Study of the electric field strength in planar multigraphene/SiC field emission nanostructures with different arrangement of the electrode planes

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Abstract. The paper describes simulation of planar field emission nanostructures on the basis of graphene on a semiinsulating silicon carbide. The effect of arrangement of the electrode planes on the field strength and field gain is shown. The model is considered with a nanoscale interelectrode distance and a potential difference of 10 V.

1. Introduction
Developments in the field emission electronics suggest a transition to terahertz electronics. Graphene films are promising for these purposes. The unique geometric and electrical properties of graphene contribute to characteristic improvement of the devices on its basis [1-4]. The properties of graphene films depend on the preparation method [5-7]. The most technological method is the thermal destruction of SiC in vacuum [7-9]. Graphene films suitable for electronic application can be fabricated with this method. A different number of graphene layers (multigraphene) can be obtained by controlling the technological parameters of SiC annealing [10, 11]. Silicon carbide substrate has high thermal conductivity, mechanical strength, resistance to aggressive environment [12]. An increase in the number of layers in the multigraphene film enhances the durability of the field emission device.

One of the directions of emission electronics is field emission nanoelectronics. Graphene is a good material for the elements of field emission nanoelectronics [13-20]. The nanometer thickness of the multigraphene makes it possible to develop planar-edge emitters with a high field gain [21-23]. A promising method for formation of nanometer interelectrode gaps and ultrasharp emitters is the method of focused ion beams [24, 25]. In this case, the minimum interelectrode distance is determined by the ion beam width. The transition to nanometer interelectrode distances helps to reduce the threshold voltages and reduce the possibility of emitter destruction due to the ion bombardment.

The design of nanoscale field emission structures should be carried out taking into account the influence of design parameters of the emission cell on the distribution of the electric field strength in the interelectrode gap. One of the important parameters of planar-edge emission structures is the relative arrangement of the electrode planes. The change in the arrangement of the electrode planes of the planar-edge emission structures leads to a change in the anode area which receives the emitted electrons and, as a result, changes in the current density. A high local current density can contribute to a process of critical overheating, leading to the destruction of individual sections [26-28].

The combination of the use of original design and technological solutions and the advantages of multigraphene and silicon carbide allow the development of stable energy-efficient devices. The object of studying is the simulation of the electric field strength in nanoscale field emission structures with...
planar-edge cathode and determination of the influence of different electrode planes arrangement on field gain.

2. Design
Field emission occurs when high electric field strength is created at the cathode surface. Emitters with a high curvature of the surface are used to obtain such fields. Planar-edge emission structures with a tip form of the emitters and a nanometer-wide interelectrode distance are considered in this work. This form of emitters based on graphene on SiC helps to reduce the threshold voltages down to few volts [19]. Geometric parameters of the model were chosen with taking into account the dimensions of the experimental emitter samples based on the multigraphene films on semiinsulating silicon carbide and are shown in Table 1. General view of the investigated field emission structure is shown in Figure 1.

Table 1. Simulation parameters.

| Parameter                                           | Symbol | Value |
|-----------------------------------------------------|--------|-------|
| Emitter length                                      | $l$    | 400 nm |
| Rounding-off radius of the cathode top              | $r$    | 5 nm  |
| Thickness of the multigraphene film                 | $w$    | 3 nm  |
| Inclination angle of lateral face of the emitter    | $\alpha$ | 10$^\circ$ |
| relative to the central axis                        |        |       |
| Initial interelectrode distance                     | $R$    | 5 nm  |

![Figure 1](image_url)

**Figure 1.** Model of planar field emission structure with tip-shaped emitter based on multigraphene films on a semiinsulating silicon carbide.

3. Simulation and results
Three-dimensional simulation was applied for the determination of the electric field strength $E$ in nanosized interelectrode gap. Laplace equation for the potential was solved numerically by the finite element method with Dirichlet boundary conditions: for the cathode $U_k = \text{const}$; for the anode $U_a = \text{const}$; for the boundary of the model $U_s = 0$. The height difference $p$ between the anode plane relative to the cathode was varied in the range: $-50$ to $+50$ nm. The change of the plane arrangement of the electrodes led to an increase in the interelectrode distance. Figures 2, 3 show the distribution of the electric field strength in the interelectrode gap of the emission structure with different arrangement of the electrode planes.
Figure 2. The distribution of the electric field strength when the cathode plane is higher than the anode plane: (a) $p = -5$ nm; (b) $p = -50$ nm

Figure 3. The distribution of the electric field strength when the cathode plane is lower than the anode plane: (a) $p = +20$ nm; (b) $p = +50$ nm

Dependences of the electric field strength on the arrangement of the electrode planes are obtained on the basis of the simulation results (Figure 4). The field strength is within the range $10^9$ V/m. An increase in the difference of the plane arrangement leads to a decrease in the electric field at the emitter surface. It was found that a decrease in the anode plane with respect to the cathode at 50 nm leads to a decrease in the electric field strength by $\sim 60\%$. The decrease in the cathode plane with respect to the anode at 50 nm leads to a decrease in the electric field strength by less than $\sim 10\%$.

The field gain $\beta$ is calculated with taking into account the obtained values of the electric field strength and the corresponding dependence on the arrangement of the electrode planes was plotted (Figure 5). The field gain is $\beta = E/E_0$, where $E_0$ is the electric field strength calculated as for a plane-parallel capacitor at identical interelectrode distances. The obtained dependences show that the electric field gain increases with increasing the height difference $p$ between the anode plane relative to the cathode. Thus, the efficiency of the design of the tip emitters decreases when nanoscale interelectrode distances $R \rightarrow r$. If the anode plane is 50 nm lower with respect to the cathode, the electric field gain will multiplicate in
5 times. If the anode plane is 50 nm higher with respect to the cathode, the electric field gain will multiply in ~ 10 times.

![Graph a) and b)](image)

**Figure 4.** The dependences of the electric field strength on the arrangement of the electrode planes when: (a) the cathode plane is higher than the anode plane; (b) the cathode plane is lower than the anode plane

![Graph a) and b)](image)

**Figure 5.** The dependences of the field gain on the arrangement of the electrode planes when: (a) the cathode plane is higher than the anode plane; (b) the cathode plane is lower than the anode plane

### 4. Conclusions
The obtained simulation results allowed to estimate the influence of the design parameters of the emission cell on the electric field distribution in the nanosized interelectrode gap. The effect of the arrangement of the electrode planes on the electric field strength and field gain was shown. The obtained values of the electric field strength correspond to the values of nanoscale emission structures. It is necessary to take into account the presented changes in the electric field strength and field gain in designing nanoscale emission structures, but find a compromise between obtaining maximum electric field strength and equipment durability.
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