Study of the thermal mode of a silicon carbide field emission cathode

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Abstract. The dependency of the thermal mode of the silicon carbide (6H-SiC) field emission arrays on the integral emission current density is considered. Experimental temperature estimates reaching values of 1100 °C are presented. Computer simulation of the thermal mode accounting for the emission of electrons from a limited area of the apex of the tip, the Joule heating at the tips, and the nonlinear dependence of the thermal conductivity of the material is performed. The possibility of increasing the integral density of the emission current above 10 A·cm⁻² is demonstrated.

1. Introduction
Field emission cathodes have found wide application in information display systems. They are promising sources of electrons for microwave vacuum electronic devices, requiring values of emission current exceeding hundreds of mA, usually provided by thermal cathodes. In recent years, thanks to the use of silicon carbide, it has been possible to create field emission arrays (FEA) with an integral emission current density exceeding 6 A·cm⁻² [1].

According to the results of the studies [2–5], a high obstacle to the increase in the density of the emission current is the Joule heating of the cathode tips. Particularly, at a temperature of 1400 °C, instability of the emission current can arise due to the transition to the intrinsic electrical conductivity of the material. The temperature of the field emission cathode depends on many factors, primarily on its configuration, material features, and effective heat dissipation. On the basis of experimental study and computer simulation, the article gives estimates of the dependence of the cathode temperature on the emission current density for the developed silicon carbide field emission arrays.

2. Experimental data
The silicon carbide (6H-SiC) field emission arrays (figure 1) is fabricated on a single-crystal n-type substrate by the method of two-stage reactive ion etching (RIE) in a fluorine-containing medium [6, 7]. At the first stage, the periodic structure of rectangular pedestals is formed. At the second stage, the upper horizontal faces of the pedestals are transformed into arrays of nanoscale tips with a surface density of 5·10⁸ cm⁻². Dimensions of a single tip are the following: the radius of the apex is 30 nm, the height is 2 μm and the base diameter is 0.3 μm. The two-tier configuration of the field emission arrays provides an amplification of the electric field near tips and, thus, increases the emission current. The field emission arrays is placed in a specially assembled vacuum diode with a fixed electrode gap (40–60 μm) and an anode area of 0.5 mm².
Figure 1. SEM micrographs: (a) – 6H-SiC array of pedestals; (b) – 6H-SiC pedestal with nanoscale tips.

Measurements of the current-voltage characteristics of the diode have been carried out in a high-vacuum chamber. Figure 2 shows the typical characteristics for the phenomenon of field electron emission.

Figure 2. Experimental characteristics of 6H-SiC FEA: (a) – current density vs electric field; (b) – Fowler–Nordheim plot.

At a current density level near 50 mA·cm^{-2}, a soft cathode glow was observed. When the voltage reached 2.6 kV, the current spontaneously increased, and the temperature of the cathode raised up to 1100 °C. The photograph of the cathode at this temperature is shown in figure 3.

Figure 3. A photograph of cathode glow at a temperature of 1100 °C.

3. Numerical setup
The tiny scale of the objects under investigation and the experimental difficulty of achieving the peak current density make it necessary to use computer simulation to estimate the cathode’s capabilities.
The 6H-SiC substrate has high electrical conductivity, and most of the Joule heat is released in the volume of the tips and pedestals. The 6H-SiC has a significant non-linear temperature dependence of the thermal conductivity. We propose and assess the hypothesis that the change in the thermal conductivity of a part of the substrate under the pedestals of the FEA, when heated by a heat flux from the pedestals, can affect the thermal mode.

To simplify the solution of the thermal problem, we consider the case of a sufficiently dense arrangement of the pedestals, and in the first approximation simulate the thermal mode of a single column on the substrate having a cross-sectional area equal to that of one pedestal. This approach allows us to further reduce the system under consideration to a single tip located on a parallelepiped with a cross-section equal to the area of one element of the array of tips. The height of the parallelepiped is a sum of the height of the pedestal and the thickness of the substrate plate below it. The results of the solution of the simplified thermal problem can be regarded as an upper estimate of the temperature for a real system.

Thus, the simulated simplified system (thermal element) consists of a tip on a parallelepiped, which we divide into two parts: the pedestal and the substrate. Since the substrate is much thicker than the height of the pedestal, we normalize the thickness of the substrate to the height of the pedestal, adjusting the thermal characteristics of the model substrate material accordingly.

The geometric configuration of the simulated thermal element is shown in Figure 4. The following physical processes are taken into account in the construction of the model: a) an increase of Joule heating at tips with the rise of the emission current; b) the nonlinear dependence of the thermal conductivity of the material [8], which leads to an increase in the temperature of the tips due to the decrease of the heat sink efficiency; c) heat transfer through the substrate under cathode. The heat transfer by radiation and the Nottingham effect are not taken into consideration.

**Figure 4.** A geometric configuration of the simulated element of the cathode: from left to right are the substrate, the pedestal, and the tip.

The general procedure is as follows: given the value of the integral current density from the surface of the FEA and the cathode configuration, the current emitted from one pedestal, as well as the current emitted from one tip can be found. From the solution of the field emission problem we obtain the effective emission area of one tip. Setting the current emitted from one tip and the effective area, we find the current density in the bulk of the element. After the calculation of the volume density of Joule heating in the bulk of the element the thermal problem is solved. The boundary conditions are as follows: on the lower (left) face is an isothermal condition of ambient room temperature; on the lateral faces of the computational domain, and over the tip, the adiabatic conditions are applied.

The maximal density of Joule heating is in the region near the apex of the tip. The difference in temperature of the tip and the pedestal is slight, being on the order of several tens of degrees. In the bulk of the substrate the temperature decreases gradually.

**4. Simulation results**

The general results of computer simulation in the form of the dependence of the maximum temperature of the cathode tips on the emission current density are shown in Figure 5. The maximum temperature of the cathode tips starts to raise at emission current density about 2.5 A·cm⁻². The temperature increases linearly to about 6 A·cm⁻² and reaches a value of 250 °C. Then a nonlinear rise in temperature begins and a current with density about 10.8 A·cm⁻² heats the cathode up to 1400 °C.

**5. Conclusions**

Numerical simulation, within the limits of the assumptions made, shows that in the developed configuration of the silicon carbide (6H-SiC) field emission arrays, it is possible to obtain an integral emission current density of no less than 10 A·cm⁻². In such case, the maximum temperature of the...
cathode does not exceed a value of 1400 °C, at which a transition to the intrinsic electrical conductivity of the material occurs and instability of the emission current can arise.

![Figure 5. Dependence of the maximum temperature of cathode tips on the emission current density.](image)

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