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Calculation of Current-Voltage Characteristics of the Optimized Triode with a Cold Cathode Based on the Ordered Array of Single-Wall Metallic Carbon Nanotubes

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The current-voltage characteristics of a triode with the plane-parallel electrodes and a cold cathode based on the ordered array of single-wall metallic carbon nanotubes with open ends have been calculated by means of a numerical solution of both the Poisson equation and the quantum-wave equation. The topological parameters of the triode have been optimized.

Keywords: Carbon Nanotube, Field Emission, Cold Cathode, Triode.

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1. INTRODUCTION

The particular attention is paid to the conductive nanostructures with the one-dimensional electron gas in recent years (see, for example, [1-11]). The huge niche among the structures like that is occupied by the single-wall metallic carbon nanotubes (SWMCNTs) [6, 7, 9-11]. In particular, they are considered as the most promising material for production of micro- and nanodevices with the cold cathodes operating on the effect of electron field emission [10]. This leads to the importance of both the experimental and theoretical study of the electrical properties of vacuum devices based on SWMCNTs which is caused, first of all, by the necessity to calculate electrical characteristics of the devices and to optimize their constructional as well as topological parameters.

Taking into account the aforesaid, the purpose of the present study is a rigorous numerical calculation of current-voltage characteristics and optimization of the topological parameters of such a base device structure of vacuum microelectronics as the triode with the plane-parallel electrodes in which the cathode is an array of vertically oriented SWMCNTs arranged on the metallic substrate in a given order, and the grid is the same nanotubes stretched between the supporting metallic electrodes of the grid along two mutually perpendicular directions lying in the plane that is parallel to the planes of metallic electrodes (cathode and anode).

2. THEORY

To optimize the triode let us consider the limiting values of their topological parameters which do not exceed beyond the values that are quite reasonable from constructional and technological points of view. In view of this by analogy with a paper [11] let us consider (9,9) SWMCNTs with open ends, with the length $L = 100$ nm and the diameter $d = 1.2$ nm. The reasons of a choice of such values for the parameters L and d are given in [11] wherein the topological parameters of the cold cathode based on the ordered array of SWMCNTs with open ends have been optimized.

The need to minimize the total capacitance grid-cathode and grid-anode, on the one hand, and to minimize the grid current, which is the leakage current from the ends of SWMCNTs to the control grid in a radial direction, on the other hand, causes necessity to locate the control grid in the same plane with the ends of the nanotubes as well as at the same distance from both the anode and metallic substrate of cathode. It is possible only in case of equality of SWMCNTs length L and the distance H between the anode and their ends. So, it is evident that the value of H must be chosen equal to 100 nm. The case of room temperatures is the most interesting from the practical viewpoint. Therefore let us suppose that $T = 300$ K.

The voltage compatibility requirement for the optimized triodes with other electronic devices along with the requirement of minimization of the anode dissipation power and the requirement of involvement of the maximum number of electron subbands into the electron transport lead to the constrains on the values of the grid φ_G and anode φ_A potentials. They must not exceed 12 V at zero cathode potential φ_C.

As a result, the only variable parameter is the distance S between SWMCNTs. S must be equal to such a value at that the average density of anode tunneling current j reaches a conditional maximum. In our case a restricting condition is the anode dissipation power. It should not exceed some reasonable value (~ 100 W/cm^2) for the maximum values of φ_G and φ_A.

For clarity in Fig. 1 a part of the triode cross-section along one of its transverse axes of symmetry is presented schematically.

As in [11] to calculate the potential φ outside of the walls of SWMCNTs the Laplace equation

$$\Delta\varphi(\mathbf{r}) = 0 \qquad (2.1)$$

is solved numerically. The Poisson equation

$$\varepsilon\varepsilon_0\Delta\varphi(\mathbf{r}) = e\delta n(\mathbf{r}) \qquad (2.2)$$

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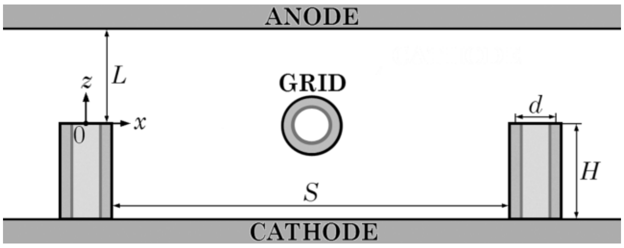

Fig. 1 – The cross-section of the triode with the cold cathode based on the ordered array of SWMCNTs with open ends

is solved numerically too. In these equations **r** is a radius-vector, e is the elementary charge, ε_0 is the dielectric constant, ε is the relative dielectric permittivity of the matter, δn is the excess concentration of electrons in the wall of SWMCNT close to its end. The Poisson equation describes the potential behaviour inside the walls of SWMCNTs (regions where the π-orbital electrons are located). The excess concentration of electrons δn can be calculated in the framework of local thermodynamic equilibrium approximation (the distance between the Fermi level and the vacuum energy level is a constant value inside SWMCNT).

As in [11] to calculate the electron transmission coefficient describing tunneling of electrons from the end of SWMCNT to the anode surface the quantum-wave equation

$$\left[\left(\mathbf{T}_{1/m}(\mathbf{r},\mathbf{p})\cdot\hbar\nabla_{\mathbf{r}}\right)^2+\left(\mathbf{T}_{1/m}(\mathbf{r},\mathbf{p})\cdot\mathbf{p}\right)^2\right]\Psi(\mathbf{r})=0 \quad (2.3)$$

is numerically solved in the framework of electron one-dimensional motion approximation. Here $\hbar$ is the Planck constant, Ψ is the electron wave function, $\mathbf{p}=\mathbf{p}(E,-e\varphi(\mathbf{r}))$ is the electron (quasi-)momentum, $\mathbf{T}_{1/m}$ is the inverse (effective-)mass tensor. E is the total electron energy. The quantum-wave equation in the presented form allows the electron transport in any region (inside and outside of a nanotube wall) to be described in a uniform way.

3. RESULTS OF CALCULATION

As the calculation results have shown the optimal value of distance S_{opt} between the nanotubes is equal to 80 nm.

In Fig. 2 the calculated dependencies $j(\varphi_{\text{G}})$ are presented for the case when the values of topological parameters and temperature are equal to the values defined above, $S=S_{\text{opt}}$, $\varphi_{\text{C}}=0$, φ_{A} is equal to 5 V (dotted curve) and 12 V (solid curve).

It follows from Fig. 2 that j is independent of φ_{A} for the considered range of values of φ_{G} and φ_{A}.

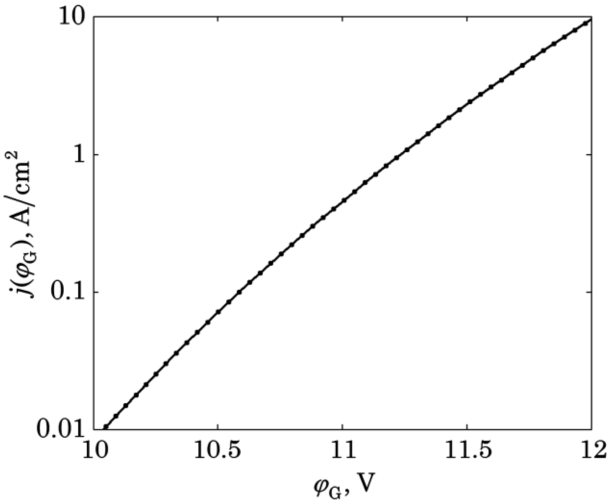

Fig. 2 – The current-voltage characteristics of the optimized triode with the cold cathode

4. CONCLUSION

The topological parameters of the triode with the plane-parallel electrodes and the cold cathode based on the ordered array of SWMCNTs with open ends have been optimized. The current-voltage characteristics of the optimized triode have been calculated.

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