Circuit Models of Field Emission Silicon Diode and Transistor with a Nanoscale Vacuum Channel

I.D. Evsikov, G.D. Demin, P.Yu. Glagolev, N.A. Djuzhev, M.A. Makhiboroda, V.A. Bespalov
MEMSEC R&D Center
National Research University of Electronic Technology (MIET)
Moscow, Zelenograd, Russia
evsikov.ilija@yandex.ru

S.V. Filippov, A.G. Kolosko, E.O. Popov
Ioffe Physical-Technical Institute of the Russian Academy of Sciences
St.-Petersburg, Russia
e.popov@mail.ioffe.ru

***Abstract*—Circuit models of field emission silicon diode and transistor with a nanoscale vacuum channel are presented. Parameters of the equivalent circuit of these vacuum devices such as parasitic resistances and capacitances have been calculated to make an analysis of the circuit performance. Models are based on the modified Fowler-Nordheim equation, taking into account the variation of field-enhancement factors from the geometric parameters at the nanoscale. Output current-voltage characteristics of the diode and transistor were calculated using SPICE simulator. The obtained results can found their practical application in the development of a new generation of nanoscale vacuum channel field emission devices.**

Keywords*—*electron field emission; nanoscale vacuum channel diode; nanoscale vacuum channel transisitor; vacuum nanoelectronics; circuit model; SPICE simulation

I. INTRODUCTION

At the beginning of an era of the electronics devices, a large part of these devices was based on vacuum tubes, which were used to perform various operations (e.g. amplification or modulation) on electrical signals. With the development of the semiconductor industry, vacuum tubes were almost replaced by metal-oxide-semiconductor (MOS) transistors. Vacuum tubes are still used in professional sound systems and high-frequency radio transmitters. Low costs and long lifetime of semiconductor devices and also the invention of the integrated technology caused the replacement of the vacuum tubes. Performance restrictions and vulnerability to the harsh environments such as radiation and high temperature of the solid-state integrated circuits force to look again at the vacuum electronics [1]. The modern state of the semiconductor integrated technology makes it possible to produce structures at 7 nm technology nodes, thus allowing manufacturing devices with high packing density of elements. Compatibility to the current CMOS technology [2] makes nanoscale vacuum channel transistor a suitable element for replacing a conventional MOS transistor widely used in modern integrated circuits (IC). The high cost of a manufacturing process for semiconductor IC elements requires careful development and verification of the final devices. SPICE simulation is a generally accepted method in the semiconductor industry for the verification of an IC at a transistor level before its implementation on a silicon substrate.

In this work, we propose SPICE models of silicon nanoscale vacuum channel diode and silicon nanoscale vacuum channel transistor. Previous investigations were focused mainly on models which were based on structures with micrometer dimensions [3-4]. In contrast, our model takes into account physical and geometrical parameters of the structure, which become crucial for making the optimization of vacuum field-emission devices at the nanometer scale.

II. CIRCUIT MODELS

Circuit models of nanoscale vacuum channel diode and nanoscale vacuum channel transistor were developed based on the results of a SPICE simulation of a field emission microtriode suggested by group of Prof. Nam [4]. The proposed circuit models are shown in Figure 1 and Figure 2, correspondingly. The letters C, G, A denote the corresponding electrodes (cathode, grid, anode) in the structure of the device. Circuit elements R_{CL}, R_{GL}, R_{AL} represent the line resistances (for the the cathode, the gate and the anode, respectively), R_{TIP} is the internal resistance of the cathode tip, R_{GC} is the resistance of an insulating silicon dioxide layer between the cathode and gate electrode.

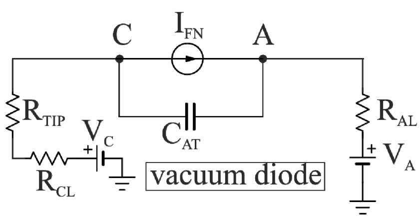

Fig. 1. Equivalent circuit model of a nanoscale vacuum channel diode.

Parasitic capacitances between electrodes are represented as C_{GC}, C_{GT}, C_{AT} and C_{GA}. Voltage sources Vc, V_A, V_G are responsible for applying voltage to the electrodes of vacuum structure. The circuit element I_{FN} describes the field emission current from a cathode tip, which is calculated using the Fowler-Nordheim (F-N) equation, and behaves as a voltage-controlled current source with two inputs in the case of a nanoscale vacuum diode and three inputs in the case of a

This work was performed using the equipment of the R&D center «MEMSEC»(MIET) and the facilities of the R&D center «Sensorics»(MIET).

nanoscale vacuum transistor. To calculate the emission current using the F-N formula $I_{FN}=A \cdot E_{AVG}^2 \cdot \exp(-B/E_{AVG})$, where A, B are the constants, the electrostatic simulation in COMSOL MultiPhysics was performed to estimate the average value of the electric field E_{AVG} on the cathode surface in the chosen design of the vacuum device. This makes it possible to calculate the field enhancement factor at the cathode tip ($\beta_{A(G)}=E_{AVG}/V_{A(G)}$), which opens the way to the integration of two- or three-input circuit element responsible for the emission current into the device model at given voltages $V_{A(G)}$ applied to the anode (gate) electrode.

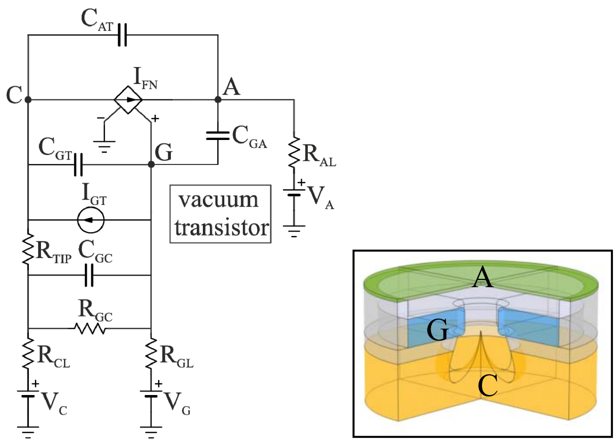

Fig. 2. Equivalent circuit model of a nanoscale vacuum channel transistor, where A-anode, G – grid, C – field-emission cathode, correspondingly.

Leakage emission current from cathode to the gate electrode is evaluated by the circuit element I_{GT} using the same expression as the equation of cathode-anode emission current.

III. SPICE Simulation and Results

Circuit models of nanoscale vacuum channel diode and transistor were created using LTspice simulation software.

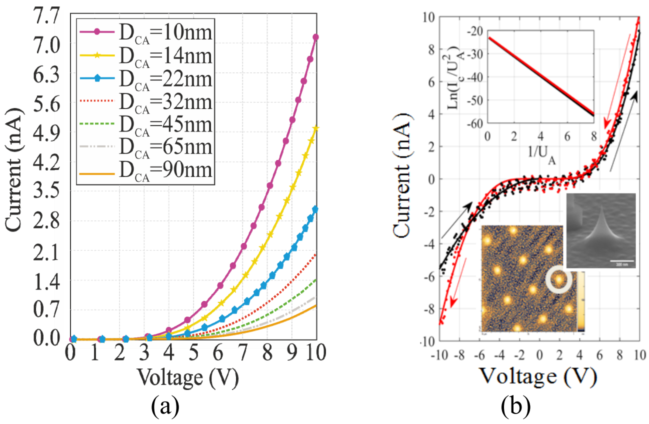

Fig. 3. (a) I-V characteristics of nanoscale vacuum channel diode obtained in the case of the different cathode-anode distances (channel length) obtained from numerical simulation. (b) Field-emission current in the nanoscale silicon diode with a vacuum gap of about 10 nm as a function of applied voltage obtained using atomic force microscopy (AFM) technique.

Figure 3a presents output I-V characteristics of the nanoscale vacuum diode obtained within numerical calculations in the case when the cathode-anode distance is varied from 10 to 90 nm (anode voltage is in the range from 0 to 10 V). It is worth noting that the field emission current numerically calculated as a function of the applied voltage in a vacuum diode with a gap of 10 nm coincides in magnitude with the experimental data obtained in our group by measuring the I-V characteristic of the "needle-type field emitter-anode" structure using AFM. In turn, output I-V characteristics of the nanoscale vacuum channel transistor were simulated for different cathode-gate distances (from 10 to 90 nm) when the gate voltage was varied from 0 to 10 V (Figure 4).

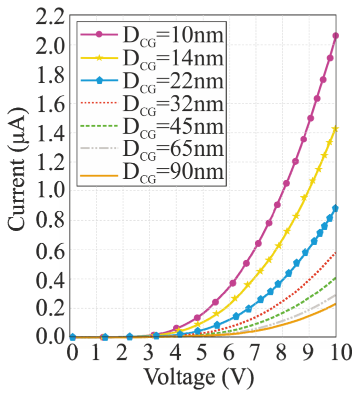

Fig. 4. I-V characteristics of nanoscale vacuum channel transistor obtained in the case of the different cathode-gate distances.

In addition to the calculations of output I-V characteristics, performance analysis of the final vacuum devices was also performed taking into account the parasitic capacitances C_{GT}, C_{GC} and output signal transconductance g_m.

IV. Conclusion

In this work we presented circuit models of nanoscale vacuum channel silicon diode and vacuum channel silicon transistor. Models have been created taking into account influence of nanoscale structural parameters on the performance characteristics of the vacuum devices. It was shown that the theoretical I-V characteristic of a vacuum diode with an air gap of 10 nm corresponds to the experimental data obtained using AFM. The variation of parameters of the vacuum channel diode and vacuum channel transistor with the variation of technology nodes was also analyzed.

Acknowledgment

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