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Numerical study on performance of pyramidal and conical isotropic etched single emitters

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Abstract

A full three-dimensional model was implemented in order to investigate the electrical characteristics of conical and pyramidal isotropic etched emitters. The analysis was performed using the finite element method (FEM). The simulations of both emitters were modeled using a combination of tetrahedral and hexahedral elements that are capable of creating a mapped and regular mesh in the vacuum region and an irregular mesh near the surfaces of the emitter. The electric field strengths and electric potentials are computed and can be used to estimate the field enhancement factor as well as the current density using the Fowler–Nordheim (FN) theory. The FEM provides results at nodes located at discrete coordinates in space; therefore, the surface of the emitter can be generated through a function interpolating a set of scattered data points. The emission current is calculated through integration of the current density over the emitter tip surface. The influences of the device geometrical structure on its potential distribution, electric field and emission characteristics are discussed.

Keywords: Field emitter; Simulation; Finite element method

1. Introduction

With an increasing interest in vacuum microelectronic technology, especially field emission devices, a variety of structure designs have been proposed with the intention to enhance the electron emission characteristics [1–8]. While most of the simulations on field emitters reported in the literature were based on a two-dimensional (2D) model [1–5], there are a few works reporting a three-dimensional (3D) analysis for a cone-type and a rounded whisker emitter [6–7]. The use of 2D approximations can be used only if the shape of the model has the uniformity along one axis (i.e. a wedge emitter) or the symmetry around one axis (i.e. a conical shape, a rounded whisker or a hyperbolical shape). A full 3D model has no restrictions about the emitter shape. However, most of the geometries studied so far are assumed to have a fixed half-angle (θ) (normally 54.7°, a result of anisotropic etching of silicon in a potassium hydroxide based solution for example [1]) along its height [6–7], while other works reports the fabrication of isotropic emitters with a variable half-angle [8–10]. The present article presents an effective 3D analysis of a pyramidal and a conicalisotropic etched emitter. Both devices can be easily manufactured using square and circle geometry as a mask, respectively [10].

2. Numerical simulation and procedures

The main geometric design parameters being considered in our model are the distance between the tip and the anode (d), the distance between the lateral boundaries of our cell (w) and the height of the emitter (h). For our simulations, the height of the emitter was set to 3 μm, which is the maximum height of an isotropic etched structure using a 6 μm mask. The apex of the emitters was approximated by a sphere with radius r, and the four wedges formed by the fabrication process in the pyramidal case were kept. The voltage applied to the emitter surface as well as to the anode surface was assumed constants during each simulation step. The Dirichlet boundary condition can then be applied by assigning both voltages to the boundaries. The maximum

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Table 1
Values for parameters used in the simulation

Fig no	d (μm)	r (μm)	h (μm)	v (V)	w (μm)
4	12	10	3	200	12
5	12	10	3	200	12
6	12	10	3	200	12
7	10	–	3	400	12
8	–	10	3	–	6
9	12	10	3	200	12
10	12	10	3	800	12
11	12	–	3	–	12
12	12	–	3	–	12
13	12	–	3	–	12

lateral dimension (w) used in our model was set to 12 μm. This value is large enough to assume that the potential distribution (Φ) at the four-sidewall boundaries varies only in z direction with a linear trend, which means we can apply the Neumann boundary condition:

$$\frac{\partial \Phi}{\partial n} = 0 \quad \frac{\partial \Phi}{\partial z} = \text{Const}$$

where n denotes the direction normal to the sidewall boundary. The parameters used in the simulation models are specified in Table 1.

The emitter geometrical structure is arbitrary, so the mesh is suggested to be irregular in regions near the emitter surface. The tetrahedral elements are suitable to create a mesh with great angular deviations. The vacuum region, however, is regular, and the mesh can be mapped using hexahedral elements. Since the FEM fails in the vicinity of the singularities, an extreme dense mesh is required at locations near the tip of the emitters, where the electric field varies very quickly. To test the credibility of our simulation using the FEM, a direct comparison between analytical and numerical solution was made using the '*hemisphere on a plain*' model [11] and an accuracy of 99.996% could be established using the full 3D model for the maximum electric field value (Figs. 1–3).

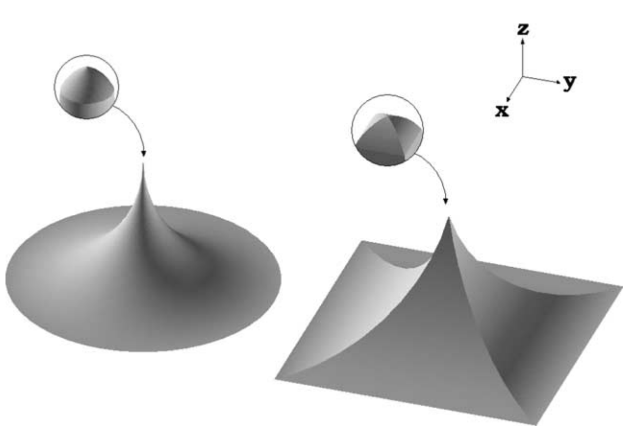

Fig. 1. The structure models used to simulate both conical and pyramidal emitters.

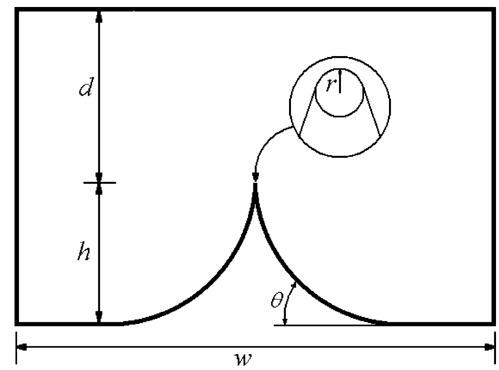

Fig. 2. 2D schematic view of our single-tip cell. Since the geometrical device (for both emitter shapes) presents an isotropic profile, the angle θ varies from 0 to 90° along the height of the emitter.

3. Simulation results and discussions

In order to perform an electrostatic analysis, we first need to calculate the potential distribution by solving the Poisson equation:

$$\nabla \cdot \nabla \Phi = -\frac{\rho}{\varepsilon}$$

And in the case of space-charge-free fields in the vacuum region between the anode and the emitter, the equation reduces to the Laplace equation, which in Cartesian coordinates is:

$$\nabla \cdot \nabla \Phi = \frac{\partial^2 \Phi}{\partial x^2} + \frac{\partial^2 \Phi}{\partial y^2} + \frac{\partial^2 \Phi}{\partial z^2} = 0$$

Fig. 4 shows the x–z cross-section plot of equipotential lines in the vacuum region for the conical emitter case. The equipotential lines cross the sidewall cell boundaries orthogonally as expected. The electric fields in Figs. 5 and 6 are calculated by differentiating the potential with respect to x, y and z coordinates at all nodes. The total electric field is the sum of the three components. From another viewpoint, the electric field can be determined by the normal spacing between adjacent equipotential lines (in one direction at a time). As a result, the dense spread of equipotential lines located over the apex of the emitter indicates the presence of the strongest electric field. As shown in Figs. 5 and 6 a sharp increase in the electric field

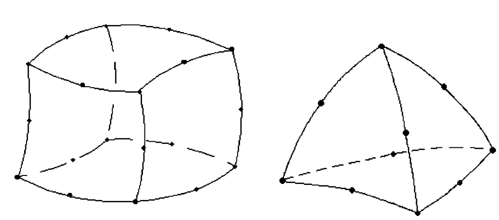

Fig. 3. The hexahedral and tetrahedral elements used to create the mesh. The 20-node hexahedral element can tolerate regular shapes without loss of accuracy and it was used to simulate the vacuum region in our model. The 10-node tetrahedral element is well suited to model irregular meshes, and it was used to create the mesh near the emitter surfaces.