Features of glow discharge ignition through a small hole in the hollow cathode of a large volume

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Abstract. The influence of the size of a cathode gap on the initiation of the effect of a hollow cathode in a glow discharge system with an extended hollow cathode in the forevacuum pressure range is shown. It was found that the threshold current for the transition of the discharge to the burning mode with a hollow cathode is determined by the ratio of the longitudinal and transverse dimensions of the cathode slit. With a decrease in the width of the slot, the threshold current increases disproportionately; at the same time, with an increase in the length of the slot, this current sharply decreases.

1. Introduction

Glow discharge with a hollow cathode has been known since the 60s of the last century [1] and, due to its peculiarities, is used in sources of electron beams of various configurations. Due to the oscillation of electrons in such discharge systems, the so-called hollow cathode effect, the plasma concentration near the emission boundary turns out to be much higher than the concentration achieved in the case of a discharge between a flat cathode and anode [2]. An extended rectangular hollow cathode with a longitudinal slot in one of the walls facing the anode is used for the formation of an electron beam of the so-called strip configuration. Research and application of sources of this type are described in [3, 4].

Electron beams are used for processing extended products or creating a large-area beam plasma in the pressure range from 5 to 50 Pa. For the formation of tape electron beams at lower pressures of 0.01-1 Pa, sources based on a hot cathode are used [5, 6]. When an electron beam is injected into the working chamber with a pressure of 0.01-1 Pa, conditions are created for initiating a beam-plasma discharge and extracting ions from it. The width of the distribution function of ions in this flow is 2-3 eV, which makes it possible to use it for "soft" defect-free etching of various semiconductor heterostructure compounds, deposition processes for micro and nanoscale films used in microelectronics and optics [7]. Ensuring the operability of the electronic source is achieved by creating a pressure difference between the regions of beam generation and the working volume. Since the ribbon hot cathode used in the source is very sensitive to pressure surges and requires the creation of a high vacuum, the electron beam injection system turns out to be rather complicated.

Unlike a hot cathode, a plasma cathode is not so sensitive to pressure drops and remains operational even when working with active gases. The use of a plasma electronic source of a ribbon configuration to initiate a beam-plasma discharge at pressures of 0.01-1 Pa can increase the reliability and energy efficiency of the plasma reactor. The optimum pressure for ignition and
combustion of a glow discharge is in the range of 1-10 Pa, i.e. an order of magnitude higher than the pressure in the working chamber required for a beam-plasma discharge. Thus, a differential pressure is required. This drop can be achieved most simply by simultaneously decreasing the width of the slit in the cathode and anode of the plasma source, i.e. a decrease in the area of the opening connecting the volumes with different pressures.

Most of the research work related to an extended hollow cathode is devoted to the study of emission from an extended cathode, as well as the transportation and application of the electron beam formed by it [8-10]. The peculiarities of discharge ignition in an extended cathode cavity in the case of a sufficiently narrow exit slit have not been investigated so far. The purpose of this work is to study the factors affecting the ignition of a discharge in an extended cathode cavity in the case when the transverse size of the slit in the cathode does not exceed several millimeters.

2. Experimental setup
For the experiments, a forevacuum plasma source was used. The schematic of the discharge system of the source, the power supply and the connection of the diagnostic equipment are shown in figure 1.

![Experimental setup schematic](image)

The discharge system consisted of an extended hollow rectangular cathode and a flat anode made of stainless steel. A frame-shaped insulator made of caprolon was used to insulate the cathode and anode. The internal dimensions of the cathode cavity were 120×30×700 mm³. There was an extended slit along the long side of the cavity, the dimensions of which could be changed using inserts of 0.6 mm thick sheet copper. The slit width in the cavity varied from 0.4 to 2 mm, and its length varied from 0.4 to 100 mm. The width limitation of 0.4 mm is due to the difficulty of maintaining the parallelism of the slit edges. A rectangular emission window in the anode with dimensions of 120×10 mm² was covered with a tungsten grid with a cell of 0.6×0.6 mm² and a geometric transparency of 70%. The presence of a large window in the anode in comparison with the dimensions of the slit made it possible to visually determine the region of the discharge plasma and evaluate the uniformity of its distribution. The voltage was applied to the discharge gap using a Spellman SR6 stabilized power supply through a 10 kΩ ballast resistor. The current in the cathode-anode circuit was measured using an ammeter connected to the cathode. The voltage across the discharge gap was measured with a TESTEC HVP-15HR high-voltage probe connected to a Tektronix2024B oscilloscope.

The vacuum chamber was evacuated by a mechanical pump to a limiting pressure of 2-3 Pa. Then, the chamber was purged with a working gas (argon) and the required pressure was set in the range from 15 to 50 Pa using a needle leak.

3. Experimental results and discussion
Experiments have shown that in the pressure range of 15-50 Pa, the ignition of the discharge in an extended cathode cavity with a slit size of 100×0.4 mm² occurs at a rather low value of the discharge current, on the order of several mA. A decrease in the length of the slit in the cathode leads to an increase in the threshold current $I_{tr}$ at which the discharge penetrates into the cathode cavity. The dependence of the threshold current on the gas pressure also appears.

Figure 2 shows the dependences of the threshold current on the length of the slit in the cathode $L$ for various pressures and widths of the slit $d$ 0.4 mm, 1 mm, 1.5 mm and 2 mm. As can be seen from the presented dependences, the largest value $I_{tr} = 250$ mA is observed for not the narrowest slit with the width of 1.5 mm, figure 2 a. This is primarily due to the limitation on the part of the power supply. During the operation of the electronic source at high discharge currents, a significant heating of the electrodes and the insulator between the cathode and the anode is observed. To prevent overheating and deformation of the insulator, the maximum current of the power supply was limited to 300 mA. It is obvious that the use of a more heat-resistant insulator would make it possible to operate at high values of the discharge current, however, the tendencies of switching the discharge into the cathode cavity and the dependence on the pressure and geometry of the slot in the cathode would remain.

![Figure 2](image)

**Figure 2.** Graphs of the dependence of the threshold current $I_{tr}$ for the transition to the mode with a hollow cathode on the length of the slot $L$ and pressure $p$ for different widths of the slot $d$, mm: a - 0.4, b - 1, c - 1.5, d - 2. Gas pressure: 1 - 15 Pa; 2 - 20 Pa; 3 - 30 Pa; 4 - 40 Pa.

Analyzing the presented in figure 2 graphs, the following conclusions can be drawn: the threshold current increases with decreasing pressure and width of the slit in the cathode. A twofold decrease in pressure, from 40 to 20 Pa, leads to an increase in $I_{tr}$ from 2 to 4 or more times, depending on the width of the slot. For a slit width of 2 mm, the transition of the discharge into the cavity takes place...
at currents not exceeding several milliamperes, i.e. almost immediately upon ignition of the discharge between the flat parts of the cathode and anode. At the same time, for a narrower gap, much higher currents are required - hundreds of milliamperes. Based on figure 2, we can conclude that the smaller the slot width, the more important is its length and gas pressure. Indeed, for a slot width of 0.4 mm in the cavity, its minimum length at which the appearance of the hollow cathode effect was observed was 24 mm. For a slit with 1 mm wide, this length is already 18 mm, and for a slit with 2 mm wide, a slit length of 2 mm and a discharge current of no more than 25 mA were sufficient for plasma penetration into the cavity.

As is known, for the initiation of the hollow effect it is necessary to fulfill the condition that the thickness of the cathode layer $l_c$ must become less than or equal to half the transverse size of the hole $d$ in the hollow cathode:

$$l_c \leq 0.5d .$$

(1)

For a simple estimate of the length of the cathode layer, one can neglect the electrons in the layer and consider it exclusively ionic. Then for the length of the layer we obtain the expression:

$$l_c \approx 1.254 n_0^{1/2} \sqrt{\frac{e_0 U_c^{3/2} (ekT_e)^{1/2}}{\varepsilon_0 }} .$$

(2)

The cathode potential drop, as a rule, weakly depends on the magnitude of the discharge current, and the main factor affecting the length of the cathode layer is the plasma concentration. Calculation by formula (2) showed that the length of the layer exceeds its transverse size and condition (1) is not satisfied for the investigated range of slot widths. However, if we apply the condition of plasma penetration into the cathode cavity for the length of the slit in the cathode, then it turns out that condition (1) can be satisfied. It is obvious that the penetration of the discharge into the cathode cavity is influenced by the ratio between the slot length and its width. It should be noted that the smaller the slot width, the more important is its length and gas pressure. For a slit width of 2 mm, the transition of the discharge to the cavity takes place at currents not exceeding several milliamperes, i.e. almost immediately upon ignition of the discharge between the flat parts of the cathode and anode. At the same time, for a narrower gap, currents of hundreds of milliamperes are required.

4. Conclusion

For a glow discharge with an extended rectangular hollow cathode, the length of the cathode gap influences the threshold current for initiating the hollow cathode effect. With an increase in the length of the cathode gap, the threshold transition current, which determines the concentration of the discharge plasma and the length of the cathode layer, decreases. Even in the case of a narrow cathode gap, for which the condition of the cathode layer rupture is certainly not satisfied, an increase in the gap length leads to the initiation of the hollow cathode effect. An increase in the length of the slit to values tens of times greater than the length of the cathode layer leads to the initiation of the hollow cathode effect at discharge currents not exceeding 300 mA.

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