FIELD EMISSION CURRENT DENSITY FROM METAL IN THE PRESENCE OF FIELD EMITTING NANOTIPS ON THE SURFACE IN ACCELERATING STRUCTURES

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Introduction

Field emission is a type of emission that is caused by the quantum mechanical tunneling of electrons from the metal surface to a vacuum induced by a strong electrostatic field [1]. It is one of the main factors, which leads to the dark currents occurring in the accelerating structures and, as a consequence, the loss of electrical insulating properties of the interelectrode gap [2]. The increasing of the field emission current value in high-gradient accelerating structures is due to following main factors: suppression of the work function of metal; irregularities on the metal surface in the form of nanoscopic tips or nanoscale voids in the surface metal layer.

The purpose of this study is to perform an analytical calculation of the field electron emission current using the model of the double potential barrier of a rectangular-triangular shape. One of the issues is to explain the analytical relationship between the de Broglie wavelength of the tunnelling electron and the width of the potential well in the case of the double potential barrier. An important issue is to demonstrate the effect of resonant tunnelling on the field emission current density using the considered model. This theory is used to find additional sources of increasing the field emission current from the metal surface [2].

Potential barrier model for the field emission process description from nano-objects on the metal surface

The proposed model makes it possible to describe two different objects such as nanoclusters and nanoscale voids. If there is a nanoscale void in the surface metal layer, in Fig. 1 the model represents h_1 as the barrier width at the metal-vacuum interface, h_2 is the distance from the metal-vacuum interface to the location of the nanoscale void in the surface metal layer, h_3 is the nanoscale void diameter. If the nanocluster is located on the metal surface, then the barrier parameters in Fig. 1 can be explained as h_1 is the barrier width at the metal-vacuum interface, h_2 is the nanocluster size, h_3 is the dipole layer thickness of metal-metal contact.

Consider a phenomenological model of a potential barrier for the metal-vacuum system. In Fig. 1 the first region on the left corresponds inner region of metal. The rectangular region width of the potential barrier is the effective thickness h_3 of the near-surface dipole layer. The triangular region of the model with size h_1 is a potential barrier at the metal-vacuum interface.

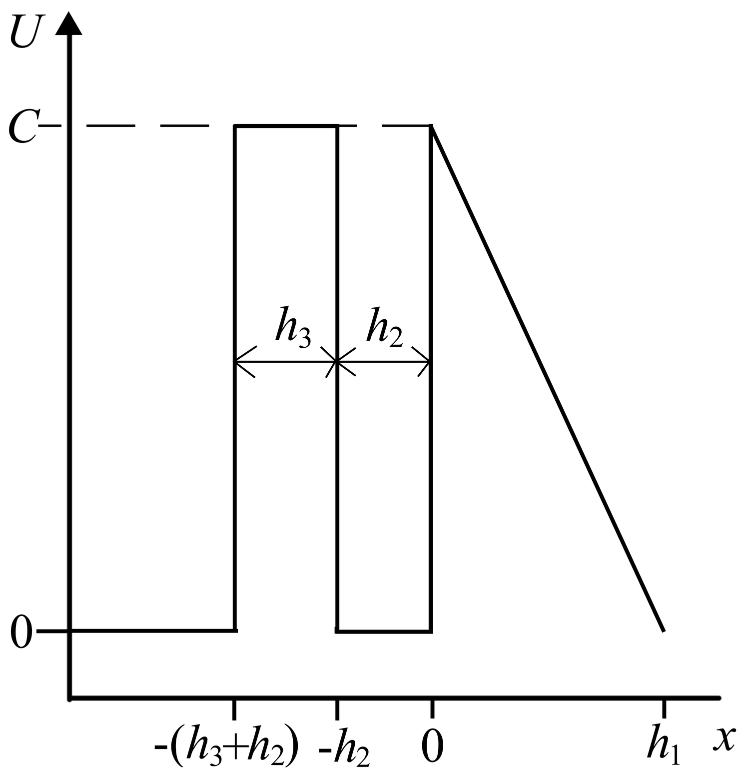

Fig. 1 Double potential barrier model of rectangular-triangular shape.

The potential barrier height C of the rectangular and triangular regions, shown in this figure, is equal to the sum of the work function χ of metal and its electrochemical potential μ, $C = \mu + \chi$, h_2 is the distance to the dipole layer [3].

Influence of nanoscale voids that appear during irradiation in the surface metal layer on field emission current density

Introduction of the additional near-surface dipole metal layer is considered as a way of taking into account the influence on the field emission current density of vacancies and nanoscale voids that appear during irradiation of the metal surface. Assume that the effective thickness h_3 of the dipole layer is defined from the sum of the volumes of all generated point defects and emptiness of the modified layer.

When an average thickness of the near-surface dipole layer is a fraction of a nanometer, in the general case, it can both weaken and enhance the field emission current density j from the modified metal surface to vacuum by several times compared to the Fowler-Nordheim current density j_{F-N} from an ideal flat surface under the condition the electric field strength E is equal to $5 \cdot 10^9$ V / m and characteristics of Cu.

Under the condition $h_3 << d_0(\mu)$, in the paper [3] the expression for the field emission current density is obtained as

$$j = j_{F-N}(1 - h_3/d_0(\mu)), \tag{1}$$

where $d_0 = (eE/\varphi + 2\sqrt{2m\varphi}/\hbar)^{-1}$; e is the electron charge; $\varphi = C - W$; W is the electron's kinetic energy; m is the free electron mass; $\hbar$ is the reduced Planck constant. At the value $E = 5 \cdot 10^9$ V / m according to the characteristics of copper: $C = 12$ eV, $\mu = 7.5$ eV, $\chi = 4.5$ eV, $W = \mu$, it is found that $d_0(\mu) = 0.5 \cdot 10^{-10}$ m^{-1}.

Using the SRIM code [4], the distribution of vacancies is shown as a function of transmission depth of Cu^{2+} ions into the volume of the copper sample to evaluate the effective thickness h_3 of the near-surface dipole layer and the value of the parameter h_2.

Fig. 2 represents the distribution of generated vacancies that depends on the depth of ion transmission in copper during irradiation of the copper sample surface by Cu^{2+} ions with an initial energy of 300 keV, which is based on the results of the SRIM calculations. The area under the line of dependence is proportional to the total number of vacancies that appear during irradiation of the metal surface by ions. Taking into consideration the influence of defect recombination process, the volume of formed vacancies is equivalent to the volume of an effective layer with width of $h_3 = 0.1 \cdot 10^{-10}$ m.

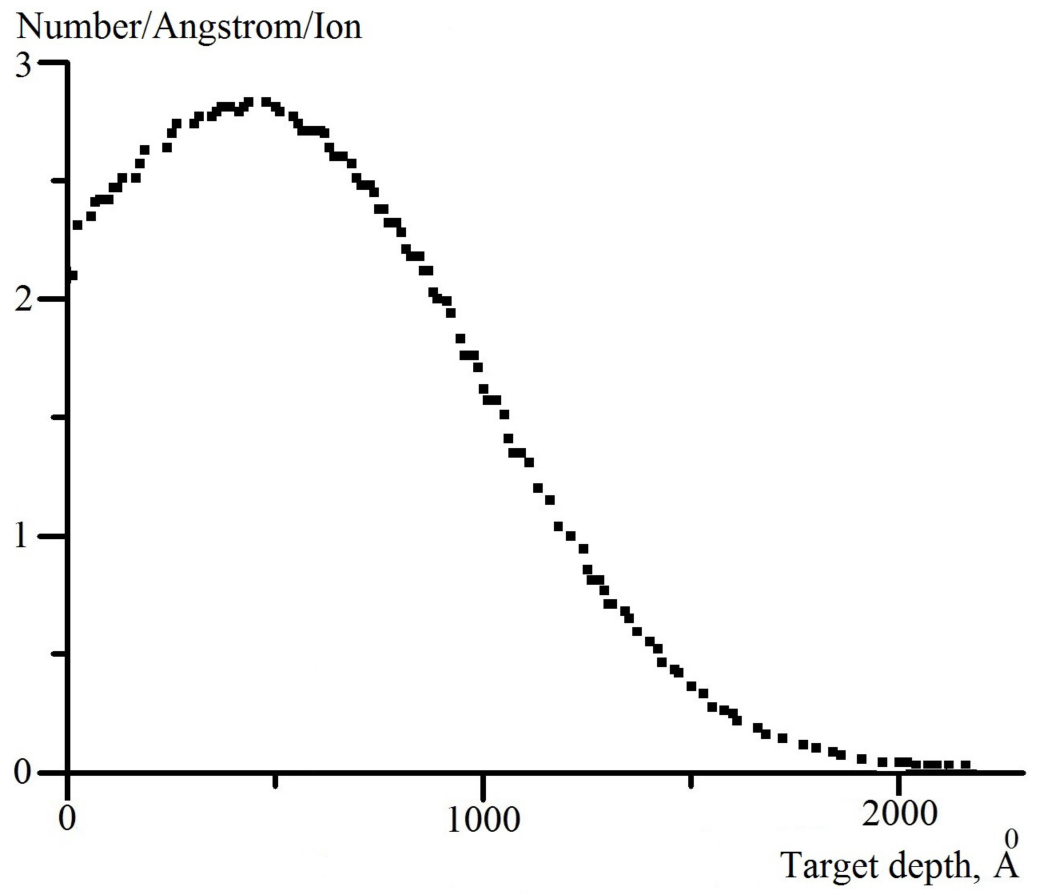

Fig. 2 Distribution of vacancies that appeared by irradiation with Cu^{2+} ions of a copper surface with an initial energy of 300 keV based on the results of calculations of the program SRIM.

Simulation of the field emission current through a double barrier in the presence of an external electric field

It was found that the field emission current takes on a maximum value when

$$h_2 = \frac{\lambda_B}{4}(2n+1), \; n = 0, 1, 2, \ldots \tag{2}$$

where λ_B is the de Broglie wavelength of an electron.

Fig. 3 demonstrates the dependence graphs of j/j_{F-N} on h_2 obtained by the numerical method at different values of h_3. At the value $E = 5 \cdot 10^9$ V / m for the copper characteristics: $\mu = 7.5$ eV, $\chi = 4.5$ eV. Then the current density j_{F-N} from the ideal copper surface is $4.2 \cdot 10^7$ A / m^2.

In Fig. 3 the maxima of the current density j are more than 5 times greater than j_{F-N} at the above parameters for $h_2 < 10^{-9}$ m. From Fig. 3 it can be concluded that with increasing h_2 the current density oscillations are decreasing. But the important contribution to the dark current in accelerating cavities and, hence, to the field emission current density is given by the oscillations of the current even when the value of the parameter h_2 is more than one nanometer. The greatest value of the current density dependence on h_2 in Fig. 3 is the first maximum at the point $h_2 \approx \lambda_B / 4$.

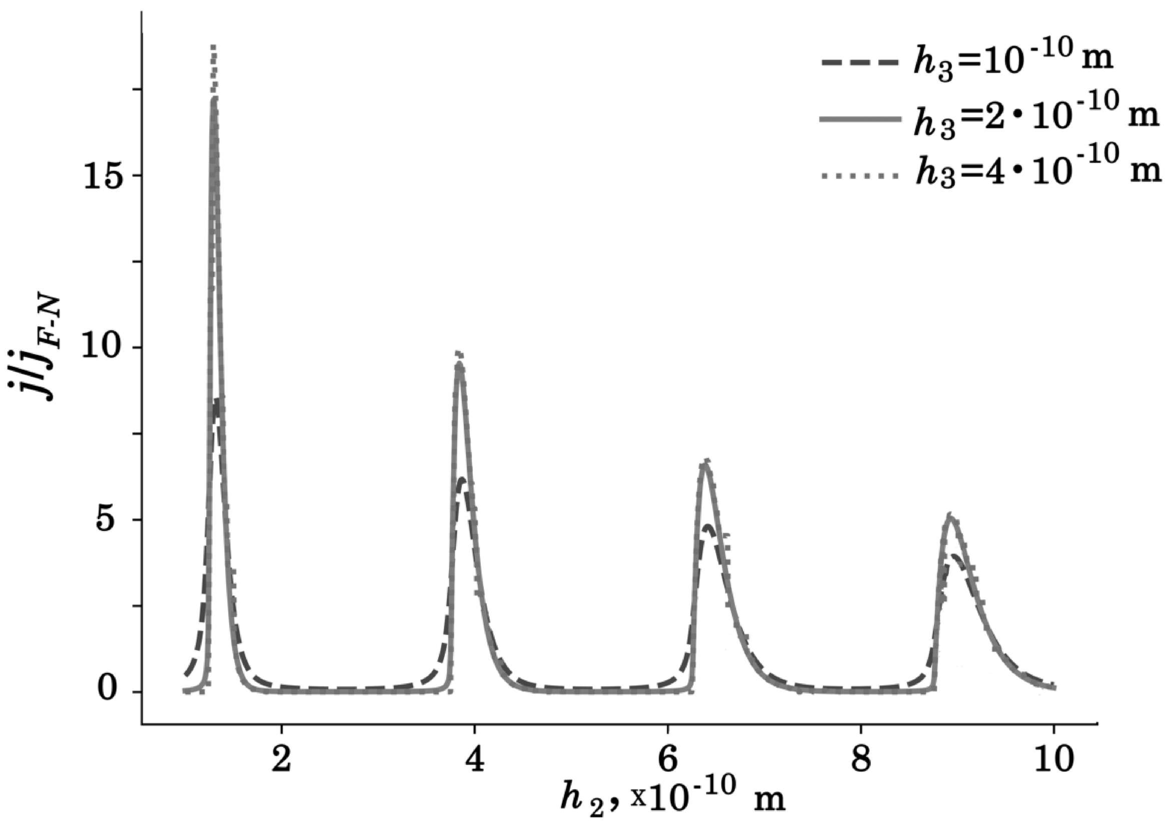

Fig. 3 Comparison of the current density j and j_{F-N} in the case of the double potential barrier model.

Conclusions

- A potential barrier model has been proposed that takes into account additional mechanisms of high-gradient high-vacuum breakdowns in accelerating structures. It is assumed that the sources of increased dark current in the accelerating cavities and, consequently, the field emission current density j_{F-N} from the electrode surface are nanoclusters on the surface and nanoscale voids in the near-surface metal layer.
- As a result, it was shown that the field emission current from the metal surface near the nano-objects has an oscillatory resonance feature. The resonance condition (2) determines the size of the nanocluster on the metal surface or the depth of the nanoscale void from the metal surface whose diameter is a multiple of λ_B / 4. The current density takes on a maximum value when the transmittance is equal to 1.
- It is revealed that at $E = 5$ GV / m the field emission current density from nanotip on the copper surface increases by more than 5 times in the case of double potential barrier model under the resonance condition (2) compared to j_{F-N}.

References

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