Empirical evaluation of the field enhancement factor as a function from electrode spacing for LAFE and single emitter

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Abstract. We have done a study of the electric field distribution on the surface of macroscopic and nanoscale field emitters. The electric field distribution was plotted by using simulation software COMSOL Multyphysics 5.2a. A numerical evaluation of the field enhancement factor dependence on the interelectrode distance was produced. We calculated parameter λ which describes this relationship for two different emission systems: elongated mono-tip metallic emitter with macro and micro scales. We conducted an experiments with model field cathodes: macroscopic tungsten tip and large area field emitter based on nanocomposite "carbon nanotubes / polystyrene".

1. Introduction
Vacuum nanoelectronics - one of the priority directions of modern technologies development. Electron sources based on field emission effect has a number of advantages over other types of electron sources: energy efficiency, inertialess, compactness [1].

Operation of the field emitters is strongly dependent on the distribution of electric field in the interelectrode space. To determine the electric field distribution in the interelectrode space a sufficiently complicated analytical calculations are required. The complexity of these calculations does not allow obtaining a field distribution for multiparameter systems, such as multi-point emitters based on nanocomposites, and even trivial electrode shapes require a series of mathematical approximations. So researchers often use computer simulation techniques.

Usually one of two emission systems is studied: a single tungsten tip or a flat emitter consisting of an array of carbon nanotubes. The crucial parameter of these systems is the distance between the flat anode and the cathode vertex. This distance affects the distribution of electric field and causes emission characteristics, such as field enhancement factor (FEF).

In [2] an analytical calculation of the FEF dependence on ratio of the geometric parameters of the mono-tip emission system "hemisphere on a post" (extended cylinder with a hemisphere at the end) was made.

The electric field distribution for metallic emitter "hemisphere on a post" was simulated using Ansys-Maxwell 2015 software [3]. The FEF dependence on the aspect ratio was constructed.

In [4] the mutual influence of the emission centers was analytically studied with a simpler point charge model and their optimal arrangement was calculated.
In [5] a system of several macro emitters was simulated using software ICEPIC. The FEF dependences on their mutual arrangement and geometric parameters were obtained taking into account the screening effect.

The current voltage characteristics (IVC) of the CNT uniformly dispersed on a Ta-metal substrate coated with a thin Ti-film were registered experimentally [6]. The shift of IVC with rise of the anode-cathode distance (up to 1 mm) was obtained. Authors explained this effect by the presence of the macroscopic projections on the nanocomposite surface, which create the effect of mutual screening of the emission centers.

In [7] the scale invariance of the electron tunnel transition with respect to the change in the distance from the tip of the emitter to the anode plane (from several nm to several mm) was shown. A displacement of the IVC of tungsten wire (emitter with a few mm of length and 250 µm diameter) with change in the interelectrode distance was observed.

The studies [8] showed that the magnitude of the electric field on the surface of the one emitting tip can be dependent on the distance between electrodes by the typical power law:

$$\Phi(z,d) \propto \Phi_d \cdot (z/d)$$

where $\Phi(z, d)$ - electrostatic potential for point with coordinate $z$ in cylindrical symmetric system, $\Phi_d$ - potential on the anode plane, $d$ - anode-cathode distance.

Using COMSOL Multyphysics 5.2a software package, as well as the experimental setup with system of multichannel registration of the field emission characteristics, we conducted a study of the electric field distribution on a surfaces of macroscopic and nanoscale field emitters.

2. Modeling

Figure 1 presents the model system "tip-cathode / plate-anode" for a macroscopic emitter "ellipsoid on a cylindrical post" with a mesh. To improve the quality / time ratio of computer calculations the vertex of the tip and the opposite part of the anode were placed in a separate virtual cylinder with mesh of high resolution.

System parameters: plate diameter $D_a = 5$ mm, tip height $H = 5$ mm, tip diameter $D_o = 10$ µm, vertex of the tip - ellipsoid with small radius $r_1 = 5$ µm and large radius $r_2 = 15$ µm, distance between tip vertex and plate of the anode $D_{ao}$ was varied from 5 to 500 µm.

Figure 2 shows the electric field distribution near the tip vertex for a distance $D_{ao} = 100$ µm and applied voltage $U = 10$ kV.

The calculation of the field $E$ in the tip vertex at a fixed distance $D_{ao}$ makes it possible to calculate the form factor $\beta$ of the given emission system:

$$\beta = \frac{E}{U} D_{ao}$$

where $U$ is the voltage applied to the system.

The obtained form factor in turn makes it possible to calculate the voltages $U_{ao}$, which needed to obtain a given value of electric field $E_o$ in the tip vertex (at a fixed value of $D_{ao}$):

$$U_o = \frac{E_o}{\beta} D_{ao}$$
Figure 1. Computing mesh for electric field evaluation in the system with monotip emitter.

Figure 2. Results of modeling with applied voltage 10 kV: electric field in the interelectrode gap (a), electric potential near the tip vertex (b), field at the tip surface (c), field near the tip surface (d).
Figure 3a shows the dependence of the electric field $E_0$ in the vertex of the tip on the distance $D_{ao}$ at applied voltage $U = 10$ kV (red line) and also dependence of the voltage $U$, which needed to obtain the field value $E_i = 10^{10}$ V/m (it is sufficiently for the electron tunneling occurs) on the distance $D_{ao}$ (blue line). Data calculated with the COMSOL software. It is worth noting that a change in the given value $E_L$ leads to a corresponding linear change in the voltage $U$.

Figure 3. Dependence of the electric field in the tip vertex and voltage $U$, which needed to obtain given field $E_i$ in the tip vertex, on the anode-cathode distance. (a) Macroscopic emitter "ellipsoid on a cylindrical post", (b) microscopic emitter "hemisphere on a cylindrical post".

The obtained dependences are in good agreement with the theoretical concepts of the electric field distribution in similar emission systems, which predict a power-law dependence of the electric field on the distance (see (1)).

Figure 3b shows analogous dependences obtained for a nanoscale emitter "hemisphere on a cylindrical post", which simulating a MWCNT. Parameters of the system: anode plate diameter $D_a = 4 \mu m$, cathode plate diameter $D_c = 4 \mu m$, tip height $H = 500$ nm, tip vertex - hemisphere with radius $r = 4$ nm, distance between tip vertex and anode plane ($D_{ao}$) ranged from 1 to 10 μm. The graphs indicate the absence of a power-law dependence of the electric field on the distance $D_{ao}$ for the nanotubes at distances of micron scale.

3. Experimental

For an experimental study of the influence of the interelectrode distance on the field distribution, we used a multichannel computerized setup which measures field emission characteristics [9].

In the experiment two model emitters were studied: the tungsten tip cathode and multi-tip emitter (10 mm in diameter) based on nanocomposite multiwall carbon nanotubes (Taunit M produced in NanoTechCenter, Tambov) in polystyrene.

The experimental setup and photographs of the samples (SEM images) are shown in Figure 4 and Figure 5. The distance between the plates of anode and cathode was manually varied by means of micrometer screw and additionally controlled with a long-focus USB microscope.

The performed experiments showed that the IVC shape depends on the interelectrode distance for both studied emitters (see Figure 6a, b). The received data was processed by a program written in the LabView. For all IVCs it calculates a voltages $U_i$ corresponding to a given total emission current (90 μA for a tungsten needle and 1.4 mA for a nanocomposite with MWCNTs).

The equality of the currents (given total emission current) at different interelectrode distances assumes the equality of the corresponding electric fields $E$ on the emitter surface, so the known power-law dependence of the field on the interelectrode distance can be used to calculate the value of the degree $\lambda$ from any two measured IVCs at distances $d_1$ and $d_2$: 
\[ E = \frac{U_1}{d_1^2} = \frac{U_2}{d_2^2} \] (4)

To increase the accuracy of the calculation, we used a series of experimental IVCs. The values of \( U_1 \) and \( d_1 \) were fixed (they corresponded to the IVC with a minimum threshold voltage, i.e., the minimum interelectrode distance \( D_{ao} \)) and values of \( U_2 \) and \( d_2 \) changed. The constructed dependences of \( U_2 \) on \( d_2 \) was approximated by a power-law dependence with obtaining the desired values \( \lambda \) for both studied emitters (Figure 6c, d).

The obtained experimental dependences are consistent with the results of the above simulation. However, there is no complete numerical coincidence because the shape of the real tungsten tip is still different from the elliptical shape of the virtual emitter.

4. Conclusion
In this paper we present the results of experimental data processing and simulations performed by software LabView and COMSOL Multyphysics 5.2a. Calculation of the \( \lambda \) was made on the basis of series of experimental data which were obtained by using a multi-channel research setup for two types of the samples: tungsten tip cathode and multi-tip emitter based on nanocomposite "carbon nanotubes / polystyrene". The resulting empirical \( \lambda \) was \( \sim 0.3 \) for the
Figure 6. IVC variation with rise of the anode-cathode distance for tungsten tip emitter (a) and nanocomposite based on MWCNT (b). Corresponding dependences of voltage at $I = 90 \mu A$ on the anode-cathode distance for tungsten tip (a) and nanocomposite based on MWCNT (b). The red lines is trend lines: $y = y_0 \cdot x^\lambda$.

tungsten tip and $\sim 1.1$ for the nanocomposite emitter. Last one is near the 1 that indicates the proximity of nanocomposites to the planar capacitor system, but difference can be connected with some protrusions on the sample surface.

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