Studying field emission characteristics of point and wedge-shaped surface defects

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Abstract. Electric field distribution and field emission current over the surface of point (sphere-on-cone) and wedge-shaped defects on a plane substrate are studied. It is found emission current due to wedge-shaped defects is more sensitive to emitter-anode distance than in case of point conical defects. This property is consequence of greater emission area of wedge-shaped defects and has important practical applications. The computer model in Matlab of field electron emission from emitter-defects arrays is used. Electrostatic simulation of electron transport processes with PDE Toolbox finite element solutions is implemented. The effects of the variations in defects geometrical structure and parameters on its potential distribution, electric field, and emission current are discussed. It is found that with increase of distance from the tip or the edge of defect the current density falls very fast and greater part of emission current is in fact produced by a very small area near the emitter tip. The closer the emitter and collector are to each other, the less significant the inter-defect distance becomes.

Field electron emitters are generally characterized by surface non-uniformity, because field emission is process in intensive electric field and surface protrusions or defects are necessary for field enhancement. For example classical field emitter tip from metal or semiconductor wire have different crystal faces on the surface with steps, kinks and edges. Its shape can be very different: ball-models for atomistic surface structure of monocrystal tip and analysis of crystal faces forms and sizes were presented in [1]. Field emitters array can also be imaged as regular grid of surface defects or protrusions on substrate plane. Emitter in unit cell of the array might have sphere-on-cone shape (like Spindt-cathodes [2]) or edged straight line shape (or circular/cylinder edge shape [3]) and etc.

In this paper we study two types of multimitter systems – models for point and wedge-shaped defects on the surface: ones with conic and straight-edge emitters. Employing the methods of mathematical and computer modeling, we analyze interactions between defects in the array and the influence its geometrical features have on the emission current value. We take in account such geometrical properties as distance between emitter and collector $d$, curvature radius of emitter surface $r$, distance between the emitters $b$, as shown on figure 1 and figure 2.
Figure 1. (a) SEM image of nanostructure of emitter surface relief [3]. (b) Results of Sobel-mask filtering, defects with spherical tops are shown.

The relation between field emission current density and strength of the field that generates the current is calculated within the framework of Fawler-Nordheim theory. Multiemitter system is regarded as a periodically structured emitter array. The tip of conic emitter is approximated with a spherical surface, and the edge of a straight-blade one with an orthogonal cylinder surface (figure 2).

Figure 2. Scheme of conical and edge-shaped emitters. The cells for modelling with conditions of symmetry (periodicity) on the side surfaces are shown.

Program complex [4] is used for computer simulation. Non-uniformity of physical conditions on defects surface (variance of work function etc.) is accounted for with a local field enhancing coefficient [1]. The influence of the space charge is neglected and electrostatic approximation is used. The results of electrostatic field calculation are shown on figure 3.
Figure 3. (a) The equipotential lines of electric field (in cylindrical coordinate system) near conical emitter (voltage of 30 V, augment of equipotentials of 2 V); (b) electric field lines of force.

Figure 4. (a) Dependence of the electric field at the emitter tip on the inter-emitter distance \(b\) and the emitter-collector distance \(d\) with constant radius \(r=10\) nm of top curvature, the voltage of 30 V, the inset shows the values of \(d\) in mkm; the curves I correspond to conic emitters and II to the edged ones. (b) Plot of the electric field strength on the surface between the emitter tip and middle of a segment between two emitters with constant voltage of 5 V; the X-axis corresponds to horizontal coordinate on the surface points. (c) Emission current density on the emitter surface from its tip up to the base. (d) Dependence of integral emission current from the emitter-collector distance with \(r=10\) nm, voltage 5 V.
Distance between adjacent emitters-defects is one of the parameters that define interactions between defects and their electric field. As shown on figure 4 (a) strength of the electric field on the tips of blade edges decreases when emitters are moved closer to each other, as the interaction between emitters gets stronger.

Influence of distance $d$ on the electric field is also illustrated on figure 4 (a). The closer the emitter and collector are to each other, the less significant the inter-emitter distance becomes. This occurs because the mutual shielding effect disappears and the emitters start working as individual tips or blades. Changes in $d$ has greater effect for conic emitters than for blade ones.

Figure 4 (b) shows the emitter electric field plotted against the surface points from the tip and up to the middle of a segment between two adjacent tips or blades. On the plot one can see rapid growth of the field near the emitter tip due to appropriately named “tip effect” and the minimum of field strength at its base because of a cavity formed by emitter side surface and the base plane.

Figure 4 (c) shows the distribution of normalized current density along the emitter surface.

It’s easy to see that with increase of distance from the tip or the edge of the blade the current density falls very fast and greater part of emission current is in fact produced by a very small area near the emitter tip. Thus, emission current is strongly localized near the tip.

The other important feature is shown on figure 4 (d): growth of emitter current with decrease of emitter-collector distance $d$. When $d$ is decreased to the value of the same order as the tip curvature radius, the blade emitter current gets bigger than the conic emitter one (figure 4 (d)). Such behaviour can be explained by the fact that with decrease of $d$ the current density becomes similar for both cases and the current value gets larger for a blade emitter because of larger emission surface. An important feature that can be seen on figure 4 (d) is that speed of change of emission current dependent on $d$ for edge emitters is higher than for conic ones, the fact that is again connected with larger emission surface. Thus edge-emitter defects are more sensitive to inter-electrode distance than conic ones. Obviously, this is right to edges of any shapes, not necessarily straight-line ones, which is practically important for several kinds of applications.

In this paper we present modelling results for potential, electric field strength and emission current of multiemitter systems of surface defects with point- and wedge-shapes. Results were obtained in a software complex created with Matlab and Matlab PDE Toolbox [4].

Acknowledgments

Financial support has been obtained from RFBR (13-01-00150) and partially from SPbSU (9.38.673.2013). Research was carried out using computational resources provided by Resource Center "Computer Center of SPbU" (http://cc.spbu.ru/en) and using experimental equipment of the Interdisciplinary Resource Center for Nanotechnology of St. Petersburg State University.

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