Modelling of static mode characteristics of a thin-film vacuum nanotriode

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Abstract. Mathematical modelling and computer simulation is performed for analysis of nanotriode characteristics in static mode. It is shown nanotriode has differential parameters, which significantly (by orders) differ from those characteristics of usual vacuum lamps, which, together with miniaturization significantly expands the possibilities of their use.

1. Introduction

The goal of this paper is to model characteristics of thin-film vacuum nanotriode (shown in figure 1) [1]. Thin-film vacuum nanotriode with cone-shaped emitters is considered. Each emitter has height 200 nm with 1 nm radius of surface curvature on the top. Current-voltage characteristics was calculated for single cylindrical triode cell (655 nm in diameter) in [1]. It was shown the value of the emission current comes to microamperes, when the voltage is less than 20 V applied on the anode-emitter gap 500 nm. Anode-cathode voltage 16-20 V can generate more than 0.5 mkA emission current flown to the anode when gate-cathode voltage is less than 14 V and gate diameter is 150 nm [1].

To achieve the goal of this paper it is necessary to investigate the behaviour of differential parameters when changing the geometric dimensions of the triode structures operating in static mode. Electron transport processes are described using electrostatic approximation and hydrodynamic flow function for finite element solution [2–4].

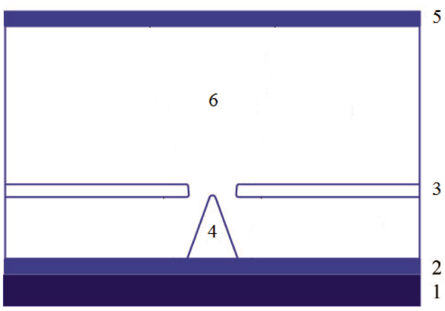

Figure 1. Scheme of the thin film vacuum field emission nanotriode cell: 1 – substrate, 2 – metal layer of cathode, 3 – metal gate electrode, 4 – metal emitter, 5 – metal anode, 6 – vacuum.

2. Mathematical model

The main characteristics of the vacuum triode in static mode are the following differential parameters. Slope S of anode volt-ampere characteristic (which is the equivalent conductivity of the alternating current (AC)):

$$S = \frac{\partial I_a}{\partial U_g}|_{U_a=const},$$

where I_a – anode current, U_g – gate voltage, U_a – anode voltage.

Internal resistance AC R_i:

$$R_i = \frac{\partial U_a}{\partial I_a}|_{U_g=const}.$$

The gain of the triode to the anode current μ. It shows how many times stronger the gate potential affects the cathode current than the anode potential. The gain depends on the distribution of space charge:

$$\mu = SR_i = \frac{\partial I_a}{\partial U_g} \cdot \frac{\partial U_a}{\partial I_a} = -\frac{\partial U_a}{\partial U_g}|_{I_a=const}.$$

The permeability of the gate D. It characterizes the penetration of the electric field through the gate of the anode to the cathode. Permeability is numerically equal to the ratio of charges induced on the cathode by the anode and by the gate, in the absence of current in the triode. It follows that the permeability depends on the geometry of the electrodes. The permeability of the gate D is expressed through the gain μ from the equation $\mu \approx 1/D$ (when $U_g < 0$) .

Modelling of processes described above is a complex task, was carried out in the software complex developed in Matlab and Matlab PDE Toolbox [2–4]. Following is description of important aspects of calculation procedure with domain triangulation.

The solution has a rapidly changing gradient in the emission area (on top of the cathode), thus the finite-element mesh has to become tighter in the neighbourhood of the emitter tip to avoid reduction of convergence rate 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 *pdejmps* 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 (*rmethod=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.

There are other parameters of *adaptmesh* that can be modified for educational or research purposes, including through the GUI: *maxt* – the max total number of triangles (*maxt=inf* for no limit); *tripick* – choice of the triangles for splitting by relative error value (*pdeadgsc*), where the triangles with error value exceeding certain scaled constant are split, or by a conditional quality criterion (*pdeadworst*), in which a triangle is split when its error value is greater than some fraction (given by a coefficient between 0 and 1) of the worst error value among all the triangles; *ngen* – max number of iterations (*ngen=inf* for no limit).

In general case, if inital mesh is not explicitly given, *adaptmesh* calls *initmesh* for initialisation of the mesh using default *initmesh* values for all the parameters. The main parameters of *initmesh* are speed of increase of the triangle size (*hdgrad*, with values between 1 and 2), defining the level of non-uniformity of initial mesh, and the max allowed length of a triangle side (*hmax*). For being able to change those parameters *initmesh* is explicitly called during the initialisation of the mesh and the triangulation therefore obtained is passed on to *adaptmesh* for checking. Parameters can also be passed through GUI.

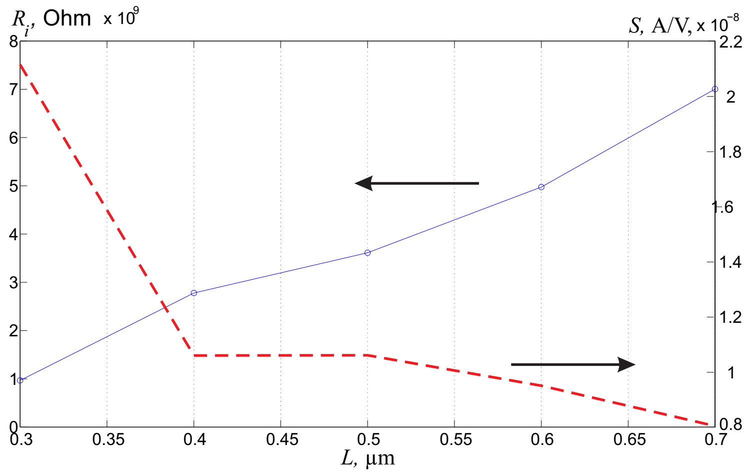

Figure 2. Internal resistance and slope of anode volt-ampere characteristic vs anode-gate distance.

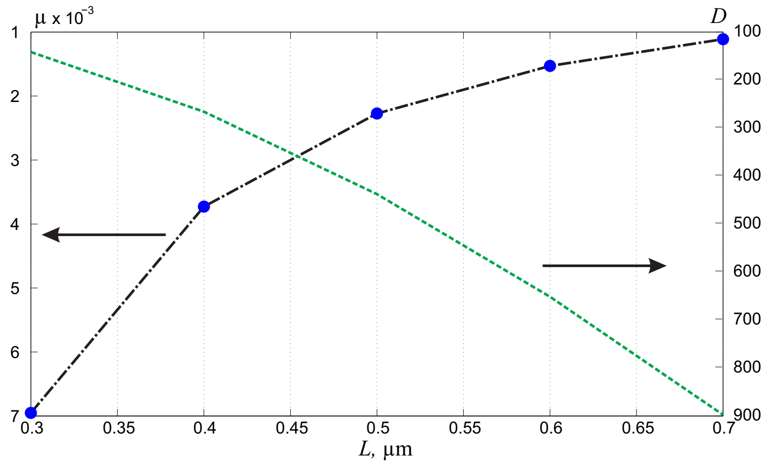

Figure 3. Triode gain and gate permeability vs anode-gate distance.

3. Conclusion
This paper presents a mathematical and computer model we've designed for solving problems of modern vacuum-nanoelectronics devices with complex sub-micron geometries with condition of large variance in electric field. The approach is based on a current function that is analogous to one used in hydrodynamics. For its analysis we use finite-element method over a non-uniform mesh and algorithms implemented in Matlab and Matlab PDE Toolbox. Results are also applicable to field emission devices simulation [4–13]. Future work is characterisation of proposed algorithm's complexity function by informational sensitivity [14–16] measurements.

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