Peculiarities of the Exciting of Explosive Emission in High-Current Electron Gun with Plasma Anode Based on a Reflective Discharge

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Abstract - The paper is devoted to peculiarities of the exciting of explosive emission on wide-area, multi-wire metal cathodes in high-current electron beam sources with plasma anode base on high-current reflective discharge. It is shown that in contrast to vacuum diodes, the time delay of the beam current appearing depends on applied voltage weakly but strongly on plasma density and vacuum conditions. A method of increasing the lifetime of the cathode operating in oil-free vacuum is proposed.

1. Introduction

Wide-area (> 10 cm^2), low-energy (10-30 keV), high-current (up to 20 kA) electron beams (LEHCEBs) find more and more applications for material surface treatment [1]. Among the different plasma-filled electron guns used for LEHCEBs production, ones based on plasma anode forming by high-current reflective (Penning) discharge (RD) are the most promising. [2, 3]. However, in spite of the success in practice, a number of physical processes taking place in plasma-filled guns remain still unclear. In particular, it concerns the exciting of explosive emission (EE) on wide-area, multi-wire metal cathodes under plasma. The necessity of the pure metal cathode use is caused by such tasks as increasing the electric strength of vacuum insulation, treatment of the medicine parts which require an improved purity of the treatment process [3, 4]. Hence, the use of graphite or metal-dielectric cathodes is unacceptable.

It is a complicated task to provide the stable EE on wide-area, multi-wire metal cathodes. For example, in vacuum diodes, the border cathodes made of copper degrade after 10^4 shots only and even the electric field on the cathodes is $E_c > 1$ MV/cm and at oil pumping [5]. As far as the acceleration voltage in LEHCEBs sources does not exceed 30-40 kV, it is evident that to achieve the stable EE is to be twice complicated. For typical argon plasma densities $n_a \approx 5\times10^{12}$ cm^{-3}, estimations done according to [6] give $E_c \approx (2\text{-}3)\times10^5$ V/cm for acceleration voltage of 30 kV and voltage rise-time 20-30 ns. The electric field is amplified on the tips of wires because the thickness of near-cathode ion space charge layer is about ten times greater than diameter of wires (100 μm). However, it is not sufficient for effective (i.e. uniform and stable) exciting of EE without the other mechanism of emission centers formation concluded in charging of non-metal inclusions and films with ions from anode plasma and their following breakdown [7]. The paper presents some results concerned the role of ion bombardment in exciting of EE on wide-area, multi-wire cathode are presented in this paper.

The other peculiarity of the considered electron guns is as follows. Besides the Penning space region of RD, there is also the coaxial magnetron discharge region, formed by the anode and the wall of electron gun. Magnetron plasma, which density is 3-5 times lower only than the Penning one, penetrates into the space between the cathode and wall. As a result, in spite of guide magnetic field counteraction, this plasma causes the essential leakage of current leading to breakdown and, hence, to limitation of beam pulse duration as well as decreasing the efficiency of energy transfer from the pulsed generator into the beam [4, 8].

For limitation of the magnetron plasma expansion toward the cathode, we proposed to install the grounded diaphragm [8, 9]. Vacuum melted copper was firstly used as diaphragm material that provided surface cathode regeneration due to partial evaporation of diaphragm in each pulse and the following deposition of the vapors on the cathode. However, the further our experiments on the improvement of electric strength of vacuum gaps have shown that the best results were achieved with the use of molybdenum diaphragm. But at that the cathode life-time decreased in comparison with the use of a copper one. It was supposed that a part of vapors of copper diaphragm still achieves the target decreasing the value of electric strength in comparison to the case of molybdenum which is a refractory metal. Thus, the second task of the present work was the search of the method to increase the cathode life-time keeping the minimum contaminating of the treated electrodes.

2. Experimental arrangement

Two LEHCEB sources distinguishing by the evacuating method were used. The first source had an oil diffusion pump, and the second one – a turbo-molecular one. The block-diagram of electron gun is given in Fig. 1, and more detailed description of the sources is presented in [3]. Plasma anode was formed with the use of high-current (100-150 A) RD in argon. An explosive emission cathode of diameter 6 cm was manufactured from copper braid of radio-frequency cable and fixed in stainless steel cylindrical holder. A grounded diaphragm preventing the magnetron plasma penetration into cathode-wall space was installed between the cathode and anode. Acceleration voltage pulse V_d was monitored with resistive divider, total cathode current I_d – by Rogowsky coil, and beam current onto the collector – by low-inductive shunt. The signals were delivered to inputs of 4-channel digital oscilloscope **Tektronix TDS 2024** (200 MHz).

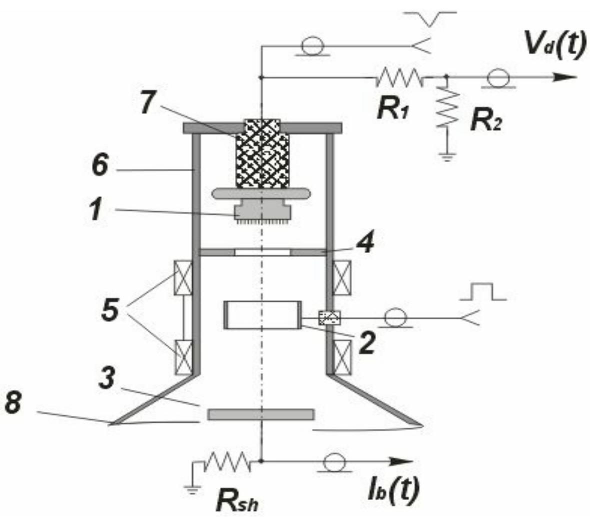

Fig. 1. The block-diagram of electron gun. 1 – explosive-emission cathode; 2 – anode of reflected discharge; 3 – collector; 4 - diaphragm; 5 – solenoid; 6 – body of the gun; 7 – insulator; 8 – working chamber. R_1, R_2 – voltage divider. R_{sh} = 17 mΩ – shunt

Varying of the plasma density n_a was performed by changing the time delay between the start of high-current stage of RD and the moment of acceleration voltage applying to the cathode. The n_a values were taken from our previous measurements [10].

3. Results and discussion

3.1. Time delay of explosive emission

The dependence of time delay t_d of the collector current appearance relatively to applying the voltage to the cathode has been studied experimentally. Typical waveforms are given in Fig. 2. The start moment of the voltage pulse was fixed at the level of 10% of the value achieved to the end of rise-time. Start of the beam current was fixed at the level of 300 A, which was certainly greater of the RD current as well as the plasma displacement current. For the defining t_d, the flying time of electrons from the cathode to the collector (3-5 ns depending on acceleration voltage and it was also assumed the absence of the potential drop in the drift channel) was deducted from the values obtained from waveforms.

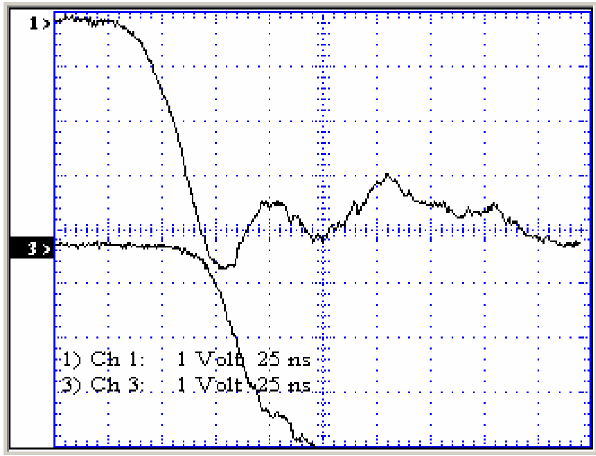

Fig. 2. Initial intervals of the waveforms of acceleration voltage (trace 1; 5.3 kV/div) and beam current (trace 3; 600 A/div). $n_a \approx 3\times10^{12}$ cm^{-3}, argon pressure - 0.45 mTorr, guide magnetic field strength – 1.25 kGs. Diffusion pumping

The dependences of t_d on applied voltage are given in Fig. 3. It is evident that t_d is weakly depended on applied voltage. In contrast, the Fig. 4 shows that changing of the plasma density influences essentially on the value of t_d. The data given in Fig. 3 show also that improvement of vacuum conditions increases t_d, but the character of dependence is the same.

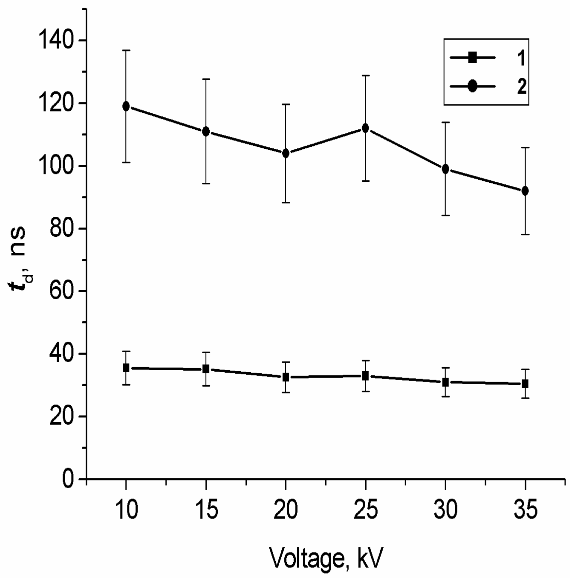

Fig. 3. Time delay of an explosive emission excitation vs applied voltage. Argon pressure - 0.45 mTorr, guide magnetic field strength – 1.25 kOe., $n_a \approx 2.5\times10^{12}$ cm^{-3}. Curve 1 corresponds to the case of diffusion pump, curve 2 – turbo-molecular one

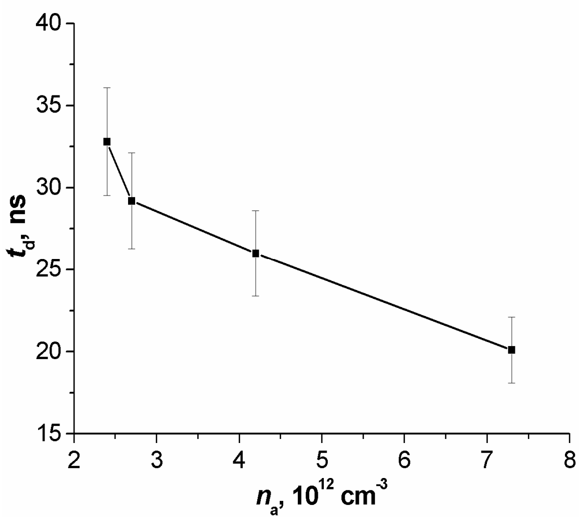

Fig. 4. Time delay of the excitation of explosive emission vs. plasma density. Argon pressure - 0.45 mTorr, guide magnetic field strength – 1.25 kOe., V=20 kV. Diffusion pumping

The behavior of the $\boldsymbol{t}_d(V_d)$ and $\boldsymbol{t}_d(n_a)$ dependences obtained shows the determining role of non-metal inclusions and films breakdown at their charging by ion current from plasma for EE excitation. In the case of vacuum diode, the dependence $\boldsymbol{t}_d$ on voltage should be sharply falling [11]. Concerning the obtained values $\boldsymbol{t}_d$, it should be noted that these values 1-1,5 order of magnitude lower than calculating ones according to well-kwon formula for glow-to-arc transition [7]:

$$j_i \boldsymbol{t}_d = \varepsilon\varepsilon_0 E_{br}, \qquad (1)$$

where ε и $E_{br} \approx$ 3-5 MV/cm – dielectric permittivity and breakdown field of the film material, respectively, j_i – ion current density, which was taken from our probe measurements. This contradiction could be explained by taking in account the local increasing of the plasma density in near-cathode region during the high-current stage of RD. This increasing is provided, first of all, by the presence of cathode spots as well as ionization of desorption products with γ-electrons and secondary oscillating electrons. As far as the duration of RD makes up tens of microseconds, the thickness of the desorbed gas layer could achieve 1 cm and the density of neutrals - 10^{16} cm^{-3}. And the most important is concluded in prevailing of ionization over their going away toward the cathode because the last is defined by the density of more rare plasma according to condition of continuity of current. Namely this current is observed during the probe measurements [10] which are quasi-stationary in essence. In opposite, in the case of fast rise-time, a splash of j_i with the amplitude essentially succeeding the stationary value is possible, and its duration is mainly defined by total ion charge in this layer.

The presence of mentioned above near-cathode plasma could also explain more gradual falling $\boldsymbol{t}_d(n_a)$ than it should be expected from the formula (1).

Increasing of $\boldsymbol{t}_d$ in the case of oil-free vacuum could be explained if one suppose that the average value of E_{br} becomes greater than in the case of oil pumping.

3.2. Increasing of the cathode life-time

Vacuum conditions influence essentially not on $\boldsymbol{t}_d$, but on the cathode life-time too. Our experience of the metallic multi-wire copper cathodes exploitation for almost ten years has shown that such cathodes operate in oil vacuum practically without a hitch in various modes. However, as it could be predicted for the case of pure vacuum conditions, the problem of stable emission of the cathode became very actually. The problem of stable cathode emission get additionally complicated in conditions of target vapors deposition on its surface if the target is manufactured of the material with low emission properties [12]. As it is mentioned above, the life-time of the cathode could be increased by deposition of diaphragm material with high emissive ability but at that it is necessary to limit at most this deposition onto the treated target.

To satisfy both of requirements, we supposed the following. The main diaphragm should be manufactured of molybdenum melted in vacuum. A copper ring of inner diameter a little bit (by 2-3 mm) greater than diameter of the diaphragm hole is installed on the side looking to the cathode. Due to the fact that this ring is placed in geometric shadow from the target deposition of the ring material toward the target decrease significantly.

Fig. 5 shows the results of the cathode life-time tests for the cases of different diaphragm materials, its absence, and for the system "molybdenum diaphragm with copper ring". The dependence of the probability of idling, $\boldsymbol{P}_{id}$, via total number of electron gun shots, $\boldsymbol{N}$, was studied. The tests were carried out at such conditions: residual gas pressure – not more than 0.001 Pa, working gas pressure (argon) – 0.04 Pa, target material – stainless steel 12X18H10T (Russian standard), beam energy density at the target – from 6 to 12 J/cm^2, the irradiation was performed by series of 30-200 shots in each vacuum cycle. The $\boldsymbol{P}_{id}$ value of 10% has been taken as a criteria of the cathode life-time limit.

It is evident from the data in Fig. 5, a:

- the use of stainless steel diaphragm reduces the life-time of explosive-emission cathode by a factor of 1.7 in comparison with case of the absence of diaphragm.
- the use of molybdenum diaphragm in combination with copper ring allows one at the moment to increase the cathode life-time by more than three times in comparison with the case of the diaphragm absence and

more than five times in comparison with the case of stainless steel one. At that, the features of the cathode degradation do not observed yet. The results obtained for the copper diaphragm are practically the same.

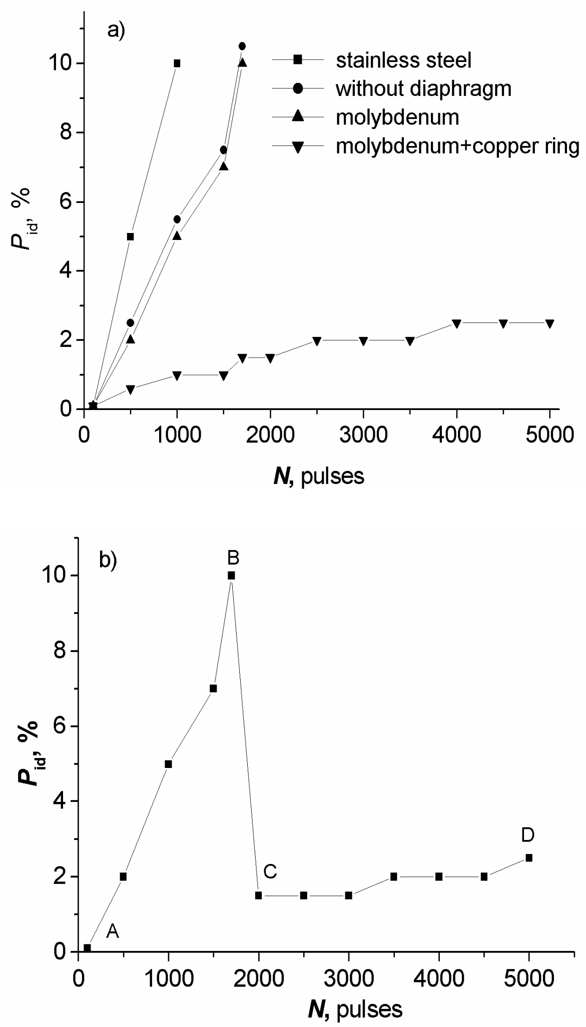

Fig. 5. The dependence of the probability of idling on total number of electron gun shots for different diaphragm materials (a) and the graph of the recovery the cathode emissive ability (b)

The use of the copper ring allows us to recover the emissive ability of the cathode. This fact is illustrated in Fig. 5, b. First 1700 shots were made without diaphragm and at the end of this cycle $\boldsymbol{P}_{id}$ achieves 10% (interval AB), cathode surface has been coated with the target material (stainless steel). Then, the molybdenum diaphragm with a copper ring has been installed and after 300 shots (interval BC), the stability of the cathode emission has significantly improved (interval CD).

4. Conclusions

1. In LEHCEB sources with plasma anode and metallic multi-wire cathode, the ion flux toward the cathode surface plays the main role in exciting of the explosive emission.

2. To increase the life-time of explosive-emission cathode, it should be provided the deposition of vapors of material with high emissive properties on the cathode surface. At the same time, an auxiliary ring being the source of vapors should be placed in geometrical shadow from target for minimizing the contaminating of the target.

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