron beam, as well as the pressure and type of a gas, it is possible to create conditions for collective interaction with the ignition of a beam-plasma discharge characterized by an increased concentration and temperature of plasma electrons.

Keywords: electron beam, medium vacuum, plasma, beam-plasma discharge, tape and focused electron beams

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INTRODUCTION

To obtain highly nonequilibrium low-temperature plasma, discharges of various types, namely, glow, arc, and microwave discharges, as well as their combinations, are usually used [1–3]. Despite the successes achieved in applying this method of plasma generation there are also a number of complexities associated with a rather narrow range of conditions, under which stable burning of discharges is observed, as well as the difficulty or inability to independently adjust operating parameters such as ion energy, ion current density, and the composition of the operating gas mixture [4]. It is also difficult to produce a homogeneous cold plasma of a large volume at a pressure of the order of 10–100 Pa and higher [5]. As well, when using gases with high chemical activity as plasma-forming media, problems associated with the poisoning of the electrodes by the products of their interaction with the plasma, as well as possible electrode destruction, arise.

Unlike gas-discharge plasma generators, the use of electron beam injection into a gaseous medium and the formation of beam plasma due to the ionization of atoms and molecules by beam electrons has several advantages. The main ones are the independence of the parameters of the electron beam on the type of a plasma-forming gas and the possibility of electron beam propagation and plasma production in a rather wide pressure range [6, 7]. Moreover, an electron beam can be injected into plasma that has already been previously produced using various types of discharges. This expands the possibilities of the practical application of electron-beam plasma in material modification operations due to the simultaneous use of two plasma-forming factors. By changing the pressure and composition of the plasma-forming medium, a wide range of plasma-chemical reactions is realized by controlling the generation of active particles in the plasma by changing the electron beam parameters [8, 9].

As a rule, in setups for electron-beam plasma production, the region of electron-beam generation and the region where the beam-plasma is produced are spatially separated. This is due to the complexity of ensuring the operability of the electron source at pressures of units and hundreds of Pa, which are usually set in the volume occupied by the gas. Thus, technical solutions that allow the transfer of powerful electron beams from vacuum to gas [6] or devices that allow the production of electron beams at pressures that correspond to the pressure in the region occupied by the gas are needed.

The pressure range of 1–100 Pa relates to the forevacuum range, which is already quite well managed by so-called forevacuum plasma electron sources. Such sources usually generate continuous electron beams with energies from 5 to 30 keV and currents of up to 300 mA at pressures of 5–30 Pa [10]. Changing the shape of the plasma emission boundary allows such sources to generate electron beams of various configurations: narrowly focused, wide-aperture, and ribbon configuration.

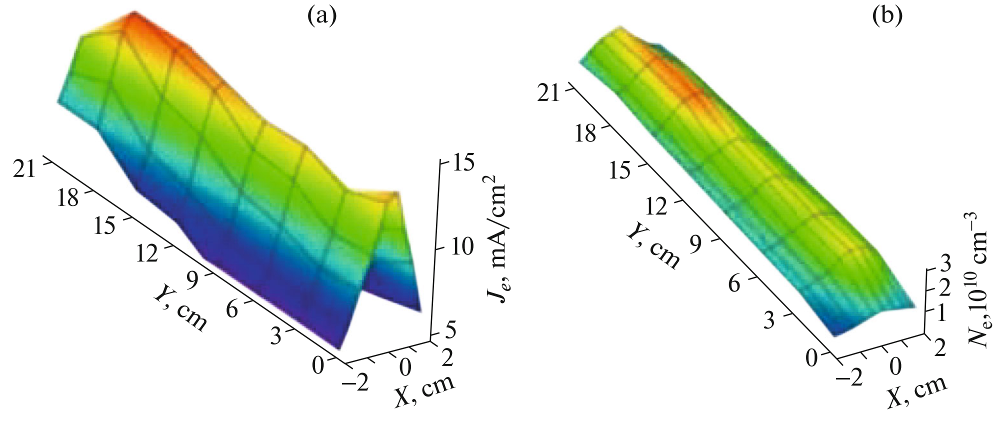

Fig. 1. The distribution of (a) the beam density and (b) plasma density in the *XY* plane perpendicular to the direction of beam propagation; pressure is 6 Pa [15].

This paper is aimed at providing a brief overview of advances in beam plasma generation when using forevacuum plasma electron sources as electron beam generators.

LARGE-AREA PLASMA GENERATION

The technological problems of ion-plasma processing of large flat surfaces, such as plasma-chemical and ion etching and surface cleaning, as well as the synthesis of protective and functional coatings due to the decomposition and synthesis reaction in plasma [11–13], require the creation of a uniform extended plasma structure of small thickness with an area of tens of square centimeters. In addition to a large plasma area, it is also necessary to provide its sufficiently high concentration, which requires an increased operating pressure.

It should be noted that the pressure range related to the forevacuum range of 1–100 Pa is optimal from the viewpoint of producing dense plasma suitable for technological purposes. One of the most promising methods for the production of a plasma formation with a large area and an acceptable concentration value is the gas ionization by an electron beam of a tape configuration. The use of electronic sources with a thermionic cathode as a tape beam generator is difficult due to the increased gas pressure. One alternative solution is the use of a plasma cathode, where the gas discharge plasma acts as an electron source. One of the advantages of a plasma cathode, in addition to its insensitivity to the composition of the gas atmosphere and pressure surges that arise from irradiation of materials, is the possibility of varying the shape of the cross section of the generated electron beam due to a change in the shape of the plasma emission boundary.

The experimental results on the spatial distribution of the electron concentration and temperature of beam plasma produced by a continuous ribbon electron beam with energy of up to 2 keV in argon at a pressure of 6 to 9 Pa were presented in [14]. To generate an electron beam of a ribbon configuration, a plasma electron source based on a low pressure discharge with an extended hollow cathode was employed [15]. An electron beam formed by a plasma source of this type had a cross section of 10–250 mm immediately at the exit of the emission gap. During argon propagation in a medium, the beam produced plasma; to retain it a longitudinal magnetic field was created in the region of propagation of the electron beam. In this study, the distribution of the electron concentration and temperature is shown to directly depend on the corresponding distribution of the current density over the beam cross section (see Fig. 1).

As well, according to the data of this study, the parameters of the plasma beam are significantly affected by the pressure in the vacuum chamber, namely, the concentration of the beam plasma increases as the pressure increases. A similar increase takes place as the beam current increases. The magnetic field strength affects the width of the “plasma sheet” in the cross section. An increase in the strength leads to a decrease in the plasma width in the cross section with a simultaneous increase in its concentration in the middle plane of the beam.

The parameters of beam plasma formed by a forevacuum plasma source of a ribbon electron beam with energy of 2 keV under conditions of its transportation without an accompanying magnetic field at 5–10 Pa were presented in [16]. The modernization of the plasma electron source allowed generation of a beam with a low divergence (Fig. 2a) and using it to produce beam plasma. The transverse dimensions of the beam at its exit from the electron source are 10 × 1 cm^2, the length of the transportation region, i.e., the distance to the collector, is 50 cm. Unlike plasma generation in the presence of a magnetic field, two modes of beam–plasma interaction are possible in this case [16]. At rel-

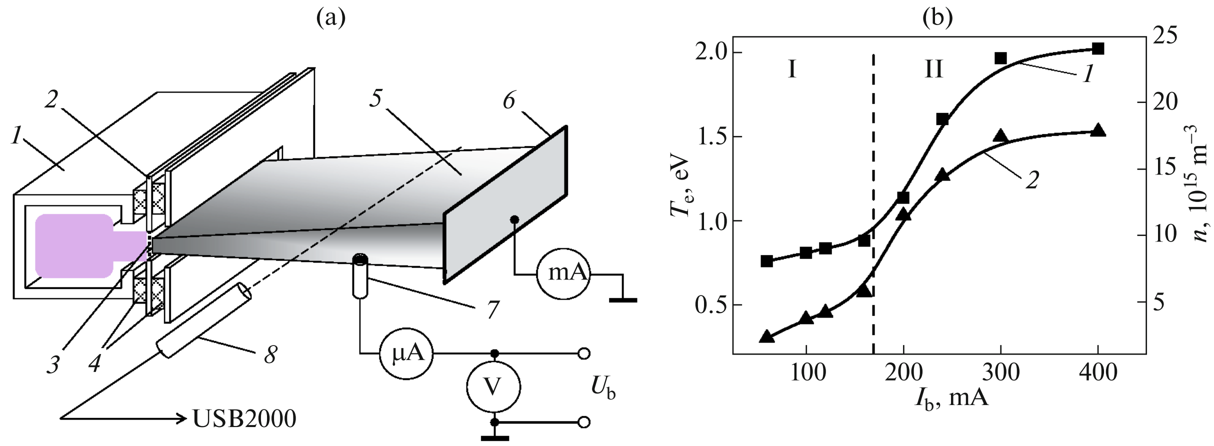

Fig. 2. A modified plasma electron source [16]. (a) The schematic of the experimental setup: (*1*) extended hollow cathode, (*2*) anode, (*3*) extractor, (*4*) insulators, (*5*) electron beam, (*6*) collector, (*7*) single probe, and (*8*) spectrometer; the cross-sectional beam size is 10 × 1 cm^2, the length of the formed beam plasma is 40 cm. (b) The dependence of the electron temperature (curve *1*) and the concentration of the beam plasma (curve *2*) on the beam current. The pressure is 7 Pa.

atively low beam currents (150–200 mA), the electron beam propagation in the transport region is characterized by a low beam-plasma concentration (of the order of 5 × 10^{15} m^{-3}) and electron temperature (0.5 eV) as shown in Fig. 2b, region I.

A two-fold increase in the beam current leads to a substantial increase in the concentration and temperature of plasma electrons to 1.5 × 10^{16} m^{-3} and 2 eV (region II), respectively. An increase in the concentration is also accompanied by an increase in the intensity of the plasma glow. These results, as well as the shift of the maximal energy of the beam electrons to the region of lower energies, indicate the ignition of a beam-plasma discharge during the interaction between the electron beam and the produced plasma. In the plasma formation of the "plasma sheet" type, the plasma concentration and electron temperature are ~10^{16} m^{-3} and 1–2.5 eV, respectively. The achieved values of the plasma parameters and dimensions allow using it in technologies for surface modification of various products of flat extended shapes.

PLASMA GENERATION BY A FOCUSED ELECTRON BEAM

Electron-beam plasma, which has, as mentioned, a number of advantages over a plasma produced using various discharges may adversely affect the electron beam propagation in some cases. The intense transfer of the electron energy of the beam to plasma electrons can lead to the formation of beam instability due to amplification of Langmuir oscillations and be accompanied by significant losses in the beam power, as well as to its defocusing.

The results of studying the formation of a focused electron beam during the selection of electrons from plasma of a stationary discharge with a hollow cathode in the forevacuum pressure range were presented in [17]. Based on measurements of the energy spectrum and the diameter of the electron beam (Fig. 3), as well as the parameters and spectra of the plasma radiation that arise from the interaction of the beam with the gas, it is concluded that a beam-plasma discharge occurs and causes deterioration in the beam focusing conditions.

The minimal current density in the beam at which a beam-plasma discharge occurs increases both with increasing accelerating voltage and with increasing gas pressure, which is shown in Fig. 4.

The results of measuring the parameters of beam plasma formed during the propagation of a focused cylindrical electron beam with energy of up to 14 keV and a current in the beam of up to 300 mA in a vacuum chamber in a helium atmosphere were presented in [18]. The operating pressure in the experiments was 40 Pa. The setup diagram and the plasma concentration distribution along the beam are shown in Fig. 5.

It is shown that the position of the region of intense interaction of the electron beam and plasma can be controlled by the beam current density. The current density is changed by changing the beam crossover position. In the absence of a crossover, i.e., when the beam electrons move to the collector along almost parallel trajectories, the concentration of plasma electrons changes slightly along the beam propagation path. When the beam focusing parameters are changed and the crossover is located near the collector (at a distance of approximately 2 cm), the maximal distribution of the plasma electron concentration is observed in the middle between the collector and the electron source or near the electron source in the corresponding region. It is noteworthy that the plasma

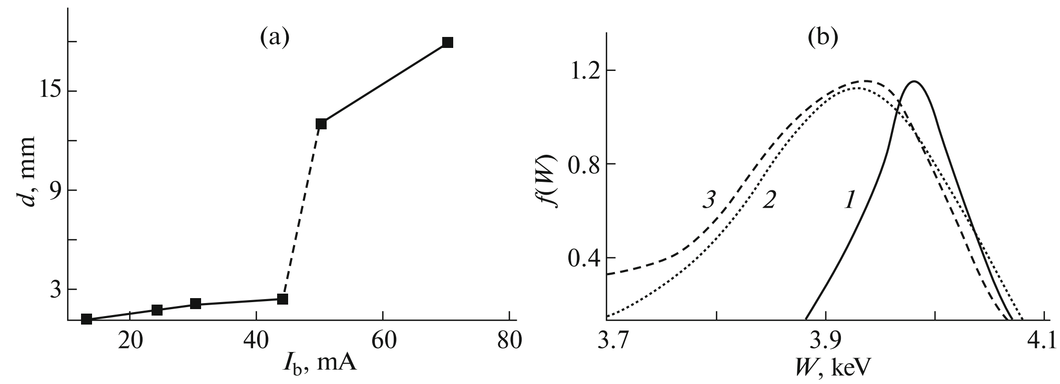

Fig. 3. The formation of a focused electron beam during the selection of electrons from plasma of a stationary discharge with a hollow cathode [17]: (a) dependence of the beam diameter on its current and (b) electron energy distribution function for various values of the beam current: curve *1*, 30 mA; curve *2*, 42 mA; curve *3*, 64 mA (the accelerating voltage is 4 kV; the pressure is 3 Pa).

concentration in this region increases three times or more compared to the case of propagation of a uniform beam without a crossover (Fig. 5b).

In addition, another effect related to the interaction of an electron beam and plasma was shown in this study: the formation of alternating bright and dark regions in the beam plasma glow (see Fig. 6). Alternating regions were observed along the beam axis in a rather narrow range of beam parameters, namely, at a beam current close to 200 mA, in the range of accelerating voltages of 8–14 kV, and at a beam crossover position of 5–7 cm from the collector (Fig. 6b).

The observed phenomenon resembles striations, that is, motionless or moving zones of uneven luminosity that regularly alternate with dark gaps in the positive column of a low-pressure gas discharge [19, 20]. Like striations, the observed alternation of light and dark regions exists in a very limited range of beam currents and electron energies and, apparently, is associated with the occurrence of beam instability [18].

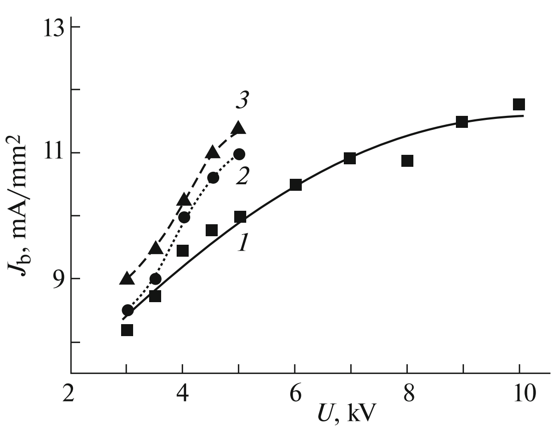

Fig. 4. The threshold electron-beam current density as a function of accelerating voltage for various gas pressures, curve *1*, 2 Pa; curve *2*; 3 Pa, and curve *3*, 4 Pa [17].

BEAM PLASMA PRODUCED BY BEAM INJECTION INTO A DIELECTRIC VOLUME

High-vacuum injection of an electron beam into a dielectric tube is possible only if the negative charge brought by the beam is removed [21]. Beam injection into a dielectric cavity in high vacuum is completely impossible due to the strong charging of the inner surface of the dielectric volume causing the electron beam to deflect, scatter, and decelerate.

However, the mentioned physical constraint can be overcome by using forevacuum plasma electron sources that operate at a gas pressure of 1–100 Pa. The possibility of generating a beam plasma in a completely dielectric volume was first shown in [22], in which the parameters of a beam plasma formed by injection of an electron beam into a cylindrical thin-walled quartz flask with an inner diameter of 4 cm and a length of 20 cm were measured (see Fig. 7). A collector was connected to a high-resistance voltmeter to measure potential at the cavity bottom inside. Experimental research of the parameters of the produced beam plasma showed that the plasma potential inside the vessel is negative and increases with increasing pressure while the concentration of the beam plasma in the vessel was higher than the concentration of the plasma produced by the beam in free space.

Later studies [22, 23] showed that modes exist, in which the plasma occupies the entire cavity volume and in the absence of any electrodes inside to remove the electric charge from the inside. In this case, the current is closed by a reverse flow of secondary electrons from the cavity surface, as well as through the beam plasma to the grounded sections of the vacuum chamber.

Plasma generation modes (mainly at low gas pressures and high beam energies), at which plasma occupies the dielectric volume only partially (Fig. 8a), were shown to exist [23]. The plasma fills the entire volume as the gas pressure increases (Fig. 8b). As well, a vari-

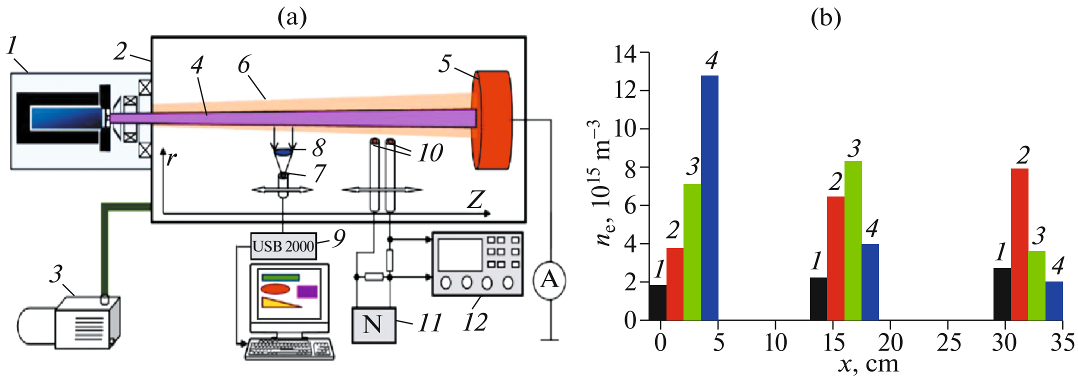

Fig. 5. The experimental setup and beam plasma parameters [18]. (a) The schematic of the setup: (*1*) plasma electron source, (*2*) vacuum chamber, (*3*) foreline pump, (*4*) electron beam, (*5*) collector, (*6*) beam plasma, (*7*) collecting lens, (*8*) receiving part of the spectrometer, (*9*) optical spectrometer with a computer, (*10*) double Langmuir probe, (*11*) sawtooth-voltage generator, and (*12*) oscilloscope. (b) Concentration distribution along the beam at an accelerating voltage of 14 kV for various beam crossover locations: (*1*) without a crossover, (*2*) crossover near the collector, (*3*) crossover in the central part of the beam transport section, and (*4*) crossover near an electron source.

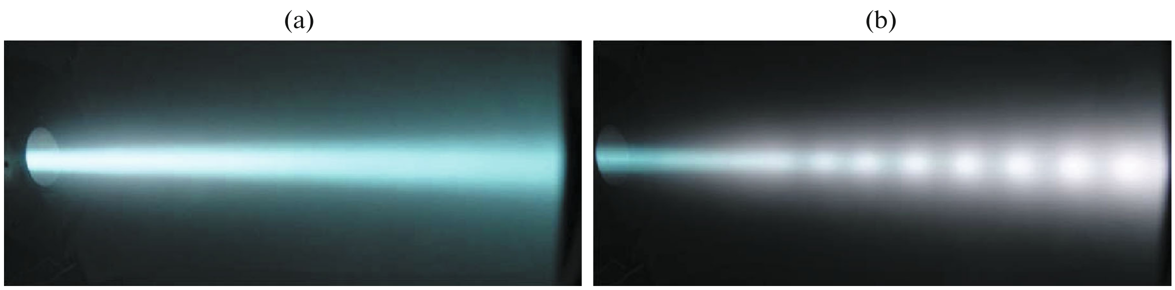

Fig. 6. Photo images of the glow of a helium beam plasma (a) in the absence and (b) in the presence of alternating regions. Beam current: (a) 180 mA and (b) 200 mA. The accelerating voltage is 10 kV; the pressure is 40 Pa [18].

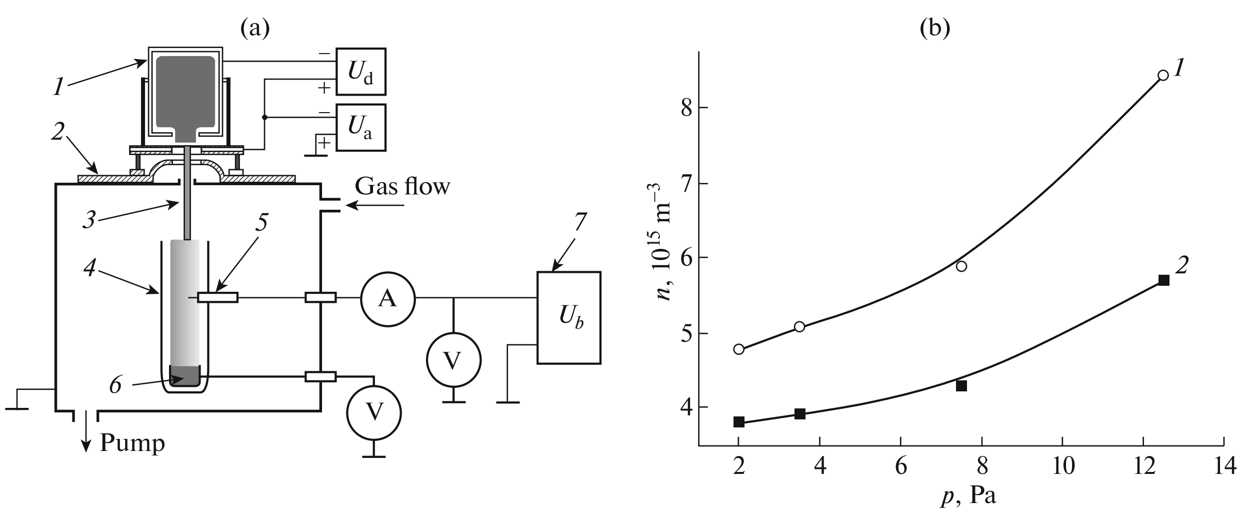

Fig. 7. Beam plasma generation in a completely dielectric volume [22]. (a) The schematic of an experimental setup for generating beam plasma in a dielectric cavity: (*1*) plasma electron source, (*2*) vacuum chamber, (*3*) electron beam, (*4*) quartz flask, (*5*) single probe, (*6*) collector, and (*7*) bias voltage source. (b) The dependence of plasma concentration on the gas pressure: (*1*) the beam is injected into the flask, (*2*) it propagates freely in the vacuum chamber. The beam energy is 3 keV; the beam current is 20 mA, air.

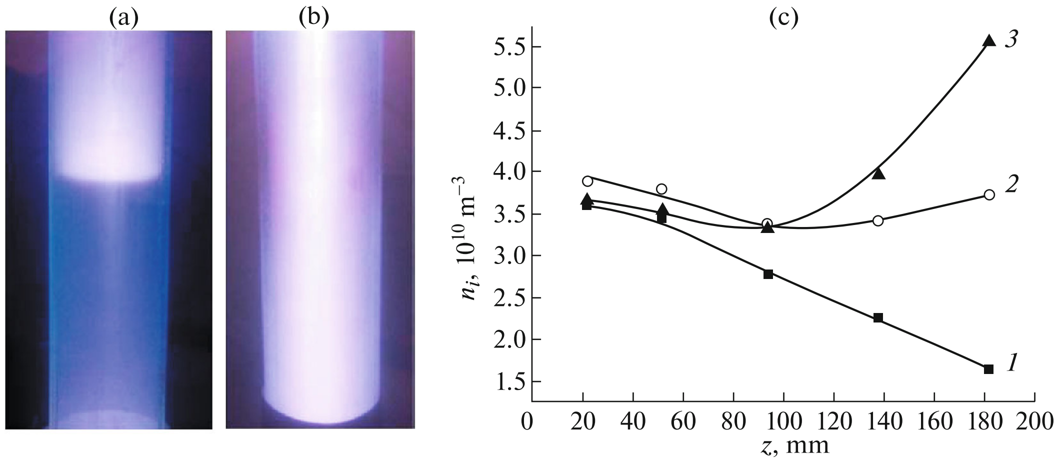

Fig. 8. The plasma glow [23] produced in a dielectric cavity at beam energy of 7 keV and a beam current of 20 mA and at an air pressure: (a) 1.5 Pa, (b) 4 Pa. (c) Longitudinal distribution of the plasma concentration in the cavity at an air pressure of 5 Pa and a beam current of 20 mA for beam energy of 2 keV (curve *1*), 5 keV (curve *2*), and 8 keV (curve *3*).

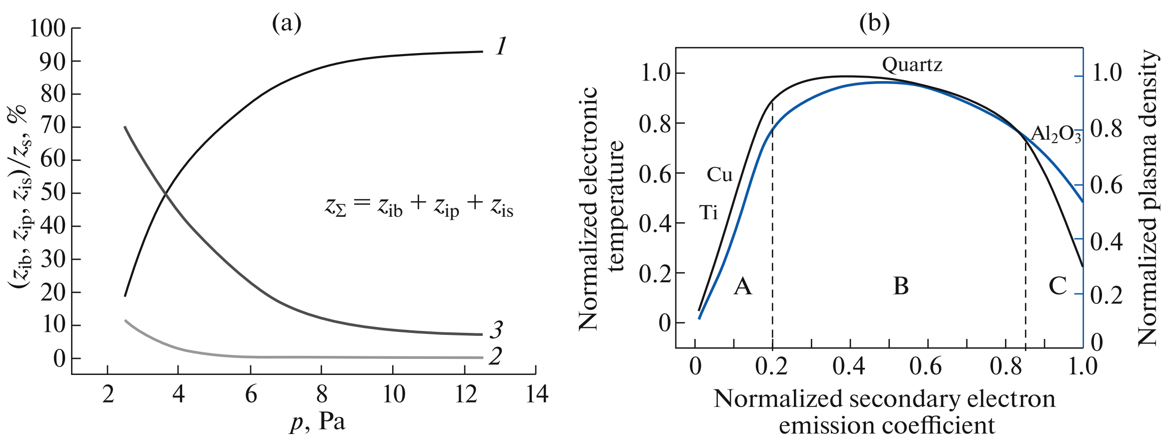

Fig. 9. A numerical model. (a) Modeled normalized ionization yields of (*1*) beam, (*2*) plasma, knocked out of the cavity bottom, and (*3*) secondary electrons during plasma generation in the quartz cavity depending on the nitrogen pressure for a beam current of 20 mA and beam energy of 3 keV [23]. (b) Modeled dependences of the normalized plasma parameters as functions of the normalized secondary electron emission coefficient at a beam current of 6 mA, beam energy of 6 keV, and a nitrogen pressure of 2.5 Pa, with marked on the graph approximate values of material coefficients (titanium, copper, corundum) of the plates placed at the cavity bottom [24].

ation in the gas pressure and the energy of the beam injected into the cavity was shown for the first time to lead to a change in the nature of the longitudinal distribution of the plasma concentration. At optimal parameters, the concentration inhomogeneity can be reduced to approximately 10%.

The increased concentration is explained based on the developed numerical model [23, 24], which is a numerical balance model explaining the increased concentration and temperature of the beam plasma electrons in the dielectric cavity by the additional energy input of the secondary electrons knocked out by the beam electrons and plasma ions from the inner cavity surface and accelerated in the near-wall and bottom layers. The contribution of secondary electrons to ionization was shown to sharply increase in the range of low gas pressures while the contribution of plasma electrons remains negligible (Fig. 9a).

The results of experimental studies and numerical simulations that demonstrate the effect of the bottom material on the plasma parameters in the dielectric cavity (Fig. 9b) were presented in [24]. The results show that previously discovered (Fig. 8c) features of the longitudinal plasma inhomogeneity can be explained by a superposition of two effects: the degradation of the beam due to its interaction with the gas and the contribution to the ionization of secondary electrons accelerated in the bottom layer. In this case, the bottom material directly affects both the bottom potential drop and, accordingly, the parameters of the

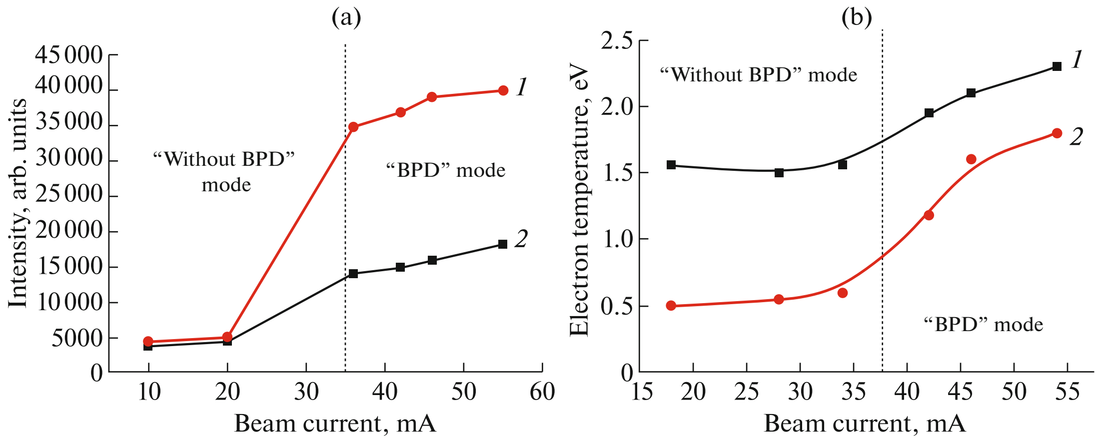

Fig. 10. The results of the experiment in [25]: (a) integrated intensity of the spectral lines as a function of the beam current during plasma production in free space (curve *1*) and inside the dielectric cavity (curve *2*) and (b) electron temperature of the beam plasma generated in open space (curve *1*) and in the dielectric cavity (curve *2*) by a beam of energy 3 keV at a nitrogen pressure of 4 Pa.

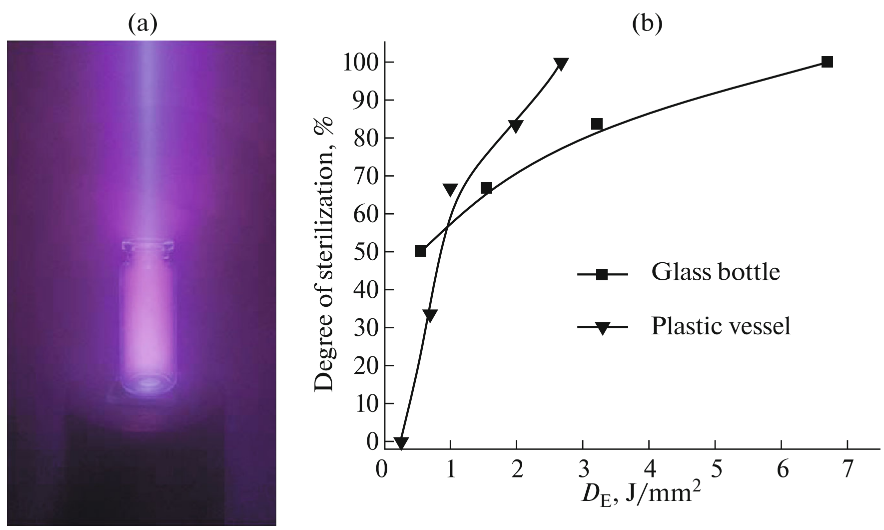

Fig. 11. Beam-plasma sterilization [26]: (a) 10-mL glass medical bottle and (b) fraction of sterile samples as a function of the dose (density) of beam energy injected into a glass or plastic vessel.

beam plasma (Fig. 9b). At low secondary electron emission coefficients, the contribution of secondary electrons to the increase in plasma parameters is small because of the low current of secondary electrons. At secondary electron emission coefficients that are too high, the contribution of secondary electrons to the increase in plasma parameters is small due to the extremely effective neutralization of the cavity bottom charge, which sharply reduces the bottom potential difference and, therefore, the energy of secondary electrons.

It is known that the efficiency of using the beam energy for plasma production can be significantly increased if conditions for a beam-plasma discharge (BPD), which contributes to intense dissipation of the beam energy used to the buildup of Langmuir oscillations, are created. This completely applies to the case of beam plasma production in a dielectric cavity with simultaneous ignition of the BPD. An experiment for generating a beam-plasma discharge upon injection of a continuous electron beam with an energy of 3 keV and a current of 10–55 mA into a quartz cylindrical cavity with a length of 20 cm and a diameter of 8 cm at a gas pressure of 4–5 Pa was described in [25]. The existence of two modes of plasma generation in a cavity, namely, either with the predominance of pair collisions or collective beam-plasma interaction (BPD mode) (see Fig. 10) was demonstrated.

In the BPD mode, the integrated luminescence intensity of plasma particles in the range of 200–800 nm is much higher if the plasma is produced in the cavity with other parameters of the experiment being equal (see Fig. 10a).

Measurements of plasma parameters in the cavity in these two modes showed that the highest plasma concentration and electron temperature in the cavity are achieved precisely in the BPD mode (Fig. 10b), which is most likely due to more intense energy transfer from the beam to the plasma.

The relevance of beam plasma production in dielectric cavities using fore-vacuum plasma electron sources is not limited to speculative interest. The possibility of successful beam-plasma sterilization of glass and plastic medical bottles with a volume of 10 and 60 mL was shown in [26], which is shown in Fig. 11.

Relatively low beam parameters (the emission current was up to 50 mA and the energy was 3 keV) and periodic exposure of the vessel (several tens of sessions of 5–10 s active irradiation) prevented thermal damage to the vessels and provided irradiation modes that contribute to the complete sterilization of the vessel from test culture microorganisms (*E. coli*). Thus, these results indicate the possibility of beam-plasma sterilization of dielectric vessels without the use of toxic gases or other chemicals and extremely high heating. The dependence of the degree of sterilization on the energy density introduced into the vessel (Fig. 11b) indicates the existence of modes for effective sterilization of glass and heat-sensitive plastic containers without damage. However, it should be noted that further experiments are required in order to understand the mechanism of action of the beam and plasma on microorganisms under these conditions.

CONCLUSIONS

This review described the main parameters of the beam plasma produced at the propagation of electron beams with energy of up to 15 kV and a current of up to 300 mA in a gas medium at a pressure of units and tens of Pa. The schemes of the setups for the production of beam plasma of various sizes were provided. The advantages and disadvantages of the interaction of the electron beam with the plasma produced by this beam were described. The generation modes of a beam-plasma discharge, which allows producing beam plasma with a high concentration and temperature of plasma electrons, were determined. These can be useful in the development of effective plasma-chemical technologies.

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