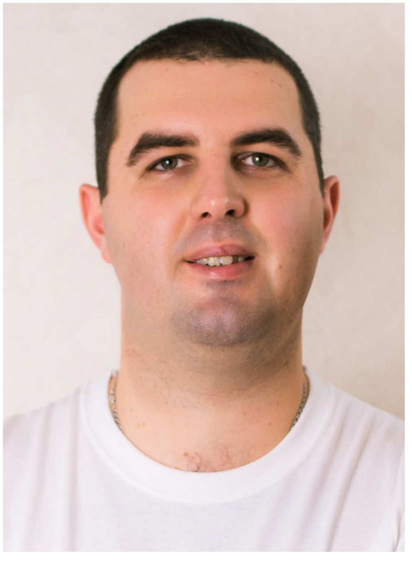
QUANTUM OSCILLATIONS AS A POSSIBLE WAY OF THE INCREASING PRE-BREAKDOWN FIELD EMISSION CURRENT



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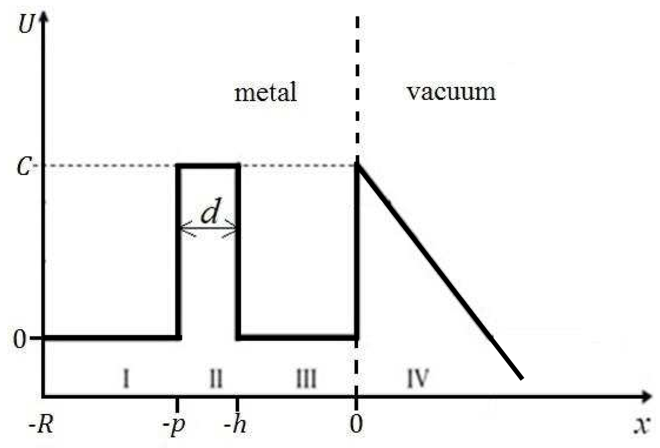
Introduction

The paper proposes a model of a potential barrier at the metal-metal-vacuum interface with an additional near-surface dipole layer. A technique has been developed to replace the potential barrier at the metal-vacuum interface and at the metal-metal dipole layer interface with a rectangular potential barrier, which makes it possible to simplify both analytical and numerical calculations. It is shown that, the field emission current can either decrease or increase several times in dependence on the thickness of the dipole layer. A model of the metal surface taking into account the tips on it is proposed. It is shown that with an increase in the spread of the radii of curvature of the tips, the exponential dependence of the field emission current on the electric field strength decreases.

Calculations of the field emission current from the metal-metal-vacuum system

Consider a phenomenological model of a potential barrier for a metal-vacuum system. The figure shows $Region\ I$ is the inner region of the metal, $Region\ II$ is the effective thickness of the d dipole layer, $Region\ II\ and\ III$ are the regions of metal modification, $Region\ IV$ is the potential barrier at the metal-vacuum phase interface. The height C of the second and fourth regions shown in the figure is equal to the sum of the work function ξ of the metal under study and its electrochemical potential μ, $C = \mu + \xi$, R is the thickness of the surface modification metal, h is the distance to the dipole layer, d is the effective thickness of the additional near-surface dipole layer, $p = h + d$.



The figure below shows the dependence of the field emission current density on the thickness of the dipole layer. For the field value $E = 5 \cdot 10^9 \frac{V}{m}$ and other parameters characteristic of Cu and the average thickness of the dipole layer of a fraction of a nanometer, in the general case, it can both weaken and enhance the field emission current j_{mod} is several times compared to the Fowler-Nordheim current from an ideal flat surface j_{FN}.

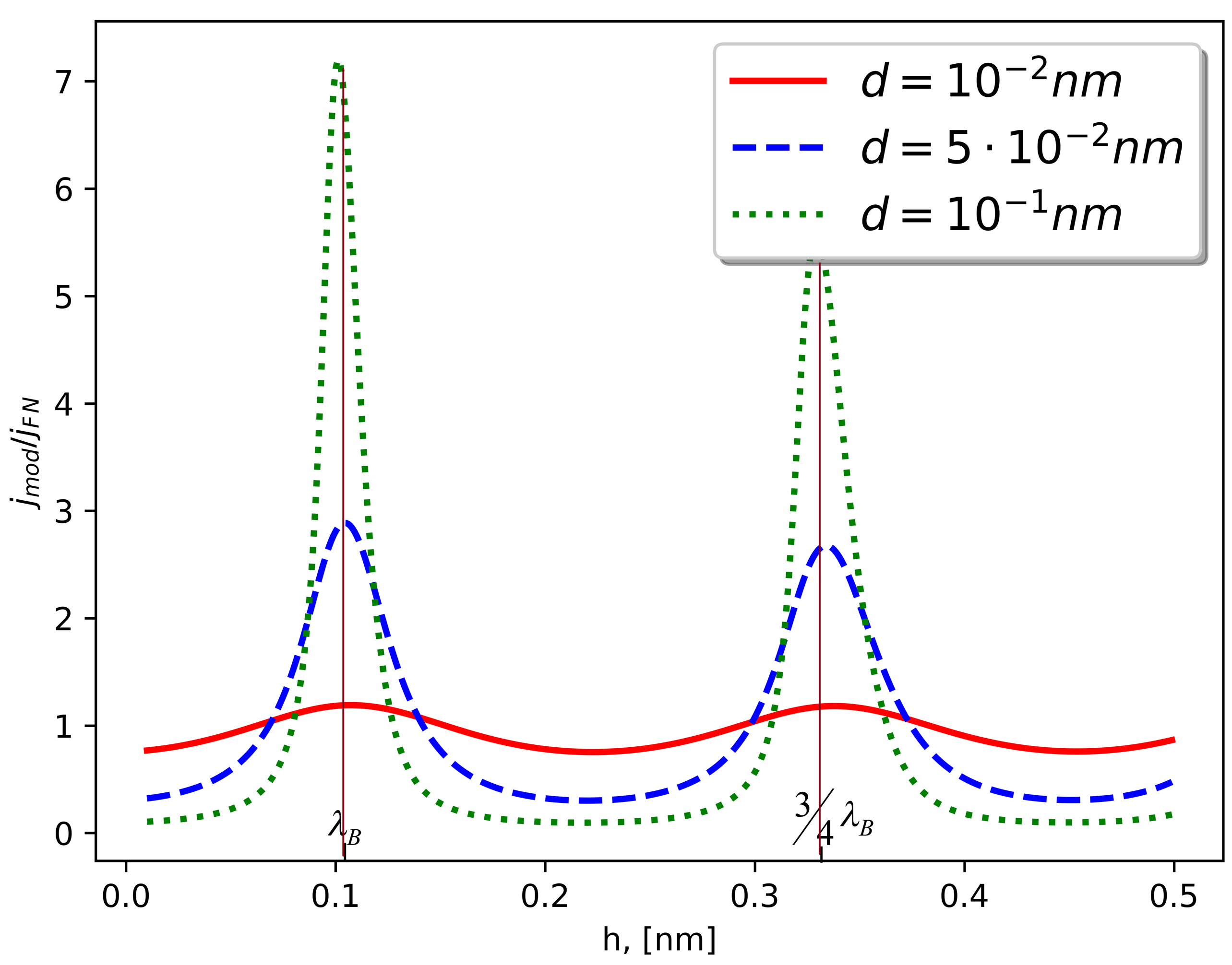


Fig.1 Dependence of the current density on the depth h and of the dipole layer thickness d.

The field emission current takes on a maximum value when

$$h = \frac{\lambda_B}{4}(2n + 1), \tag{1}$$

where λ_B is an electron De Broglie wavelength,

Replacing the potential barrier at the metal-vacuum interface

In the case of the presence of an electric field in (both external in $Region\ IV$ and contact in $Region\ II$), the electron wave function is described by Bessel functions of the third kind. The problem of finding the tunneling coefficient in this case becomes analytically cumbersome and leads to a slowdown in numerical calculations. In addition, software packages have their own restrictions on the arguments of special functions, which can interfere with calculations with the required parameters. To solve these difficulties, we propose in the model of a potential barrier at the metal-vacuum interface to replace triangular potential barriers with rectangular ones, where the width of the rectangular barrier is a function of the electric field strength $h = f(E)$. Since the coefficient of tunneling through a rectangular potential barrier is well known and has a simple analytical form, this will significantly simplify and accelerate the calculations of the field emission current.
Equating the expressions for the transparency coefficient of the rectangular and triangular potential barriers, we obtain the value of the width of the rectangular potential barrier as a function of the electric field strength:

$$h_{eff} = \left(k\sqrt{C-W}\right)^{-1} arsinh\left(W^{1/4}(C-W)^{1/4}C^{-1}\sqrt{4\sqrt{C-W}\sqrt{W}+C}\right) \tag{2}$$

Taking into account that the expression under the arc-sine hyperbolic takes large values for the corresponding parameters of the field emission, we use its schedule in a series. As a result, we obtain an expression for the effective width of the potential barrier:

$$h_{eff} = \frac{2(C-W)}{3eE} + \frac{\ln\left(2W^{1/4}(C-W)^{1/4}C^{-1/2}\right)}{k\sqrt{C-W}}, \tag{3}$$

where $k = \frac{\sqrt{2m}}{\hbar}$, C is the potential barrier height, W is the electron's kinetic energy.

Differential current

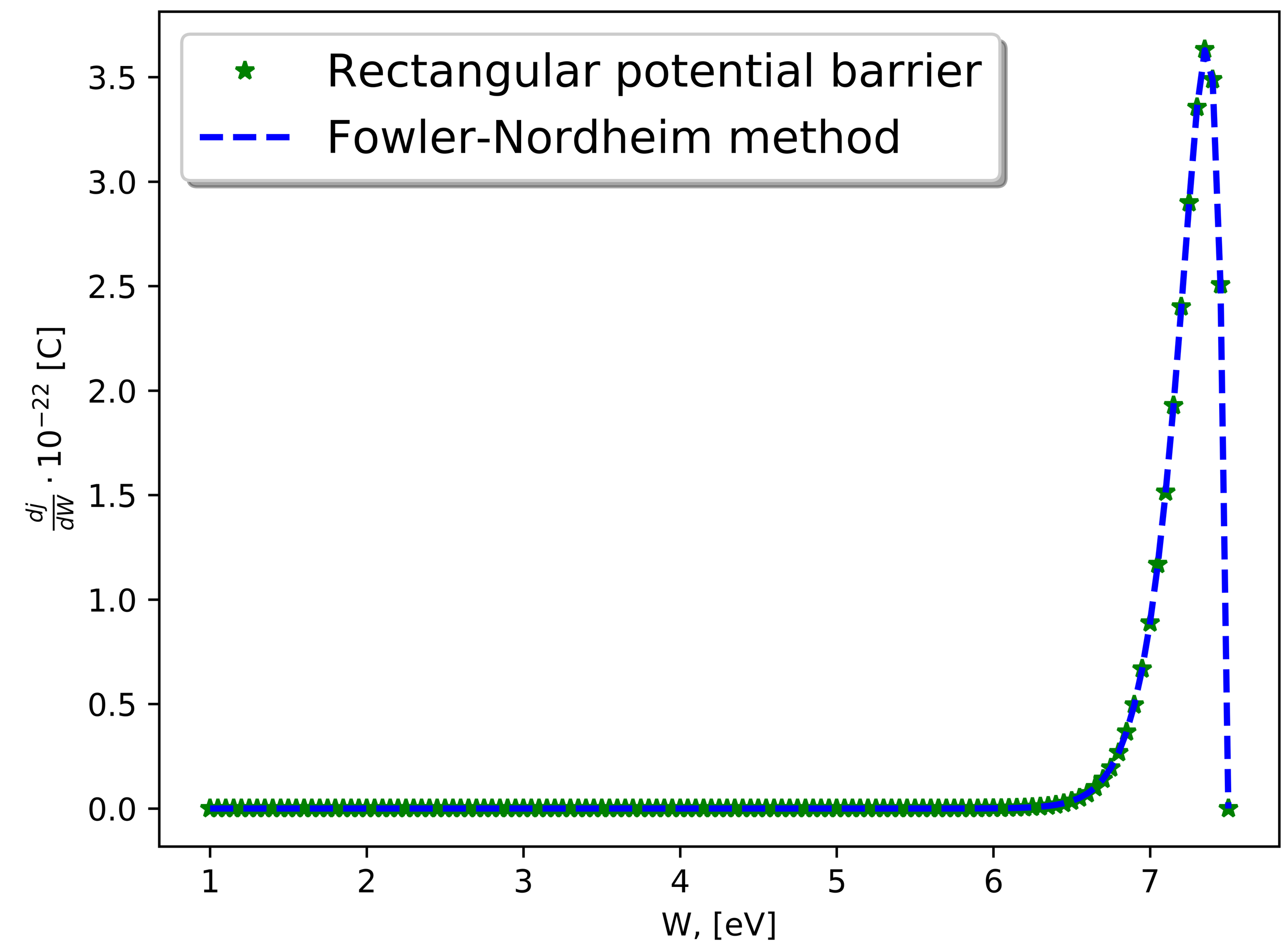


Fig. 2 Differential current on the electron energy calculated using various methods: the asterisk marks the method of replacing a triangular barrier with a rectangular one of width h_{eff}; dashed line - numerical calculation of the current by the Fowler-Nordheim method.

Simulation of the field emission current from a real metal surface

The real metal surface is not perfectly smooth, but has a large number of nano- and micro-dimensional irregularities. These irregularities will enhance the local electric field and, accordingly, the field electron field emission current. We have modeled such irregularities on the metal surface and calculated the field electron emission current taking them into account. The inequality was modeled using the tip of the radius of curvature which was generated using a normal distribution with a mathematical expectation of $\mu = 100\ nm$, and a standard deviation of σ of several tens of nm. The tip occupies the entire cathode area. In the case of a close location of the tip, the screening effect can be neglected. The figure shows the graphs of the dependence of the electric field enhancement factor β on the electric field value depending on the electric field strength for the given values of the standard deviation of the radius of curvature of the tip. And β was calculated for the all surface square from the equality $E_{local} = \beta E_{applied}$

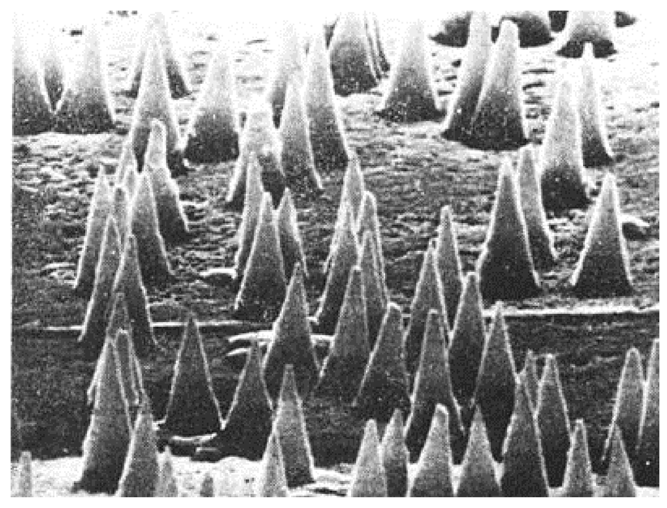


Fig. 3 A micrograph of an emitter with a pointed surface obtained at the JINR (Dubna). In shape, the tips are cones with an average radius of curvature $0.1\ \mu m$

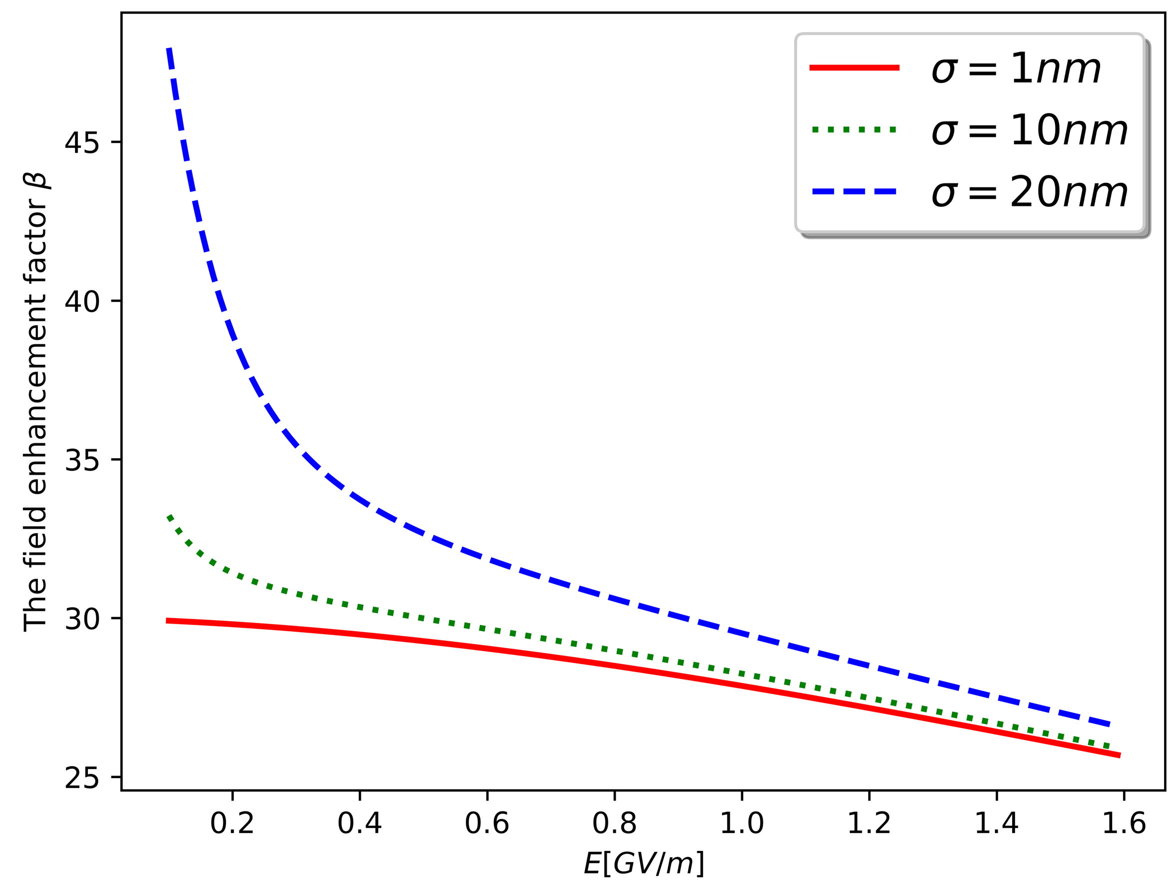


Fig. 4 Dependence of the field enhancement factor vs electric field strength for the different σ values.

The figure shows that with an increase in the scatter of the radii of curvature of the tip on the metal surface, the field gain β does not change linearly, which may indicate that in this case the dependence of the field emission current on the electric field strength is exponential.

Conclusions

- The model of the flow of the field emission current taking into account the morphology of the cathode surface and theoretically investigated the effect of modification of the metal surface on the field emission current in the case of multi-layer metal-metal-vacuum systems was constructed.
- In the model of a potential barrier at the metal-vacuum interface, triangular potential barriers are replaced by rectangular ones, where the width of the rectangular barrier is a function of the electric field strength: $h = h(E)$.
- A model of the flow of the field electron emission current is constructed taking into account the surface irregularities. It is shown that the presence of a tip on the cathode surface non-linearly changes the electric field enhancement factorβ.

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