Electric Field at a Cathode Microprotrusion under Intense Field Emission[1]

I.V. Uimanov

Institute of Electrophysics, 106, Amundsen str., Ekaterinburg, 620016, Russia
Fax: 8(3432) 67-87-94, E-mail: uimanov@iep.uran.ru

Abstract – The effect of the space charge of the emitted electrons on the strength of the self-consistent electric field at the surface of a pointed microprotrusion on a metal cathode has been investigated for the first time in the framework of a two-dimensional axisymmetric statement of the problem. Based on the method of large particles in cells (PIC), a model has been developed and self-consistent calculations of the electric field and of the field emission characteristics of a metal cathode taking into account the space charge have been performed. It has been shown that for a pulse peak voltage of ~ 250–300 kV and a microprotrusion radius of ~ 10^{-5} cm the current density in the microprotrusion can reach ~ 10^{10} A/cm^2, which suffices for the field-to-explosive emission transition within 10^{-10} s.

1. Introduction

Much progress in the development of high-current pulsed devices operating on the subnanosecond and picosecond scale has been recently [1]. For the most part the devices of this type use explosive-emission cathodes for electron beam production. It is well known that under the conditions of high vacuum and pure electrodes, explosive electron emission (EEE) is initiated by the current of field emission (FE). According to criterion for pulsed breakdown [2], the FE current density more than $10^9 \div 10^{10}$ A/cm^2 is necessary for achievement of the picosecond explosion delay times.

The question of the field-emission properties of metals in strong electric fields (~ 10^8 V/cm and higher) still remains open from both the theoretical and the experimental viewpoints. An important aspect of the applications based on high-current field emission is the effect of the space charge of the emitted electrons on the magnitude of the electric field at the cathode. The experimental and theoretical investigations of the field-emission characteristics of emitters of micron and submicron dimensions in the nanosecond pulse mode performed by now allow the statement that at current densities > 10^7 A/cm^2 the external field at the cathode surface is largely screened by the space charge of the emitted electrons.

This indisputable fact testified by the deviation of the experimental current-voltage characteristics from the Fowler–Nordheim plot given by a straight line was observed by many researchers, and it is often treated as the phenomenon of limitation of the field emission current density by the space charge. The assumption was expressed [3], that the influence of this effect can result in drama consequences even, i.e., it will be impossible to achieve the essentially large FE current density, which would allow to reduce the explosion delay time up to picosecond range.

From the theoretical point of view the self-consistent calculations of the electric field strength near the surface of a point microprotrusion on a metal cathode by using a 2D axisymmetric problem statement taking into account the space charge have hot been carried out till now. The investigations were limited only to one-dimensional solutions of the Poisson equation in case of the flat [4] or spherical diode [5, 6] or to quasi two-dimensional solutions within the framework of the effective gap model [7]. A comparative analysis of calculations performed for a spherically symmetric case with experiments performed by the authors of [6] has allowed them to speak about experimentally achieved electric fields at the cathode $E = 1–1.3\ \ 10^8$ V/cm and current densities up to $2 \cdot 10^9$ A/cm^2 in the case of needle cathodes of submicron radii and a gap voltage of 15 kV. Note that the edge (blade-type) explosive emission cathodes used in subnanosecond vacuum diodes [1] operate at pulse amplitudes of 100–300 kV and about the same electrode separations. We also note that the spherical symmetry only approximately reflects the potential and space charge distributions in an actual electrode system; therefore, for a correct consideration of this phenomenon it is necessary to perform calculations of the self-consistent field at the cathode surface using at least a two-dimensional model.

2. The problem statement and task geometry

Figure 1 presents the model geometry of the problem. As a whole it is the coaxial diode with distance the cathode-anode 1 cm. The cathode is the metal needle with the tip radius r_c. On the surface of the cathode there is a microprotrusion of height h_m, tip radius r_m, and the half-angle of the conical part θ.

[1] This work was supported by the Russian Foundation Research for Basic (Grant Nos. 08-02-00720 and 08-08-00801).

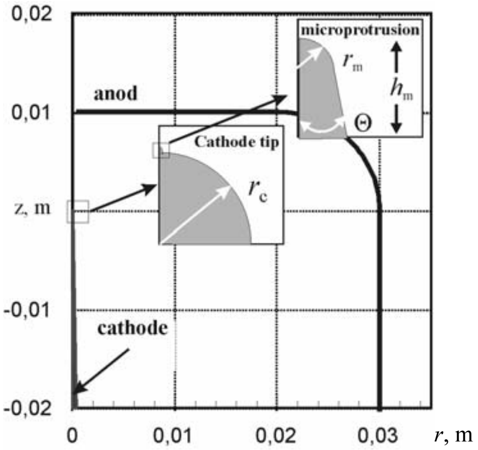


Fig. 1. Task geometry. Calculated parameters: r_c =50 μm, h_m =5 μm, r_m = 0.1 μm, θ = 5°

Approximately the factor of electric field enhancement for such geometry is $\beta_{tot} = \beta_c\beta_m$, where β_c is the factor of electric field enhancement of the point cathode, β_m is the factor of the microprotrusion. The large difference in characteristic scales of the microprotrusion and all diode is one of the main difficulties of the task.

The electric field potential U in the diode is calculated with the Poisson equation:

$$\Delta U = -4\pi\rho\,, \tag{1}$$

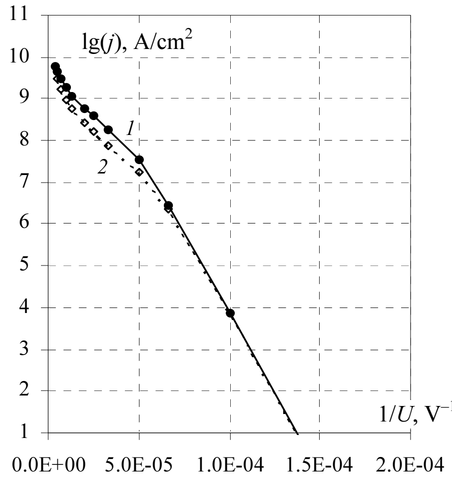
where the FE current density was assumed to depend on the self-consistent electric field at the microprotrusion surface in accordance with Fowler–Nordheim relation, ρ is the space charge (SC) density, which was found by the particle-in-cell method (PIC). The forces were interpolated and the charge redistributed with help of bilinear averaging over the four nearest grid points. The task was solved by a set up method up to decision of a stationary solution at the boundary fitted net.

3. Results

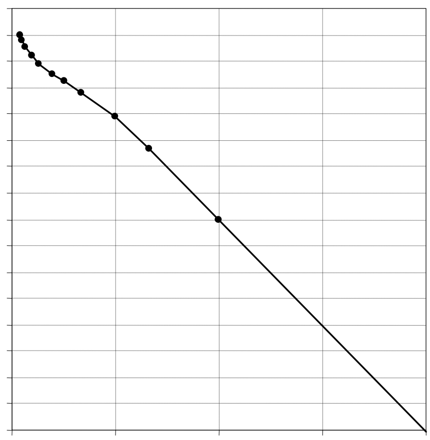
PIC simulations were performed for a copper cathode in the voltage range 5÷250 kV. The results of the numerical calculation of the FE characteristics for Cu cathode are presented in Fig. 2. Fig. 2, *a* gives the results of computation for the maximal FE current density on the microprotrusion tip. Fig. 2, *b* presents the results of the PIC simulations of the total FE current.

The results of the numerical calculation of the screening effect of the SC of the FE electrons are illustrated in Fig. 3. Analyzing the obtained curves, it can be noted that the effective gap model overestimates influence of the SC of the FE electrons.

Figure 4 presents the FE current density distribution at the microprotrusion surface for various voltages. Analyzing the curves in Fig. 4, it can be noted



a



b

Fig. 2. Calculated current-voltage characteristics for Cu cathode with work function 4.4 eV: *a* – the FE current density on the microprotrusion tip (*1* – PIC simulations, *2* – numerical calculations within the framework of the effective gap model); *b* – PIC simulations of the total FE current

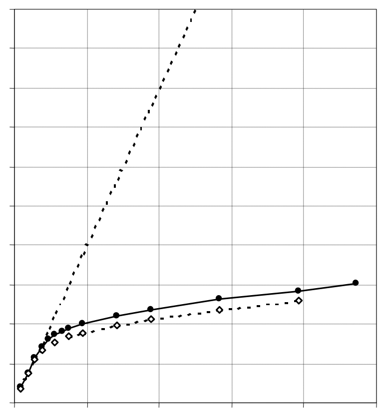


Fig. 3. SC-limited self-consistent electric field at the microprotrusion tip versus geometric field (without taking into account the space charge effect): 1 – geometric field; 2 – PIC simulations, 3 – effective gap model

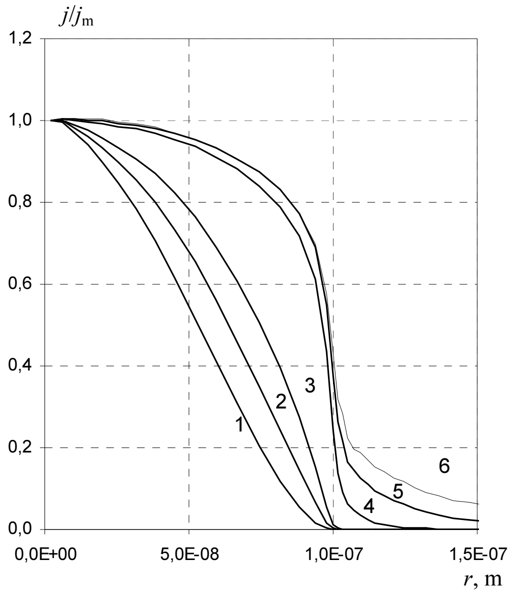


Fig. 4. FE current density distribution at the microprotrusion surface for various voltages: 1 – 5 kV; 2 –15 kV; 3 – 20 kV; 4 – 50 kV; 5 – 100 kV; 6 – 250 kV

that the screening effect results in increase of the "effective" emission surface.

4. Conclusions

This work is devoted to a study of the effect of the space charge of emitted electrons on the electric field strength near the surface of a point microprotrusion on a metal cathode by using a two-dimensional axisymmetric problem statement. Based on the particle-in-cell (PIC) method, a model has been developed and self-consistent calculations of the electric field strength at a microprotuberance and its field emission characteristics have been performed. For the geometry under investigation it has been shown that for applied pulsed voltage amplitudes of 250–300 kV the current density in the microprotrusion can reach ~ 10^{10} A/cm^2 even if the electric field is substantially screened by the space charge of emitted electrons. Based on the criterion for pulsed breakdown, it has been shown that, in view of Joule heating, this current density suffices for the FE-to-EEE transition to occur within less than 10^{-10} s.

References

[1] G.A. Mesyats and M.I. Yalandin, Usp. Fiz. Nauk **48** (3), 211–229 (2005).

[2] G.A. Mesyats, *Cathode Phenomena in Vacuum Discharge: the Breakdown, the Spark and the Arc*. Moscow, Nauka, 2000.

[3] A.V. Batrakov, I.V. Pegel, and D.I. Proskurovsky, *in Proc. of XVIII ISDEIV* **1**, 1998, pp. 44–47.

[4] T.E. Stern, B.S. Gosling, and R.H. Fowler, Roy. Soc. Proc. A **124**, 1929, 699–722.

[5] N.B. Aizenberg, Zh. Tekh. Fiz. **24**/11, 2079–2082 (1954).

[6] A.V. Batrakov, I.V. Pegel, and D.I. Proskurovsky, Pis'ma Zh. Tekh. Fiz. **25**, 78–81 (1999).

[7] J.P. Barbour, W.W. Dolan, J.K. Trolan, E.E. Martin, and W.P. Dyke, Phys. Rev. **92**/1, 45–51 (1953).