PROGRAM COMPLEX FOR VACUUM NANOELECTRONICS FINITE ELEMENT SIMULATIONS

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Abstract

The program complex in MATLAB intended for vacuum nanoelectronics simulations is described. Physical and mathematical models, computational methods and algorithms of program complex are presented. Electrostatic simulation of electron transport processes is discussed under electron massless approximation; current function method and Matlab PDE Toolbox finite element solutions are used. Developed program complex is able to simulate diode and triode structures with complicated submicron geometry, current-voltage characteristics, calculate electric field distribution, estimate electric line interaction. The modelling results by the example of two different triode structures are presented. Matlab stand-alone application with graphical user interface for demonstration purposes is presented.

INTRODUCTION

The development of a new accelerator electron gun with the lowest possible emittance is actual important problem. Due to the recent advances in nanotechnologies and vacuum nanoelectronics, a field-emitter array (FEA) based gun is a promising alternative for thermionic or photocathode technologies. Indeed, several thousands of microscopic tips can be deposited on a 1 mm diameter area. Electrons are then extracted by a grid layer close to the tip apex and maybe focused by a second grid layer or anode several micrometer above the tip apex. Although simple diode system is sufficiently to start electron emission, triode configuration with field emitter as cathode, extractor electrode as gate and distant anode as collector is used for many applications. It is necessary to perform computer simulations for design and development of various types FEAs. First of all we'll say a few words about emission nanostructures by the example of wich we'll demonstrate wide possibilities of programmes writen in Matlab. The first one is FEA Spindt-type nanotriode from the company SRI Inc. A schematic of triode cell from is shown in Figure 1.

The second one is the FEA cathode with NbN sharp-edged cylindrical emitters from JSC Mikron. The SEM image in Figure 2 represents NbN thin-film emitters on heavy As-doped Si wafer.

PROGRAM COMPLEX

The device modeling is broken traditionally into two different projects. The first is to model the fields and particle motions within the device to verify the design parameters and to locate design possible problems before fabrication. The second project is to model the operation of the device and its electrical interaction with an external circuit.

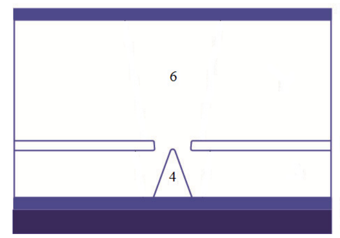

Figure 1: Vacuum nanotriode cell: 1 – wafer, 2– cathode layer, 3 – gate layer electrode, 4 – Mo emitter tip, 5 – anode, 6 – vacuum channel.

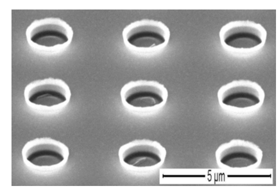

Figure 2: SEM picture of FEA cathode with NbN sharp-edged cylindrical emitters (diode/triode operation is possible).

Electron trajectories

In zero order approximation emitted electron trajectories are supposed to coincide with electric field force lines. This approach is known as electron massless approximation and used for electrostatic simulation of vacuum emission micro/nanoelectronic devices. In vacuum micro/nanoelectronics due to strong dependency of emission current density upon electric field strength the main part of electron current is formed on areas with maximum surface field. On the other hand due to potentiality of electrostatic field the larger field strength is, the smaller force lines curvature will be and the more adequate electron massless approximation will be. Figure 3 represents visualization example of trajectories simulation for Spindt triode nanostructure.

Electric field distribution

Due to axial symmetry of considered FEAs cells we use Matlab two-dimensional static field finite element analysis code (functions from Partial Differential Equations Tool-

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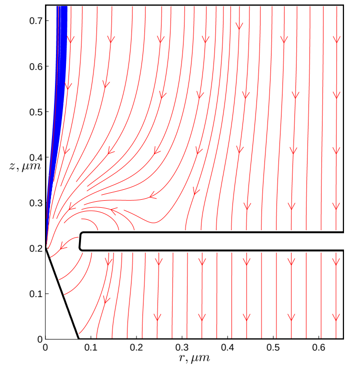

Figure 3: Electron trajectories (blue) and electric force lines for Spindt-type triode cell.

box) to model the electric field profiles in the device for various design variations and applied voltages. The code calculates the electrostatic potential and electric field in neglect of space charge in a volume defined by metallic boundaries and filled with vacuum or dielectric. Examples of simulation results are shown in Figure 4 and Figure 5 for second nanostructure sample.

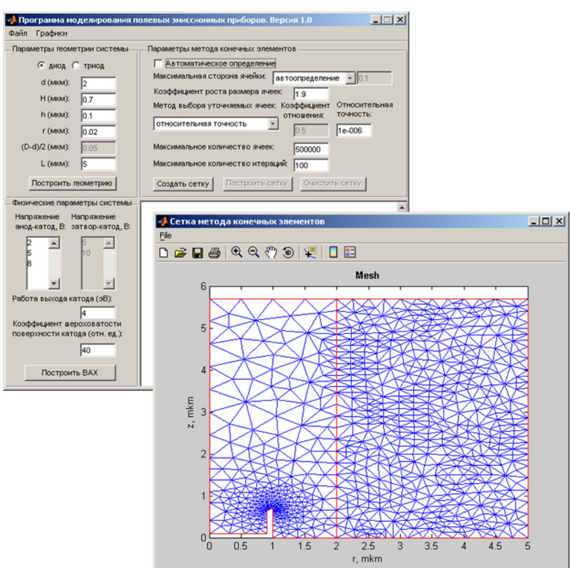

Figure 4: Graphical user interface of the programm, (left) main window, (rigth) adaptive finite element mesh in domain corresponding to the second nanostructure.

Current-voltage characteristics

Trajectory analysis in massless approximation is performed by introducing the current function ψ, well known in hydrodynamics. The physical meaning of current function ψ: it is constant along the force lines of electric field, and the vector flux of the electric field intensity between two force lines (surfaces in 3D case because of axial symmetry) is equal to the difference of relevant values of current function ψ [1]. Comments are given in Figure 6.

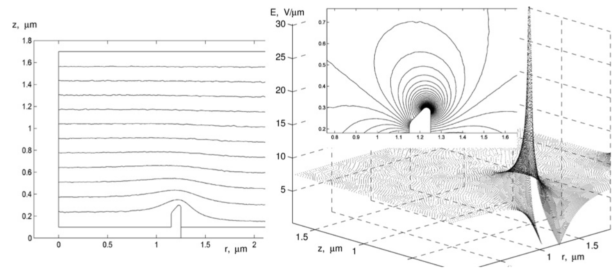

Figure 5: (left) Equipotential line plot of cylindrical field emitter cell in diode configuration at a given bias condition (only one half of cell is shown in cylindrical coordinates due to axial symmetry), (right) electric field distribution around the emitter. Insert: constant-electric field distribution contours around the top of a cylindrical emitter.

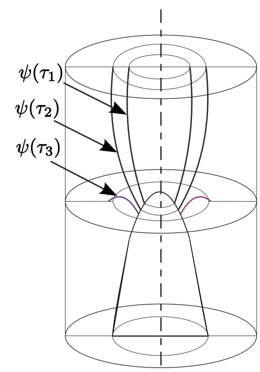

Figure 6: Force lines crossing the cathode at points τ_1 and τ_2 make a beginning at anode, $\psi(\tau_1)$ and $\psi(\tau_2)$ are corresponding values of current function; electron current flows to anode along these force lines. $\psi(\tau_3)$ corresponds to force line, connecting cathode and gate electrode, so electron current flows to gate.

ψ distribution over calculation domain is defined in cylindrical coordinates as

$$\psi_i(\tau) = \psi_{0i} + 2\pi \int_0^\tau r(\tau')\mathbf{E}(\tau')\mathbf{n}d\tau', \qquad (1)$$

$$E = \frac{1}{2\pi r}\frac{d\psi_i(\tau)}{d\tau}, \qquad (2)$$

where r – cylindrical coordinate, τ – local variable on boundary i, ψ_{0i} – start value of ψ-function on boundary i, $\mathbf{E}$ – electric field strength, $\mathbf{n}$ – boundary normal vector.

There is functional dependence $I(\psi)$ for electron current I inside surface ψ=const, as it is shown in Figure 7. Thus

$$\frac{dI(\psi)}{d\psi} = \xi(\psi), \qquad (3)$$

and in the presence of emission current flow along given force line:

$$\xi(\psi) = \frac{2\pi r j(E)}{d\psi/d\tau}, \qquad (4)$$

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else:

$$\xi(\psi) = 0, \quad (5)$$

where $j(E)$ is defined by known Fowler-Nordheim equation.

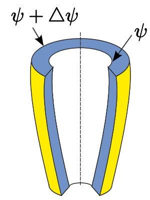

Figure 7: Limit $\frac{I(\psi+\triangle\psi)-I(\psi)}{\triangle\psi}$ when $\triangle\psi \to 0$ is equal to current density along ψ force line.

In second project using the modeling data from the first one, operating characteristics of considered vacuum nanostructures are calculated. The model supplies current-voltage characteristics, including the effects of grid leakage current. The Fowler-Nordheim equation gives current density from the electric field near the cathode surface. Knowledge of the trajectories allows determination of the grid and anode current densities from the cathode current. Device integral currents are determined by numerical surface integration.

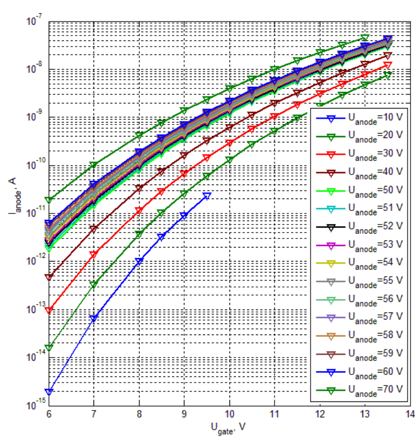

Figure 8: Anode current vs. gate voltage characteristics for triode-type emission nanostructure.

CONCLUSION

Programming with Matlab opens wide possibilities of the development of the complex program intended for vacuum nanoelectronics simulations. Matlab stand-alone application with graphical user interface was used to investigate electric field effects in real FEA nanostructures [2].

REFERENCES

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[2] K. A. Nikiforov et al., "Non-gated Field Emission Array as Low-Energy Electron Source: Experiment and Simulation" FRBOR03, these proceedings.

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