Planar multigraphene/SiC blade-shaped field emission nanostructures

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Abstract. This paper reports on study of blade-shaped field emission nanostructures based on multigraphene films on silicon carbide. We carry out numerical simulations of the distribution of the electric field in a nanoscale interelectrode gap of a planar field emission cell. The simulation parameters are based on the dimensions of the experimental sample of a planar emission cell with a blade-shaped emitter. Design of the field emission cell aimed at minimizing the local field amplification at the emitter corners have been proposed. The initial difference in the electric field strength at the corners of the emitter and in the center was 2.5 times. The proposed design allows to obtain the electric field strength at the corners corresponding to the values in the center of the emitter.

1. Introduction
The development of aerospace electronics is an important task. Field emission devices are promising for navigation, radar, space communications and special purposes. Moreover, more stringent requirements are imposed on speed of operation, reliability and durability of field emission devices. Thus, the problems of choosing the material and design of the field emission electron source must be solved.

Carbon materials are currently promising for field emission cathodes. A study of electrodynamic tether propulsion system with carbon nanotube field emission cathode was conducted in the Institute of Space Technology and Aeronautics, Japan Aerospace Exploration Agency [1]. The use of carbon nanotubes as a field emission cathode for a traveling-wave tube in C-band for space was studied in [2] with the support of the European Space Agency. Stable and environment-hard a-C field emitter arrays can be used for the highly efficient and reliable vacuum electronic devices such as electric propulsion engines for aerospace applications [3].

The use of graphene-based materials allows lowering the threshold field and increasing the durability of emitters [4-8]. Multilayer graphene (MLG) films obtained by thermal decomposition of silicon carbide in vacuum are used as the basis of the planar design of the field emitters [9, 10]. The method of thermal decomposition of SiC differs manufacturability [11-14]. Silicon carbide is characterized by increased resistance to aggressive environments. The number of layers in a multigraphene film depends on the process parameters. The nanometer thickness of multilayer graphene of a large area allows to create on its basis field emission structures with high field enhancement factor.

Field emission is based on electron tunneling through a potential barrier at a solid state/vacuum interface. An external electric field (about $10^9$ V/m) must be applied to initiate the field emission. Emitters with a high curvature of the surface allows to achieve the required electric field strength at
lower voltages compared with a flat surface. In this paper, we study planar field emission structures in the form of a rectangular blade. Field emitters in the form of a blade contribute to an increase in the density of the emission current. At present, planar field emission nanostructures in the form of a blade on the basis of multigraphene/SiC are insufficiently studied. An important task is to study the homogeneity of field emission from the surface of the blade emitter. The degradation of the blade-shaped field emission cathode in the corners occurs during operation. The rounding of the corners of the blade-shaped cathode is due to the increased emission current density in this region. Local overheating and high electric field lead to a shape change of the field emission cathode. A preliminary modification of the field emission cathode is carried out in order to minimize the shape change during operation. Mechanical processing of the field emission cathode and processing by corona discharge allows stabilization of the parameters of the field emission cathode [15, 16]. Focused ion beam allows preliminary modification of nanoscale field emission cathodes [17, 18]. Theoretical studies of the shape of the field emission cathode by a modeling method of the electric field distribution in the interelectrode gap can eliminate the preliminary processing of the field emission cathode and reduce financial and time costs.

Thus, the purpose of the article is to study the distribution of the electric field strength along a planar blade-shaped multigraphene/SiC emitter and to find the design of the emission cell, which allows reducing the electric field strength at emitter corners.

2. Design and simulation

The use of modern nanotechnology methods allows us to reduce the size of electronic elements and increase the performance of electrophysical characteristics. Reducing the interelectrode gap helps reduce threshold voltages. The use of FIB-technology allowed the formation of planar field emission structures with an interelectrode gap of 30 nm or less.Focused ion beam (FIB) technology was used for the formation of planar-type field emission nanostructures [19-22]. The advantage of the method is the possibility of local precision unmasked etching. The relevance of this method is also in the high labour-intensiveness of the processing of silicon carbide.

The thickness of the multigraphene film obtained by thermal decomposition of silicon carbide in vacuum was about 3 nm. In this work, silicon carbide is also an insulating substrate, contributing to the removal of heat released during operation. The dimensions of the experimental sample formed the basis of the parameters of the model of the field emission nanostructure and are presented in Table 1.

The three-dimensional Laplace equation for the potential was solved numerically by the finite element method with Dirichlet boundary conditions. The finite element mesh with higher density was located near the corners of the emitter.

| Parameter                                | Symbol | Value  |
|------------------------------------------|--------|--------|
| Emitter length                           | $l$    | 1000 nm|
| Emitter height                           | $h$    | 1000 nm|
| Thickness of the multigraphene film      | $w$    | 3 nm   |
| Interelectrode gap                       | $R$    | 30 nm  |
| Rounding-off radius of the cathode corners| $r$    | 50 nm  |
| Standard deviation                       | $\sigma$ | 1-10 μm|

3. Results

General view of the planar field emission structure with blade-shaped cathode is shown in Figure 1. The shape of the emitting edge changed in accordance with the normal distribution. Standard deviation varied from 1 to 10 microns. Figure 2a shows the shape of the emitting edge for several standard deviation. The simulation results showed that the field enhancement at the corners of the field
emission cathode compared with the center region is observed and reaches values of about \(1.5 \times 10^9\) V/m. The electric field strength is increased about 2.5 times at the corners of the emitter compared with the central region, when a potential difference of 10 V is applied. Thus, we modified the emitter by rounding the corners and changing the emitting edge according to the normal distribution. The distribution of the electric field strength along the emitting edge of various configurations was plotted on the basis of the simulation results (Figure 2b).

![Figure 1. General view of planar field emission structure with blade-shaped cathode](image)

![Figure 2. Change in the shape of the emitting edge (a) and the electric field strength distribution along emitting edge (b) at \(\sigma = 1, 2, 3, 5 \text{ and } 10 \mu m\)](image)

Changing the shape of the emitting edge contributes to reducing the electric field strength at the corners of the emitter. The dependence of the electric field strength at the corners of the emitter with a rounding of 50 nm and without it is presented in Figure 3. It was founded that a change in the emitting edge from \(\sigma = 10 \mu m\) to \(\sigma = 1 \mu m\) contributes to the achievement of almost identical values of the electric field strength at the emitter corner and in the center. At the same time, the electric field strength between the center and corner decreases by more than 3 times. Additional rounding of the emitter corner to 50 nm makes it possible to achieve identical values of the electric field strength at the corner and in the center of the emitter at \(\sigma = 5 \mu m\). In this case, the electric field strength between the center and corner of the emitter decreases only 1.1 times. Designs with rounded corners and \(\sigma < 5 \mu m\) also make it possible to eliminate the excess of the electric field strength at the corners of the emitter.
compared to the center. However, their use becomes impractical, since it will ultimately contribute to the decrease in the emission current.

**Figure 3.** The dependence of the ratio of the electric field strength at the corner $E_{c0}$ with a rounding of 50 nm and without it to the central region $E_{ce}$ on standard deviation $\sigma$.

4. Conclusions

The designs of planar nanoscale field emission cells with a blade emitter are considered on the basis of numerical simulation. Electric field strength corresponds to the values and character of the distribution of nanoscale blade-shaped field emission structures [23, 24]. Results have been obtained that make it possible to determine the design of a nanoscale field emission cell, which contributes to an increase in the emission homogeneity from the edge of a planar blade-shaped cathode. The design of the emitter based on multigraphene/silicon carbide underlies the model, but the results must be taken into account when designing similar emission cells from other materials.

Acknowledgments

The equipment of the Research and Educational Center "Nanotechnologies" of Southern Federal University was used for this study. This work was funded by Internal grant of the Southern Federal University No. VnGr-07/2017-26 and Grant of the President of the Russian Federation for state support of young Russian scientists - candidates of sciences (Project No. MK-1811.2019.8).

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