Studying fringe field effect of a field emitter array

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Abstract. Field emitter arrays on heavy As-doped Si wafer are studied in vacuum nanoelectronics diode configuration. Different shapes of emitters are considered: cone-shaped point-emitters and cylinder-shaped sharp-edge-emitters are compared. Micro scale field enhancement factor on the edge of cylindrical emitter was calculated via home-developed Matlab application and the results are presented. Two types of anode geometry are proposed: plane anode and spherical anode. Experimental and modelling results of surface electric field distribution are presented. The spherical shape of anode allows higher voltage (and higher field emission current) without destructive arcs risk.

1. Introduction
The standard emission mechanisms of the cathodes used in many applications are photoemission and thermionic emission. One alternative technology is field-emitter arrays (FEA) where electrons are emitted with energies close to the Fermi level. Such cathodes have potentially a lower mean transverse kinetic energy of the produced electron beam, which is mainly determined by the geometry of the electric field lines. There are 2 main architectures of field-emission cathodes: the needle cathode, i.e. one single sharpened tip and FEA which are arrangements of field emitters on a periodically spaced lattice. We have present ed first measurements on edge-type FEA in atmosphere pulsed low-voltage operation and DC high-vacuum high-voltage regime as well as numerical simulations of the electric field near the cathode surface [1]. It was shown fringe enhancement of electric field on the boundary of FEA plays negative role on destabilization of emission current.

On the contrary field enhancement is necessary near the curved emission surface on the top of nanostructure emitters. This effect was experimentally studied in case of cylindrical-shaped field emitters (figure 1) on heavy As-doped Si wafer [1] and computer simulation was used to study in this paper.
2. **Finite element solution**
Study of micro-scale non-uniformity of electric field with a software complex developed in Matlab [2] has shown that field enhancement factor depends on the distance at which the field is applied to the sharp margin of cylindrical microemitter (figure 2). As this distance grows, the dependence becomes less significant, and at about 6 times the height of emitter protrusion becomes negligible. Figure 3 shows dependence between field strength and absolute value of the applied uniform field strength.

Numerical solutions of corresponding electrostatic boundary problems were carried out with Matlab and Matlab PDE Toolbox. Software implementation should take into account the specifics of emission systems:

- Calculation are of complex shape includes the emitter boundary with high curvature and multi-scale size, which leads to considerable diversity of characteristic measurements in the same geometric configuration.
- The exponential dependence of current density on field strength requires increased precision when considering boundary conditions on the emitter.

The solution has a rapidly changing gradient in the emission area (on edge of the cathode), thus the finite-element mesh has to become tighter in the neighborhood of the emitter edge to avoid reduction of speed of convergence towards the exact solution and increase of the number of variables (i.e. the dimension of the finite-element system).

With adaptable mesh it is natural to employ an error indicator, that would include the residual norm of the equation and fluctuations of the gradient of finite-element solution, as they are connected with one of the basic values given for this problem – that is, with the electric field strength. This indicator is implemented in pdejumps function which is called by adaptmesh function aimed for the adaptive solution of the problem. For making the mesh more fine a way of splitting finite elements was chosen, such that they are split along their longest side (method=longest), i.e. a triangle (based on the value of error indicator) is replaced with two smaller triangles by splitting its longest side in half.

For the case of conical-shape emitters the macro-scale field was calculated by Comsol Multiphysics coupling with Matlab via LiveLink.

3. **Results**
It was found the surface field and emission current of emitters in the center of the array is less dependent on the emitter to emitter spacing than on emitters on the boundary of array.
Figure 2. Equipotential lines (with step 1 V) of electric field near the edge of nanosized wall cylinder of microemitter. One half cross section is shown in cylindrical coordinates.

Figure 3. Angle distribution of the field enhancement factor. The uniform field \( E_0 = 1.43 \times 10^7 \text{ V/m} \) is applied on the distances 0.2-1.4 \( \mu \text{m} \) with step 0.2 \( \mu \text{m} \) (the lower line corresponds 0.2 \( \mu \text{m} \), the upper line corresponds 1.4 \( \mu \text{m} \)).

The shape not only of emitters, but also of anode is important in case of macro-scale uniformity of electric field distribution over the array surface. The fringe enhancement effects of macro-scale field distribution can be reduced due to spherical (see figure 5 instead of plane as on figure 4) anode more than two times. After parameter optimization procedure (in mathematical simulation) it was found for case of square (1 by 1 cm) FEA the best diameter of spherical anode is also 1 cm, and gap between electrodes can be increased to 1-3 mm with applied voltage up to 20 kV.

Figure 4. Electrostatic potential distribution with fringe effect non-uniformity between electrodes in case of plane anode and conical emitters.

Figure 5. Spherical anode and square FEA cathode.
4. Conclusion
This study includes multi-scale modeling of electric field distribution on nanostructured cylinder and conical emitter surface in FEA.

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