Generation of homogeneous emission plasma in a discharge system with an extended hollow cathode

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Generation of homogeneous emission plasma in a discharge system with an extended hollow cathode

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Abstract. The results of an investigation of a discharge system with an extended hollow cathode used in the forevacuum plasma source of a ribbon electron beam are presented in the article. The influence of the geometry of the cathode cavity and the type of the plasma-forming gas on the homogeneity of the distribution of the plasma concentration in the region of the emission boundary is studied. To estimate the plasma density, we used the probe technique, as well as measurements of the optical emission spectrum of the plasma. Both methods showed qualitatively identical results. It is shown that the geometric parameters of the discharge gap of the electron source, as well as the gas pressure, exert the greatest influence on the homogeneity of the distribution of the plasma density.

1. Introduction
In technological plasma processing of materials, both the equilibrium plasma produced by electric arc sources and the nonequilibrium plasma generated by discharges of various types (microwave, glow discharge, etc.) are used [1-8]. Equilibrium plasma is used mainly in the metal processing industry in the traditional technologies of plasma processing of metals and their alloys, allowing to produce cutting, welding, processing of a thin surface layer of materials, especially refractory [9]. The field of nonequilibrium plasma sources application is much broader and covers the processes of plasma cleaning, surface modification, its hardening, and also in technologies for creating various protective, thermal barrier coatings [10-11]. It is also relevant to use highly nonequilibrium plasma in plasma-chemical equilibrium plasmas for the production of hydrocarbons from natural gas, the creation of thin films, the synthesis of pure ultradisperse silicon powders, silicon carbide, aluminum oxide, carbide, silicon nitride, etc., disinfection and purification of toxic waste [12-14]. Feature of nonisothermal nonequilibrium plasma is sufficiently strong difference between the electronic and ionic component temperature. This determines the chemical activity of the plasma, as a result, it becomes possible to carry out technological processes at a sufficiently low temperature, minimizing the damage of materials due to their thermal heating, allowing to affect polymers having low temperature resistance [15-18]. The treatment is performed due to the flows of chemically active charged particles, as well as a wide spectrum of radiation, allowing to change the properties of a thin surface layer (wettability, coefficient of friction, hardness, etc.), including etching to a depth of one atom layer [19-22]. Different types of discharges, which are used to create a nonequilibrium plasma, allow you to control its parameters. However, a significant change in the plasma parameters-its concentration, temperature, and also the area, makes it possible to realize the so-called beam plasma, which is formed due to ionization processes during the passage of an accelerated electron flux through the gas medium at pressures of several Pa [23-24]. Foremost plasma electron sources make it possible to generate...
electron beams at a pressure range of 1-100 Pa without loss of the current and energy range of the beam electrons. The glow discharge with a hollow cathode used in such sources makes it possible to obtain a dense emission plasma, and the special design of the accelerating gap provides acceleration of electrons to an energy of several tens of electronvolts without loss of electrical strength. For the generation of beam plasma, ribbon sources of electrons are used. Such sources allow simultaneous plasma processing of long products. The efficiency and quality of the plasma treatment essentially depends on the spatial distribution of the parameters of the electron-beam plasma, in particular, the homogeneity of the distribution of its concentration and the temperature of the electron component. The homogeneity of the beam plasma is determined by the homogeneity of the beam current density distribution, which in turn depends on the homogeneity of the distribution of the emission plasma, and also on the distribution of the electric field in the accelerating source gap. In this paper, studies of a hollow cathode discharge system in a plasma source of a ribbon electron beam used to generate an electron beam and a beam plasma in an average vacuum are presented.

2. Experimental setup
An electron-beam device equipped with a plasma electron source [25-26], a pumping system and the necessary power supplies and diagnostics for experimental investigations was used (figure 1).

![Figure 1. Scheme of the experiment: 1 – hollow cathode; 2 – anode; 3 – extractor; 4 – plasma of a glow discharge; 5 – emission grid; 6 – insert 7 – Langmuir probe; 8 – optical spectrometer.](image)

The electron source consisted of an extended hollow cathode 1, a flat anode 2, and an accelerating electrode 3. The anode and cathode of the source of electrons had water cooling. The hollow-cathode glow discharge was ignited between the anode and the hollow cathode and was an emission plasma generator 4. The internal dimensions of the cathode cavity were 280×60×30 mm³. The distance between the output aperture of the hollow cathode and the anode plane was set equal to 5 mm. When the electron source was operating as a generator of a ribbon electron beam, the extraction of electrons from the discharge plasma was carried out through an extended emission window in the anode with dimensions 280×10 mm². Emission window in the anode was overlapped by fine-grained tungsten mesh 5 with transparency of 80%. The use of tungsten as a mesh material is necessary for maintaining the efficiency of the electron source under conditions of intense heating of the grid by the reverse flow of ions arising in the accelerating gap of the source. All electrodes of the electron source were made of stainless steel. The internal dimensions and geometry of the cathode cavity could be changed by placing metal inserts inside the cathode cavity. The depth of the cavity varied from 24 to 60 mm. Significant difficulties with ignition and discharge maintenance occurred when the depth of the cavity was less than 24 mm, the discharge burned unstably and the discharge voltage was more than 1.5 kV.
The width of the cathode cavity varied from 30 to 14 mm. It was also possible to set the inserts into the central and peripheral parts of the hollow cathode.

A single Langmuir probe was used to measure the plasma concentration near the emission surface. The working surface of the probe was a disk with a diameter of 3 mm. The probe was placed in a ceramic tube and mounted on a moving device inside the vacuum chamber. The plasma concentration was calculated from the ion current to the probe. The processing of the probe characteristic was carried out according to a standard procedure [27]. The probe was placed behind the emission grid on the displacement device, which allowed it to move along the extended cathode cavity. A negative bias of -20 V was applied to the probe from a source of stabilized voltage. The probe current was determined using a resistor $R_1 = 10 \, \Omega$ and Tektronix TPS2024B oscilloscope.

In addition to probe measurements, the optical emission spectrum of the plasma was also measured. With the help of a special device, the fiber optic cable 8 was installed in a vacuum chamber opposite the emission grid of the electron source. The spectrometer was located in the focus of a collecting lens with a diameter of 5 mm. This made it possible to measure the intensity of the emission of a plasma in a local region of a size commensurate with the diameter of the lens. The measurements were carried out in an atmosphere of argon, helium, and oxygen at pressures of 12 Pa, 18 Pa, and 26 Pa.

3. Experimental results and discussion

The source generates a ribbon electron beams unlike electron sources generating cylindrical electron beams to obtain a uniform distribution of the plasma density is much more difficult. This is due to the large dimensions of the plasma emission boundary and the rather large difference in beam dimensions in the longitudinal and transverse cross sections. The transverse dimension of the hollow cathode in the sources of the ribbon electron beams is much smaller than its longitudinal dimension. In this connection, the concentration of the discharge plasma proves to be more homogeneous in the cross section than in the longitudinal (axis X, figure 1). In the cross section, the plasma concentration decreases monotonically from the central part of the cavity to the periphery; in the longitudinal section, the concentration distribution turns out to depend on the discharge current, the gas pressure, and also the geometry of the cathode cavity. The influence of the gas pressure, as well as the discharge current on the longitudinal distribution profile of the plasma concentration in the cathode cavity is illustrated in figure 2.

![Figure 2](image_url)

**Figure 2.** Distribution of plasma concentration at a discharge current of (a) 400 mA, (b) 200 mA in argon gas medium.

As can be seen from the presented dependences, an increase in pressure leads to an increase in the plasma concentration at the periphery of the cathode cavity. Such an inhomogeneous distribution of the plasma concentration will lead to an inhomogeneity in the beam current density distribution.

The distribution of the plasma concentration also depends on the grade of the working gas. In the oxygen, an increase in the concentration in the middle part of the cavity is observed, in the argon, an
increase in the concentration at the periphery, and the distribution taken in the helium practically does not change (figure 3).

**Figure 3.** Dependence of the ion current on a single probe moving along the cathode cavity. Pressure 20 Pa, discharge current 1 A. For various gases: oxygen, helium, argon.

Similar trends are observed for spectral measurements. The use of the spectrometer makes it possible to determine the intensity of the emission of the plasma, which depends, in particular, on its concentration. Figure 4 shows typical spectra of the glow discharge plasma in a cathode cavity for various gases. Figure 4 shows the plasma emission bands for a given type of gas and also the emission bands of nitrogen. The presence of nitrogen is associated with its presence in the residual atmosphere of the vacuum chamber.

**Figure 4.** Typical spectrum of plasma glow for oxygen, argon and helium.
The location of the spectrometer on the moving device made it possible to measure the change in the emission spectrum of the plasma along the cathode cavity. When the receiving part of the spectrometer was moved, the plasma emission spectrum was recorded with an interval of 1 sec. Based on the known speed of movement and the magnitude of the traversed path, a position corresponding to a certain spectrum was calculated. From the obtained array of data, the wavelengths of plasma glows characteristic for argon and oxygen were chosen. The results of the spectral measurements are shown in figure 5. The intensity distribution agrees qualitatively with the measurements of the ion current shown in figures 2 and 3. The difference lies in a less dramatic change in the glow of the plasma with increasing gas pressure, but as the pressure increases, maxima are observed at the periphery too (see figure 2).

![Figure 5](image)

**Figure 5.** The distribution of radiation intensity of argon and oxygen atoms along the extended cathode cavity size at different pressures and discharge current of 400 mA. Pressure: 1 – 12 Pa; 2 – 26 Pa.

The explanation for the appearance of maxima can be as follows: as is known in the glow discharge, the main mechanisms for the production of charged particles—ions and electrons—are the ionization of the gas, with both relatively slow plasma electrons and fast electrons produced by ion-electron emission from the walls of the cathode cavity participating in the ionization and accelerated in the cathode layer. At the forevacuum pressures range, the mean free path of electrons in an argon atmosphere is several centimeters and the ionization of neutral atoms by secondary electrons occurs mainly near the end walls of the cavity. These processes can cause an increase in the plasma concentration near the end walls of the cathode cavity.

4. Conclusion
The paper presents the results of an investigation of a discharge with an extended hollow cathode used in a source of a ribbon electron beam. The ion current from the discharge plasma to a single probe depends on the geometry of the cathode cavity, the pressure and the type of gas. The most uniform distribution of the ion current from the plasma in the entire investigated range of pressures is observed in the case of using helium as a working gas and a sufficiently deep cavity when the mean free path of electrons exceeds the depth of the cavity by several times. Optimal parameters of cavity geometry are determined, under which it is possible to obtain an even distribution of the plasma concentration.

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