Evaluation of The Field-Emission Characteristics of The Different Types of Triode Structure with The Nanoscale Vacuum Channel

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***Abstract*— Over the past few years vacuum electronics is becoming one of the most promising directions of modern nanoelectronics, which is connected with the progress in the development of triode semiconductor devices with nanoscale vacuum channel, demonstrating the high performance, resistance to the radiation and aggressive environment, and low power consumption [1-3]. With a decrease of the minimum topological size the important issue is to find the optimal performance of the vacuum triode, providing a stable field emission, taking into account the variation in geometry of the triode structure during the transition to the submicron design rules. In this work the simulation models describing the field-emission characteristics of the three different types of field-emission triode structures with nanoscale vacuum channel are presented: a) for the planar geometry of the cathode and grid electrodes, b) for the vertical geometry of the cathode and with the circular aperture of grid electrode, and c) for the planar geometry of the cathode in the case of isolated grid electrode. Based on these models, the geometrical parameters of the triode structures, allowing achieving maximum amplification of the electric field on the cathode surface with the variation of the cathode radius, the "cathode-anode" and "cathode grid" distances, are found which determines the tendency of the parametric change of the field emission in the process of scaling. As the minimum size of the vacuum triode, the technological design standards typical for the modern microelectronics industry was used in the range from 90 to 22 nm (90 nm, 65 nm, 45 nm, 32 nm and 22 nm).**

Keywords—Field emission, vacuum triode, scalability, electric-field enhancement factor, nanoscale vacuum channel, planar field emitter, vertical field emitter, insulated grid electrode

I. Introduction

In the process of transition of existing semiconductor devices, developed by CMOS technology, to 90 nm design rules and below, one of the main problems is to keep high performance and sufficiently low power consumption that opens the way to further scaling. However, the scattering of charge carriers on the lattice of the semiconductor material, the presence of additional defects and current leakage in MOS transistors occurring with the reduction of the lithographic size, lead to a rapid degradation of its performance. On the contrary, the ballistic transport in vacuum provides the rapid velocity of electrons transferring from the cathode to the anode (the maximum speed of the order of 1010 cm/s) in the absence of collisions, which, in turn, is the key to long lifetime of carriers and the high ratio of the operational frequency to the output power. Despite the fruitful steps in the development of vacuum microelectronics, there were a number of serious shortcomings, which stopped its further progress. The vacuum devices were still needed in a sealed package, which was not allowed to proceed to the integration circuit. To generate the effective field emission high operating voltages were required, and the leakage current of the gate in the process of scaling significantly reduced the emission properties of the developed triode structures [4]. This, ultimately, led to the widespread use of silicon technology in the industry of low-power and efficient semiconductor devices that is relevant for today. However, starting in 2012, the considerable success has been achieved in experimental studies of semiconductor field-emission triodes with nano-sized vacuum channel [1,2,5], where the field emission was observed at voltages below 10 V for the distance from emitter to collector of less than 100 nm, which gave rise to the emergence of the field of vacuum nanoelectronics. Recently, the emission properties of various types of field-effect transistors with nano-scale vacuum gap and variable design of the grid electrode were theoretically analysed in TCAD, which demonstrated the advantage of using the circular aperture of grid electrode in the terms of cut-off frequency and energy consumption [3]. Previously, they different designs of the vacuum triode were also considered in a large number of works. Based on the standard methods of photolithography, the vacuum structures with planar geometry of the cathode and grid electrodes were obtained in [6] for the easy integration of this technology into CMOS process technology with the high control of parasitic capacitance between the cathode and control electrodes. The development of the vacuum triode with an insulated grid electrode made it possible to prevent the disadvantage of such a planar design of the triode associated with the leakage current in the process of emission [7]. For a long time the vacuum structure with the vertical geometry of the field emitter remains relevant, where the improvement of the Spindt technology [8] helps to create the array of field emitters for the generation of large field-emission current over a large area [9,10]. However, there is still no comprehensive analysis of the electronic properties of the above types of vacuum triode systems in case of scaling of the vacuum channel to the nanometer level, which may be useful for the selection of optimal both structural and electrical parameters of nanoscale vacuum transistors with respect to

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their implementation in the space industry, ultra-fast electronics and wireless telecommunications.

This paper gives a quantitative evaluation of the field-emission characteristics of these types of triode structures with nanoscale vacuum channel, which is given by the variation of the enhancement factor of the electric field at the cathode depending on the radius of the cathode, the "cathode-anode" and "cathode-grid" distances for the scaling of design rules in the range varied from 90 to 22 nm.

II. The Field-Emission Triode Structures With Nanoscale Vacuum Channel: The Simulation Model

For the comparison of field-emission characteristics of a triode with a nanoscale vacuum channel the three most common types of vacuum structures were chosen that is shown in Fig. 1: a) planar geometry of the cathode and grid electrodes, b) vertical geometry of the cathode with the circular aperture of the grid electrode, and c) planar geometry of the cathode with isolated grid electrode.

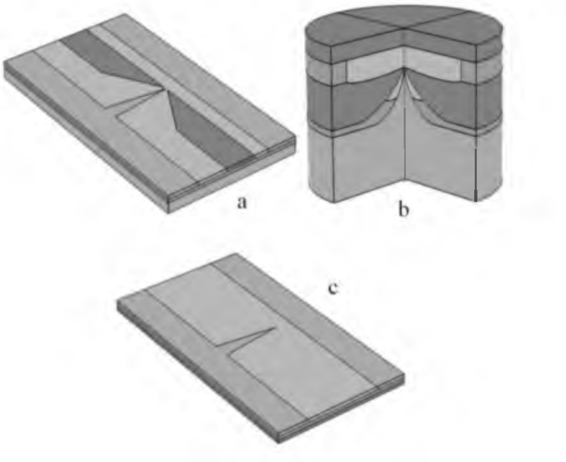

Fig. 1 Three types of field-emission triode structures with nanoscale vacuum channel: a) the cathode and the grid electrodes are in the plane of the layers, b) the cathode perpendicular to the plane of the layers, and the grid electrode is considered as the circular aperture and c) the cathode is in the plane of the layers, and the grid electrode is isolated from the system "cathode-anode" by the thin dielectric layer.

As the scalable parameters of the vacuum triode configurations (a) and (b), the following parameters was selected here: $d_{CA}=d_{CG}+d_{GA}$ is the distance between the cathode and the anode (distance "cathode-anode"), where d_{GA} is the distance between the control grid electrodes and the anode (distance "grid-anode"), d_{CG} is the distance between the cathode and the grid electrodes (distance "cathode-grid"), d_G is the half of the distance between the control grid electrodes (for the configuration (b), it is the radius of the circular aperture of grid electrode). For the configuration of the triode (c) the distance d_{CA} also was ranged, while the value d_G was taken as the thickness of the dielectric layer separating the bottom electrode from the vacuum system "cathode-anode" with the nanoscale vacuum gap. Since it is known that with decreasing radius of the emitter tip the electric field at the cathode surface also increases, this radius was taken in the simulation equal to 5 nm.

As the parameter of technological design rules, determining the minimum lithographic size, the value d_G scaling from 90 to 22 nm by the next steps: 90 nm, 65 nm, 45 nm, 32 nm and 22 nm. By default, the distance was assumed equal to 500 nm, whereas for a triode configurations (a) and (b) the grid electrodes were located at the center of curvature of the surface of the cathode, that is, when the distance d_{CG} is equal to 5 nm.

As one of the major characteristics determining the efficiency of the field emission in the vacuum triode is the form factor of amplification of the electric field on the cathode surface. Usually this factor can be described by two components each of these determines the relationship between the local electric field E_{loc} near the surface of the cathode tip and the potential difference "cathode-grid" $\varphi_{CG}=V_C-V_G$ and cathode-anode" $\varphi_{CA}=V_C-V_A$ correspondingly, when the cathode potential is zero:

$$\beta_G = -\frac{dE_{loc}}{d\varphi_{CG}} = \frac{dE_{loc}}{dV_G},\ \beta_A = -\frac{dE_{loc}}{d\varphi_{CA}} = \frac{dE_{loc}}{dV_A} \quad (1)$$

where β_G is the enhancement factor from the grid electrodes, β_A is the enhancement factor from the anode.

$$\vec{E}_{loc} = \vec{E}_G + \vec{E}_A, \quad (2)$$

$$E_G = E_{loc}(V_A = 0V) = \beta_G V_G\ E_A = E_{loc}(V_G = 0V) = \beta_A V_A \quad (3)$$

where E_G, E_A are individual contributions to the electric field from the grid electrodes and the anode, respectively, the values β_G and β_A in the linear approximation of the electric fields can be represented as:

$$\beta_G = \frac{E_{loc}(V_A = 0V)}{V_G},\ \beta_A = \frac{E_{loc}(V_G = 0V)}{V_A} \quad (4)$$

In this work we consider the variation of the enhancement factor β_G which contributes most to the formation of an electric field on the cathode surface, in the dependence from the variation of geometry of the considered triode configurations.

III. A Comparison of the Electric-Field Enhancement Factors on the Cathode Surface, Depending on the Design Rules of Various Types of Field-Emission Triode Structures With Nanoscale Vacuum Channel

Fig. 2 shows the non-monotonic dependences of the electric-field enhancement factor from the distance for the configurations of the triode (a) and (b), where there is the extremum close to the shift of the grid electrodes at the distance of about 5 nm relative to the cathode surface, that indicates the amplification of the influence of grid electrodes in relation to the anode. It is easy to see, that the value in the case of vertical geometry of the cathode (b) is two times higher than the analogous value in the case of its planar geometry (a), while it changes similarly with the scalability for two types of triodes.

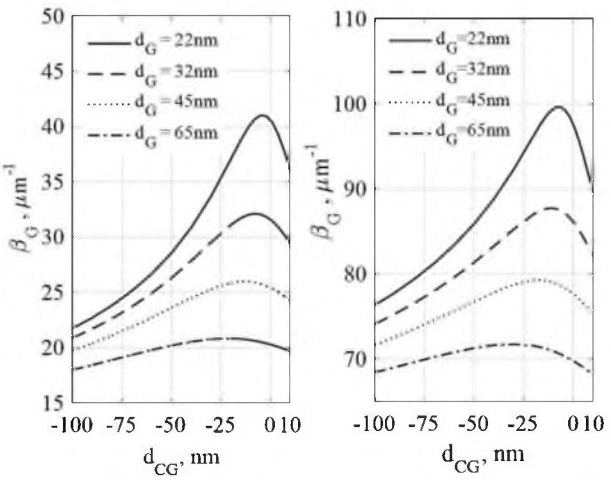

Fig. 2. – The dependence of the electric-field enhancement factor β_G, induced by the influence of the grid electrodes, from the distance d_{CG} for the configuration of the triode: (a) the planar geometry of the cathode and grid electrodes and (b) vertical geometry of the cathode and circular aperture of the grid electrode for the different topological design rules (value d_G).

The dependences of electric-field enhancement factor β_G from the distance d_{CA} are shown at Fig.3-5 for three types of configurations of the vacuum triode for the different scalability, which in all three cases point to the weakening of the influence of the anode and the growing influence of the grid with increasing value of d_{CA}. Thus, it is noticeable that in the range d_{CA}>90 nm the form factor β_C tends to the saturation value.

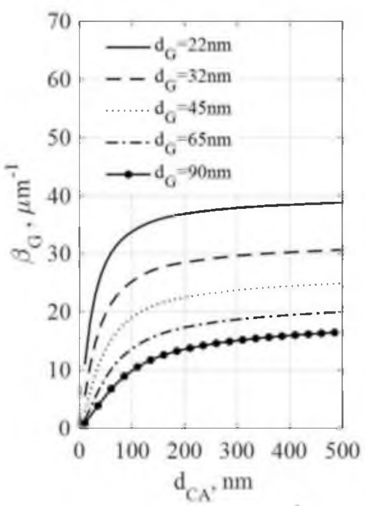

Fig. 3. – The dependence of the electric-field enhancement factor β_G, induced by the influence of the grid electrodes, from the distance d_{CA} for the configuration of the triode with the planar geometry of the cathode and grid electrodes for different topological design rules (value d_G).

From Fig. 4 it is clear that the form factor β_G increases significantly in the transition from planar to vertical geometry of the cathode.

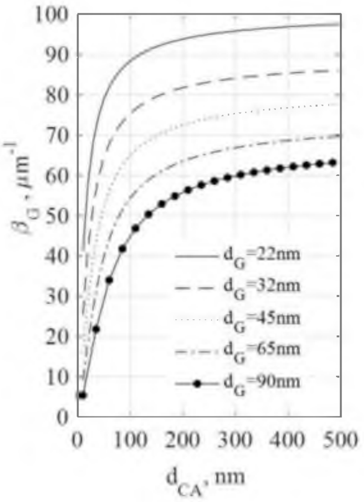

Fig. 4. – The dependence of the electric-field enhancement factor β_G, induced by the influence of the grid electrodes, from the distance d_{CA} for the configuration of the triode with the vertical geometry of the cathode and the circular aperture of grid electrode for different topological design rules (value d_G).

As shown in the Fig. 5, in the case of the use of isolated grid electrode in the triode, which corresponds to configuration, the magnitude of the β_G takes an intermediate value between the value in the configuration with the planar geometry of the cathode and grid electrodes, and the configuration with the vertical position of the cathode and the circular aperture of grid electrode. The given structure is most prospective because it helps to avoid leakage currents.

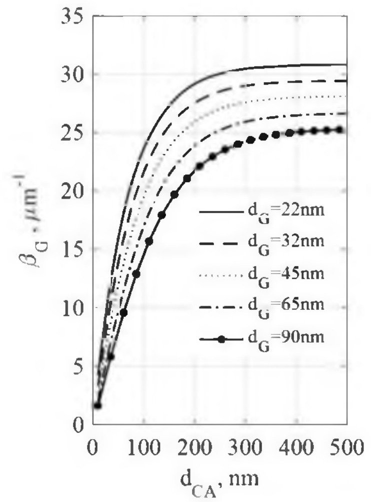

Fig. 5. – The dependence of the electric-field enhancement factor β_G, induced by the influence of the grid electrodes, from the distance d_{CA} for the configuration of the triode (c) with the planar geometry of the cathode for the case of isolated grid electrode for different topological design rules (value d_G).

The given structure is most prospective because it helps to avoid leakage currents.

IV. Conclusions

Thus, the results of simulation of the field emission characteristics in three different configurations of a vacuum triode with a nanoscale vacuum channel, in particular, the electric-field enhancement factor on the cathode surface, proved that it significantly changes with the variation of the scalability of vacuum structure. The maximum value of β_G is achieved in the case of the configuration of the triode, the minimum one – in the case of a configuration of a triode. The new geometry of the triode with isolated grid electrode allows achieving the intermediate values of this form factor.

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