The formation of a plasma anode in a Penning discharge cell combined with a planar magnetron

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Abstract. In the paper, a number of specifications of a plasma anode formed by a hybrid discharge which combines high-current reflective (Penning), low-pressure (argon, 0.053-0.133 Pa) gas discharge with a discharge in planar magnetron built into explosive-emission cathode of high-current electron gun was studied. Time delays of the transition of Penning discharge into high-current stage as well as radial distributions of electron and ion current densities of discharge plasma have been measured. It was shown that sometimes the current density distribution increased in the peripheral part of plasma anode is observed. This is needed for improvement of energy density uniformity via the cross section of high-current electron beam produced in such electron gun. The results of preliminary testing of electron gun with this plasma anode are presented.

1. Introduction

The uniformity of low-energy (up to 40 keV), high-current (up to 25 kA) electron beam (LHEB) formed in a gun with an explosive-emission cathode and plasma anode based on reflective (Penning) discharge (RD) is one of key parameters for surface modification of materials, especially when solving problems associated with the formation of surface alloys from pre-deposited coatings. The electron and ion current densities in the double layer, in which electron beam is formed, are related by Langmuir formula: \( j_e = j_i \left( \frac{M}{m} \right)^{1/2} \) (\( M \) and \( m \) are ion and electron mass, respectively). On the face of it, to ensure homogeneity of the LHEB density \( j_e(r) \), it is necessary that the ion current density, \( j_i(r) \), be homogeneous over the cross section of plasma anode. However, the research and operational experience of high-current electron guns have shown that, passing through a homogeneous plasma channel in a guide magnetic field, the beam transforms and acquires the maximum current density in the near-axis region [1, 2]. To compensate this negative “focusing” effect, it is necessary to create a plasma anode with an increased ion density in its periphery.

For this purpose, in the paper [3], the arc plasma sources built into the anode of RD and provided increased ionization in the peripheral part of plasma anode were used. In such a system, it was possible to improve the beam uniformity but the beam stability became some worse because of non-stability of arc sources operation.

Recently, we suggested another idea how to form the profile of ion density \( n_i(r) \) amplified in the peripheral part of plasma anode [4]. This idea is concluded in the use of hybrid discharge scheme matching an annular Penning anode and a planar magnetron built into an explosive-emission cathode. Magnetron generates an annular cloud of plasma near the cathode and a flow of neutrals due to
sputtering. Therefore, at further burning of RD, which forms plasma anode, one may expect the increasing of ion density in the peripheral part in comparison with the central one.

In comparison with the method [3], the last suggested idea looks more promising. Besides, the creation of magnetron plasma should improve the stability of cathode emission. Preliminary testing of a new electron gun [4], in which plasma anode is formed by hybrid discharge matching pulsed magnetron discharge (MD) and high-current RD, have shown its operability. Using high-speed video-frame photography, the glow dynamics of such a discharge was investigated in different modes [5] (see figure 1). It was found, that guide magnetic field should be applied several milliseconds later than MD starts, so in this case it does not hinder MD operation.

The paper presents continuation of the investigations started in [5]. First of all, we were interesting in charged particle distribution via plasma anode cross section. Besides, we tried to produce LHEB in this new electron gun.

![Figure 1. The glow of MD after ~9 ms after start of the pulse of discharge current.](image)

2. Experimental arrangement and technique

Figure 2 presents schematically the electron gun "VEKSM" created by us in [4], which was used for experiments. Current densities of charged particles were measured using 4-channel system probe techniques. While probe measurements, the foil 8, window 9 and thermal imager 10 were removed, and the grounded collector with the probes on it was installed (figure 3). To measure electron current density, single probes made of Ø2-mm copper rods inserted into ceramic tubes were used, and ion current density was measured by double probes with galvanic decoupling of the signals from the ground by pulsed transformers.

![Figure 2. Experimental arrangement. 1 – cathode assembly; 2 – disc magnet; 3 – ring magnet; 4 – emitters of the cathode; 5 – ring anode of RD; 6 – anode plasma; 7 – solenoid; 8 – stainless steel foil (200 μm); 9 – infrared window; 10 – thermal imager.](image)
While measurements of electron current density, the bias made up +300 V and the load resistance was 1700 Ω. While measurements of ion current density, the bias made up 45 V and the load resistance was 500 Ω. Big resistance of the loads prevented the appearance of cathode spots on the probes that could distort measurements. Both balanced (diameter of the central disc magnet was 46 mm) and unbalanced (diameter of the central disc magnet was 20 mm) magnetron were used in the experiments.

Time delays of the RD transition into high-current stage were measured with oscilloscope (Tektronix TDS 2024, 200 MHz).

![Figure 3. Scheme of the probes. Single probes – at the left and double probes – at the right.](image)

### 3. Results and discussion

Typical waveforms of RD current and burning voltages of MD and RD are given in figure 4. Time delay of the RD transition into high-current stage, \( t_d \), is defined as the duration of high-voltage stage of RD. The type of magnetron (balanced or unbalanced) does not influence on this time delay. It was found, that preliminary triggering of MD decreases the time delay from typical 20–30 \( \mu s \) [2] to 6-8 \( \mu s \) (at argon pressure of 0.06 Pa). This decreasing can be interpreted as zeroing of statistical time delay of gas discharge pulsed breakdown [6], since free electrons are injected to Penning discharge cell from the MD plasma.

![Figure 4. Typical waveforms. Ch1: burning voltage of MD (800 V/div); Ch2: current of RD (160 A/div); Ch3: anode voltage of RD (3 kV/div). Argon pressure is 0.06 Pa; time delay of the start of solenoid relatively to the start of MD is 2 ms; time delay of RD relatively to the start of solenoid is 5 ms (relatively to MD – 7 ms). Horizontal scale is 10 \( \mu s/\text{div} \).](image)
In the figure 5, typical waveforms obtained from single probes as well as corresponding radial distributions of electron current density are presented. These distributions show the increased plasma density in the case of MD starts several microseconds before RD starting. However, absolute values of plasma density according to these measurements does not exceed \((3\div4)\times10^{11} \text{ cm}^{-3}\) (we assume that temperature of electrons is 5 eV), which several times lower than expected values obtained earlier for pure RD [2, 7].

In the case of MD did not burn, the distribution of current (plasma) density had, as a rule, a maximum in the central part of plasma column and pulse durations essentially decreased (figure 6).

Figure 5. Waveforms of electron currents to the probes (at the left, horizontal scale is 50 \(\mu\text{s}/\text{div}\)) and radial distributions of electron current density in different times from the start of these pulses: curve 1 obtained at 150 \(\mu\text{s}\), curve 2 – at 175 \(\mu\text{s}\) and curve 3 – at 200 \(\mu\text{s}\). Balanced magnetron. MD is switched on. Argon pressure is 0.06 Pa, time delay of the start of solenoid relatively to the start of MD is 2 ms; time delay of RD relatively to the start of solenoid is 4 ms (relatively to MD – 6 ms).

Figure 6. Waveforms of electron currents to the probes (at the left, horizontal scale is 50 \(\mu\text{s}/\text{div}\)) and radial distributions of electron current density in different times from the start of these pulses: curve 1 obtained at 50 \(\mu\text{s}\), curve 2 – at 75 \(\mu\text{s}\) and curve 3 – at 100 \(\mu\text{s}\). Balanced magnetron. MD is switched off. Argon pressure is 0.06 Pa, time delay of the start of solenoid relatively to the start of MD is 2 ms; time delay of RD relatively to the start of solenoid is 4 ms (relatively to MD – 6 ms).

Double probes measurements have given the plasma density of 3-4 times higher than those obtained by single probes. But the radial distribution, as a rule, was similar to those given in figure 6, e.g. with maximum in the central part of plasma anode. The reason of this contradiction is not understandable yet.
We have also carried out preliminary measurements of the LHEB energy density distribution using the thermal imaging according to technique described in [8]. Typical thermogram and corresponding energy density distribution, \( W(r) \), are given in figure 7. Comparing these results with those obtained by us earlier for the case of usual RD [9], we have found that the LHEB uniformity in the case of hybrid discharge is not worse, at least, but even a little bit better.

Figure 7. Thermogram (at the left) and corresponding LHEB energy density distribution obtained in the case of hybrid discharge (at the right). Amplitude of accelerating voltage is 25 kV, argon pressure is 0.06 Pa. Copper-braid cathode with emitters of 0.8-cm height.

**4. Conclusion**

Preliminary triggering of the magnetron discharge decreases several times the time delay of the reflective (Penning) discharge transition into high-current stage by zeroing of statistical time delay of gas breakdown.

The measurements of the distribution of electron current density via radius of the plasma anode formed by hybrid discharge matching pulsed magnetron discharge and high-current reflective discharge have shown the possibility to obtain an increased ion density in the peripheral part of plasma anode in comparison with its central part. Such distribution is needed for improvement the uniformity of high-current electron beam formed in electron gun with this plasma anode.

Preliminary testing of high-current electron gun with plasma anode based on hybrid discharge have shown that uniformity of the beam energy density distribution via its cross section is not worse, at least, but even a little bit better than in the case of traditionally used high-current reflective discharge.

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