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Study of the field emission graphene/SiC nanostructures using scanning probe microscopy

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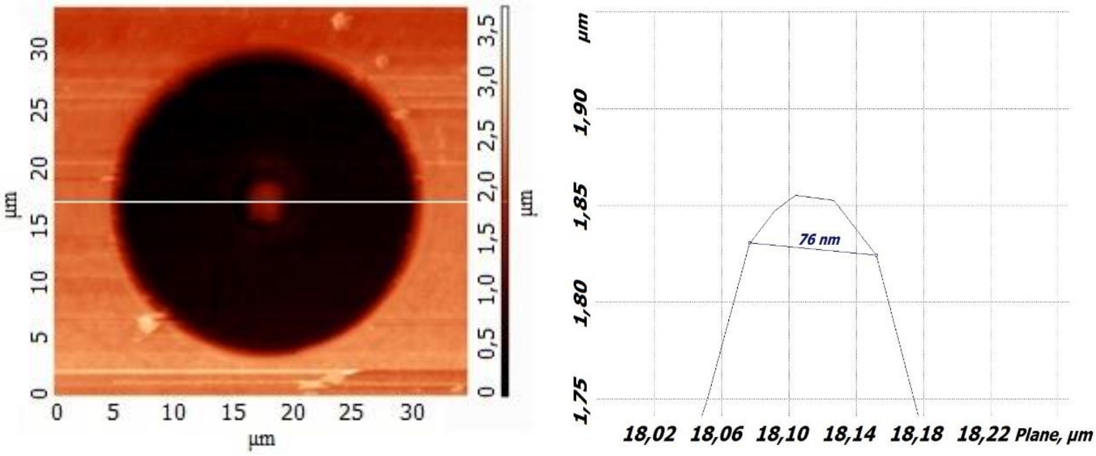
Abstract. We investigated the topology and electrical characteristics of the field emission graphene/SiC nanostructures using scanning probe microscopy. The effect of design of graphene/SiC nanostructures on field emission properties was estimated. The current-voltage characteristics were measured at different rounding-off radii of the emitting top and the interelectrode distances.

1. Introduction
One of the important tasks of nanoelectronics is development of the field emitters with low operating voltages. In this case, an emission cell should satisfy certain geometric requirements and requirements for the cathode material. An emitter must be made of a mechanically strong, heat-resistant material with a low operating function. The electrical and mechanical properties of graphene on SiC make it possible to produce field emission structures with increased resistance to destabilizing factors. Thus, nanoscale graphene/SiC field emitters are promising electron sources [1-6].

At the same time, the development of nanoscale field emission systems requires using special research methods. The scanning probe microscopy (SPM) methods are universal and allow obtaining information about the geometry of nanometer field emitters with subsequent measurement of their electrical characteristics with nanometer locality and high precision [6-10].

The purpose of this work is the application of SPM methods for investigation of field emission cathodes based on graphene films obtained by thermal decomposition of silicon carbide in vacuum.

2. Design and production
It has been found recently that emission structures with nanometer interelectrode distance and the rounding-off radius of the emitter top have a high field gain [11, 12]. The electric field strength reaches values about 10^9 V/m with a potential difference below 10 V. Thus, tip-shaped field emission cathodes with different nanometer rounding-off radius of the emitter top were produced. Silicon carbide 6H-SiC doped with nitrogen with an impurity concentration of 10^{18} cm^{-3} was used as a substrate. Focused gallium ion beams were used for etching of the emission nanostructures [4-6, 13, 14]. This method is characterized by high accuracy of etching, locality, and the ability to fabricate nanometer structures. The liquid etching methods of SiC require high temperatures, longer time, and



(a) (b)

Figure 1. (a) AFM image of the tip-shaped field emission graphene/SiC nanostructure and (b) cross-section of the emitter top along the white line.

the application of more laborious methods of photolithography. Graphene films on the emitter surface were obtained by the thermal decomposition of SiC [1, 4, 5]. This method is manufacturable and allows creating low-defect graphene films on the entire surface of a SiC substrate.

3. Experiment and results

The geometry of field emission cathodes based on graphene/SiC was measured by atomic force microscope Ntegra Vita (NT-MDT Spectrum Instruments). AFM-images of nanostructures showed that a series of emitters with rounding-off radii of the top ranging from 20 to 40 nm were fabricated. The AFM image of the emitter with a 40 nm rounding-off radius of the top is shown in Figure 1.

Field emission from a flat surface was investigated at the first stage to estimate the emission ability of the graphene films on SiC. Current-voltage characteristics of the flat graphene/SiC surface at an interelectrode distance less than 1 nm are shown in Figure 2. The threshold voltage at a cathode-anode distance of less than 1 nm was tenths of a volt. An increase of the interelectrode distance leads to a reduction of the emission current.

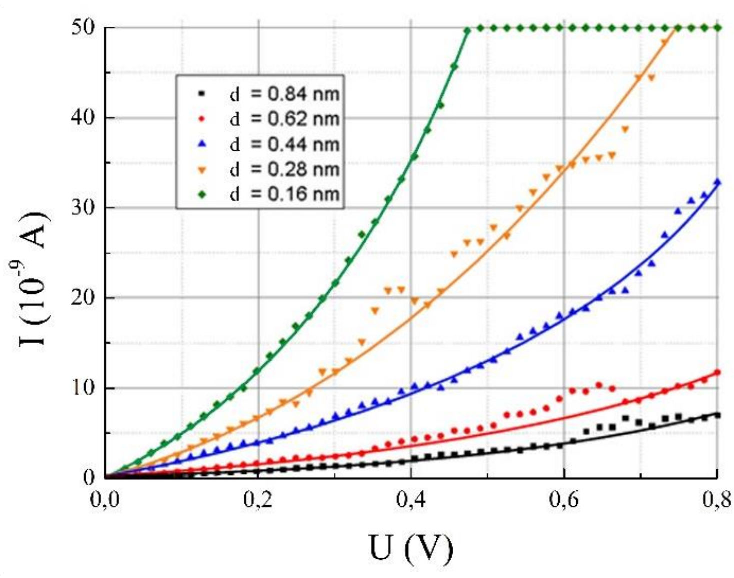
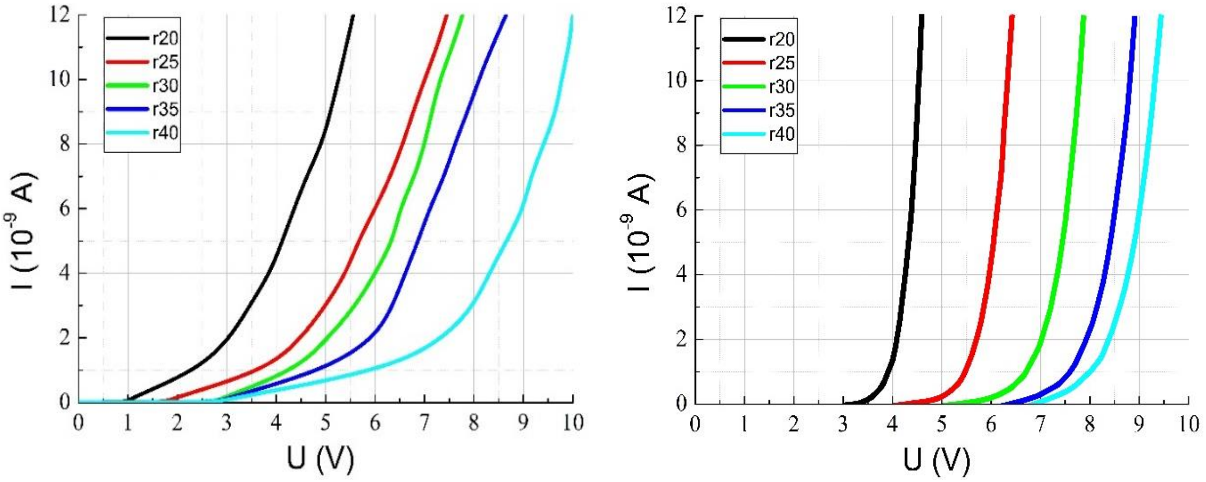


Figure 2. Current-voltage characteristics of the flat graphene/SiC surface.

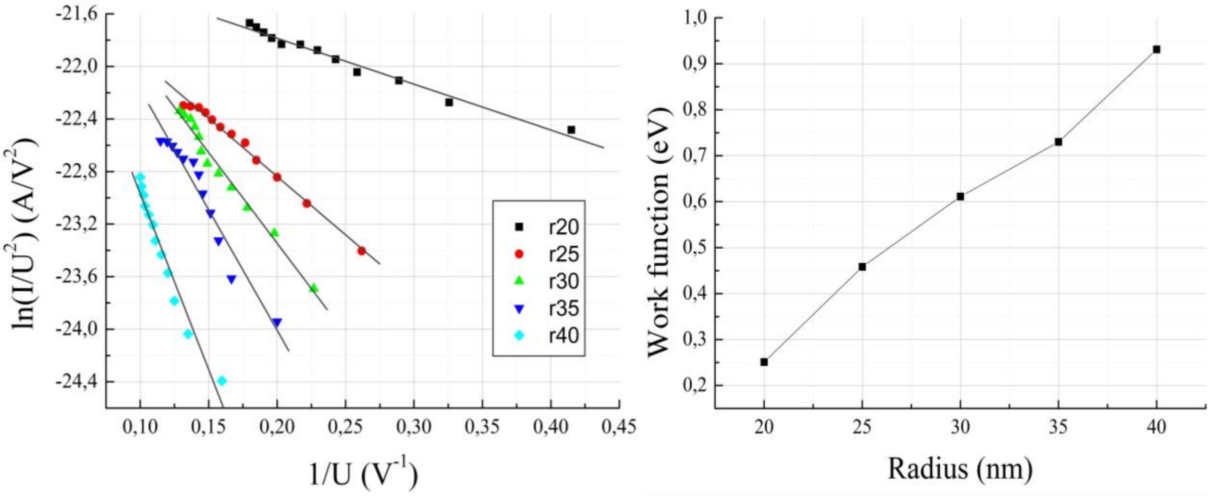


(a) (b)

Figure 3. (a) Experimental and (b) theoretical current-voltage characteristics of the tip-shaped field emission graphene/SiC nanostructure.

Simulation of the tip-shaped field emission nanostructures shows that a decrease of the rounding-off radii of the top leads to an increase in the field gain. The use of SPM for the study of the field emission allows revealing the effect of the nanosized rounding-off radius of the top at a nanometer interelectrode distance on the current-voltage characteristics. The effect of the rounding-off radius of the emitter top on field emission was estimated. The emitters with 5 nm interelectrode distance were investigated experimentally and current-voltage characteristics were simulated theoretically (Fig. 3). It was found that reducing the rounding-off radius of the emitter top from 40 to 20 nm contributed to decrease of the threshold voltage from 2 to 1 V and increase of the emission current.

The current-voltage characteristics in the Fowler-Nordheim coordinates based on the experimental data were plotted (Fig. 4a). The plot slope was used to determine the work function. The dependence of the work function on the rounding-off radius of the emitter top was plotted on the basis of the calculation results taking into account the slope of the F-N plot (Fig. 4b).



(a) (b)

Figure 4. (a) Experimental Fowler-Nordheim plots and (b) dependence of the work function from a rounding-off radius of the emitter top.

4. Conclusion

It is shown that the application of modern SPM makes it possible to carry out complex studies of nanoscale structures. The emission characteristics at nanometer interelectrode distances were measured by SPM with high localization. The obtained data are in good agreement with the theoretically calculated current-voltage characteristics. The dependence of the work function on the rounding-off radius of the emitter top was obtained on the basis of experimental studies. The work function is 0.25 eV for rounding-off radius of the emitter top of 20 nm. The calculated low values of the work function correspond to the results for emitters based on graphene and graphene-like materials [4, 5, 15]. Our studies of nanoscale field emitters based on graphene films on SiC at nanometer interelectrode distances can be used for the development of energy-efficient vacuum nanoelectronics.

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