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Investigation of the Thermal Degradation of the Silicon Field-Emission Cathode as a Two-Phase System

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Abstract—The factors affecting the thermal degradation of a single silicon field-emission pointed cathode during the take-off of the emission current are described experimentally. The results of the numerical modeling of the temperature dynamics of the field-emission cathode in conditions of the presence of a free interface between the liquid and solid phases allowing for the surface tension are described.

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Currently, the possibility of using the field electron emission is limited by the presence of some unresolved technological and physical problems. They are poor reproducibility of emission characteristics, instability of the emission current, and degradation of cathodes during the operation. It is considered that the main cause of degradation of field-emission cathodes is the intense heat liberation during the flow of the conductivity current across the cathode [1]. In the Fowler–Nordheim theory, the maximally possible emission current density can reach 1.1×10^{11} A/cm^2. This value corresponds to the complete removal of the potential barrier at the cathode boundary by the external field, when the complete tunnel transparency of the barrier is attained. In practice, the attainable current densities are much lower since the destruction of the emitter associated with the thermal heating of the cathode and the appearance of the phase reconstruction of the phase structure of the point and its degradation occurs much earlier. The investigation of heat conductivity and transient processes at the phase interface in the field-emission cathode with the nanodimensional emitting region is of important applied significance; therefore, the detailed analysis of mechanisms of the development of degradation phenomena is necessary.

In this article, we describe the experimental investigation and theoretically analyze the modes of heat liberation during field electron emission using numerical methods.

The object of the investigation is the single point cathode formed by anisotropic etching in the bulk of the silicon single-crystal substrate. Its sizes are the following: the height of the silicon cathode is 15 μm, the angle at the vertex is about 20°, and the curvature radius of the point is less than 10 nm.

EXPERIMENTAL INVESTIGATION OF THERMAL DEGRADATION OF SELF-EMISSION CATHODES DURING THE TAKE-OFF OF THE EMISSION CURRENT

The experimental investigation is performed in three stages. Initially, each sample is investigated using the scanning electron microscope (SEM). Then, the electrical measurements are performed, during which the emission current is taken-off from cathodes for various time intervals. After the take-off of the emission current, the samples of the cathodes are repeatedly investigated using the SEM, and the variation in their geometric parameters is fixed.

The emission currents are measured in the diode configuration. Special accessories were fabricated for this purpose. A metal anode plate is brought to immobile the fastened crystal with a cathode using a micrometer screw. The distance between the cathode and anode ranges from 0.3 to 0.5 mm. The accessory with the sample is placed into a vacuum chamber providing a technical vacuum with the residual gas pressure down to 10^{-6} mmHg during continuous pumping. The threshold anode voltage, at which the emission current began to be detected, is about 1.5×10^3 V. The electric voltage strength at the cathode point reaches 5×10^7 V/cm at this voltage. The minimal experimentally detected current is 10^{-8} A. The maximal observed current from a single cathode reached 15×10^{-6} A, which corresponds to the current density from the cathode point of about 10^7 A/cm^2. The dependence of the current on the anode voltage has a typical exponential character in this case. Stable emission for several hours is observed for the current at a level of 10^{-6} A. The amplitude of fluctuation oscillations of the current does not exceed 3×10^{-8} A in this case.

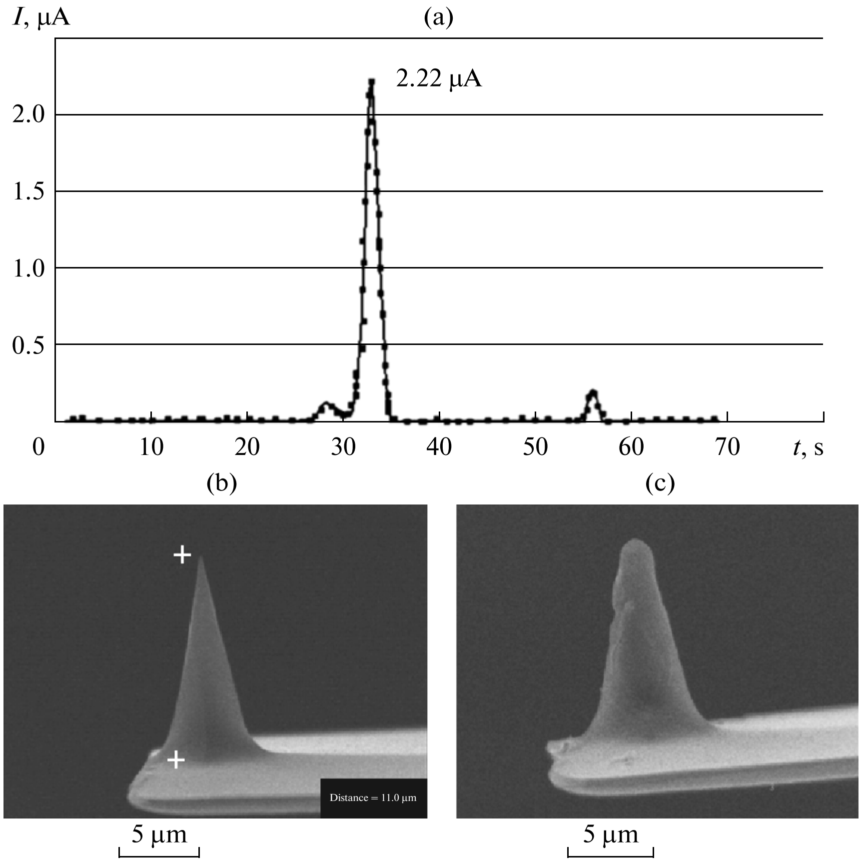

Fig. 1. Influence of the short-term current take-off on the degradation of the field-emission cathode. (a) The time dependence of the emission current of the cathode, (b) the SEM image of the cathode before the take-off of the emission current, and (c) SEM image of the cathode after the take-off of the emission current.

We investigated the influence of the average level of the taken-off current and the duration of its take-off on the character of the degradation of the field-emission cathode. We investigated more than 100 samples of field-emission cathodes. In these experiments, the average level of the emission current varied from 5×10^{-7} to 1.5×10^{-5} A, while the operation time of the cathode varied from 1 s to 8 h. Figure 1 illustrates the influence of the short-term take-off of the emission current on the field-emission cathode. The pulse duration, which was evaluated by the rise and decay fronts of the current, is about 3 s. The peak value of the current strength in the pulse is 2.2 μA. Figure 2 shows the results of the prolonged take-off of the emission current of various levels for three experimental samples of field-emission cathodes.

Repeated investigations of experimental samples using the SEM (Figs. 1, 2) revealed the degradation of the emitter and reconstruction of its geometry caused by the partial melting of the cathode in all the cases; however, the character of thermal degradation was different for various take-off modes of the current.

It is established that the level of the taken-off emission current affects the variation in the cathode shape. Figure 3 shows the SEM images of cathodes after the take-off of the current of 0.5 and 3 μA. In the first case (Fig. 3a), the melt zone is accumulated in the upper part of the emitter but does not touch the cathode point, which retained the starting geometric parameters. In the second case (Fig. 3b), the top of the cathode is completely melted. The localization of the melted zone without output to the top of the emitter was observed in most experiments at an emission current weaker than 1 μA.

We found no pronounced dependence of the degree of degradation on the duration of cathode operation. Thus, the described degradation occurs shortly (within 1 s) after the beginning of the field electron emission.

NUMERICAL MODELING OF THE HEATING OF THE NANODIMENSIONAL POINT AS A TWO-PHASE SYSTEM

The most complete and correct description of the kinetics of heating of the solid point field-emission cathode is given in [2], where it is shown that the temperature maximum has the time to shift into the emitter depth for the time of the development of the ther-

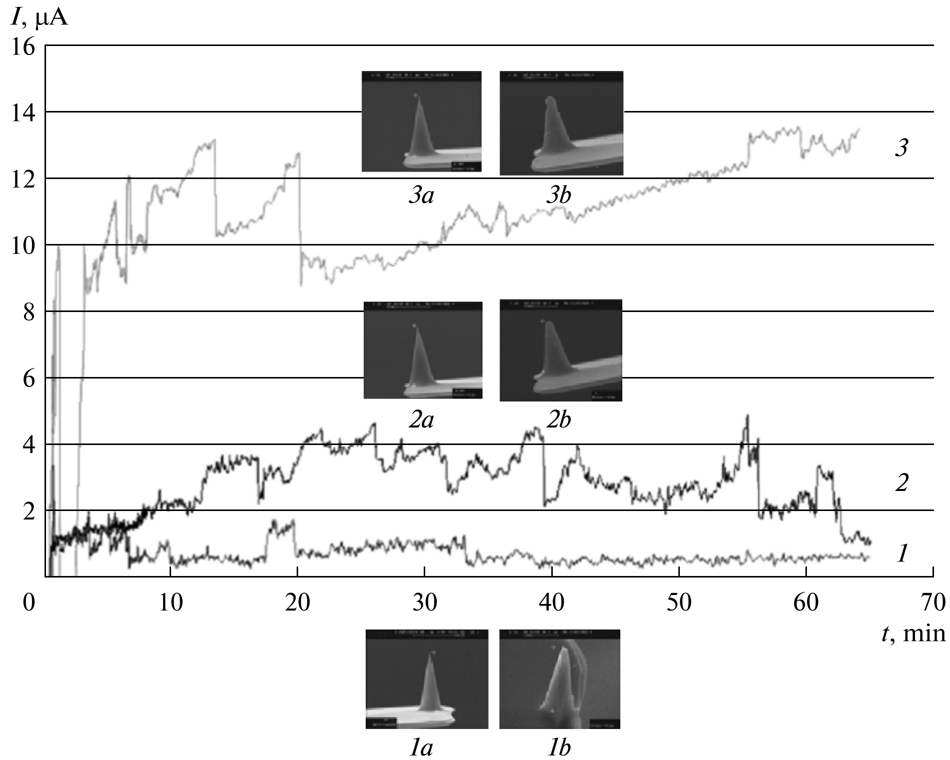

Fig. 2. Influence of the level of the current taken-off on the degradation of the field-emission cathodes. (*1*, *2*, *3*) Time dependences of the emission current of the cathode, (*1a*, *2a*, *3a*) SEM images of cathodes before the take-off of the emission current, and (*1b*, *2b*, *3b*) SEM images of cathodes after the take-off of the emission current.

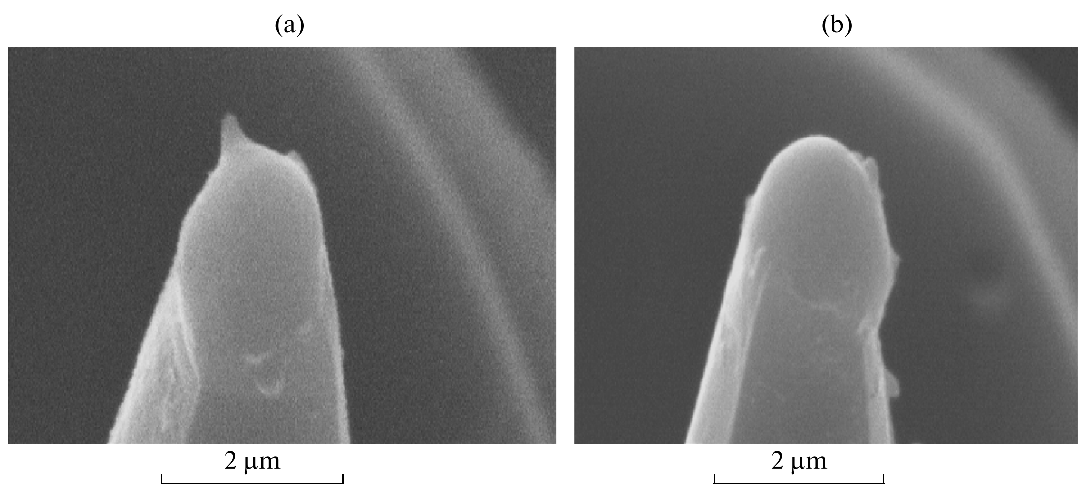

Fig. 3. SEM images of two cathodes after the take-off of the current of different levels. (a) 0.5 μA and (b) 3 μA.

mal instability (units nanoseconds). In this case, the cathode material can actually start in its depth at a certain distance from the top.

Starting from the results presented in [2] and the described experimental investigation, let us perform the numerical modeling of the heat dynamics of a single field-emission cathode as a two-phase system assuming that the segment with a liquid phase had already formed in the cathode bulk and is localized at a certain distance from the top in the initial instant.

For the qualitative evaluation of the processes occurring in the cathode with the formation of solid and liquid phases during heating with the emission current, the phase field model suggested by Caginalp is used [3, 4]. When implementing the numerical computations, a two-dimensional model is used, in which

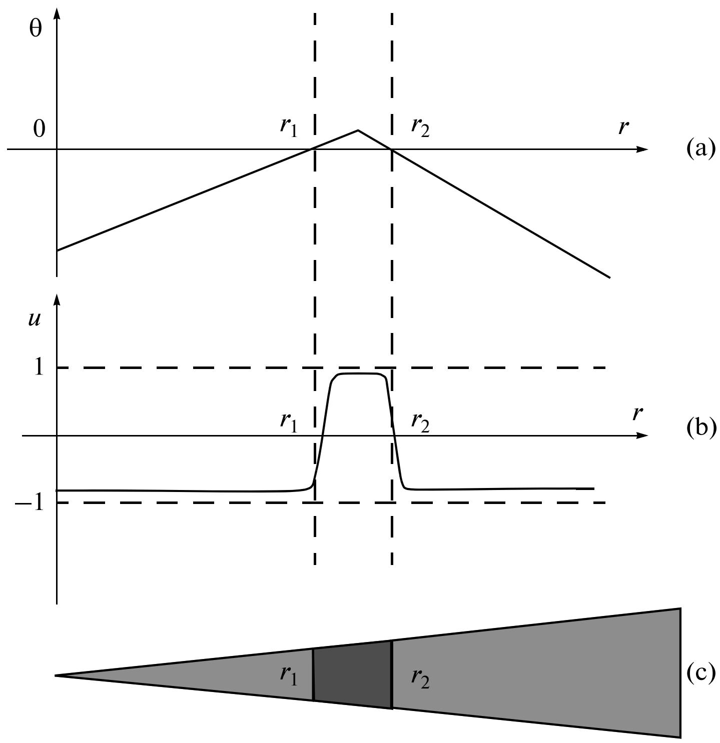

Fig. 4. Initial conditions for the problem of numerical modeling of heat processes in a two-phase field-emission cathode. (a) Function θ, (b) function u, and (c) scheme of localization of the liquid and solid phases in the field-emission cathode.

the cathode is a plane cone with the top in the origin of the coordinates. In connection with this, let us pass to polar coordinates. In this case, the set of equations of the phase field takes the following form:

$$\frac{\partial\theta}{\partial t} - k\Delta\theta = -\frac{l}{2}\frac{\partial u}{\partial t} + I^2R, \quad (1)$$

$$\alpha\frac{\partial u}{\partial t} - K\Delta u = \frac{1}{\varepsilon}(u - u^3) + K\theta(1 - u^2), \quad (2)$$

$$\Delta = \frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial}{\partial r}\right) + \frac{1}{r^2}\frac{\partial^2}{\partial\varphi},$$

where $\theta = (T - T_0)$ is the temperature of the cathode material relative to melting point T_0, r is the polar radius, φ is the polar angle, u is the order function [4], l is the latent heat of melting, α is the relaxation time, k is the thermal diffusivity, K is the surface tension, ε is the small parameter of the system, I is the total field-emission current of the cathode, $R = \rho/r$ is the ohmic resistance of the cathode material, and ρ is the resistivity of the cathode material.

In the suggested model, due to the small sizes of the computational region, we can neglect the temperature dependence of thermal diffusivity and resistivity of silicon and accept $k = \text{const}$ and $\rho = \text{const}$.

Order function u asymptotically tends to the value of −1 on the right for the liquid-phase region and to the value of 1 on the left for the solid-phase region. In this case, the substance transfer from the solid phase into the liquid phase occurs on the segment with length ε. As the initial data for u, we consider the following function [5, 6]:

$$u\big|_{t=0} = \frac{1}{2}\left[1 + \tanh\left(\frac{r_1 - r}{\varepsilon}\right) + \tanh\left(\frac{r - r_2}{\varepsilon}\right) - \tanh\left(\frac{r_1 - r}{\varepsilon}\right)\tanh\left(\frac{r - r_2}{\varepsilon}\right)\right],$$

where $r = r_1$ and $r = r_2$ specify the location of the phase interface.

The initial data for temperature are selected in the following form:

$$\begin{cases} \theta = (a_1 r - b_1), \ r \in \left(0; \dfrac{R_{\max}}{2}\right); \\ \theta = (-a_2 r + b_2), \ r \in \left(\dfrac{R_{\max}}{2}; R_{\max}\right], \end{cases}$$

where a_1, a_2, b_1, and b_2 are certain positive constants.

The selected initial data correspond to the case when the liquid phase already localized in the cone region between the section by radii r_1 and r_2 in the initial instant (Fig. 4). This selection of the initial conditions is governed by experimental observations, which point to the fact that the thermal mode in the field-emission cathode is established shortly after the beginning of emission. Therefore, the mechanism of the

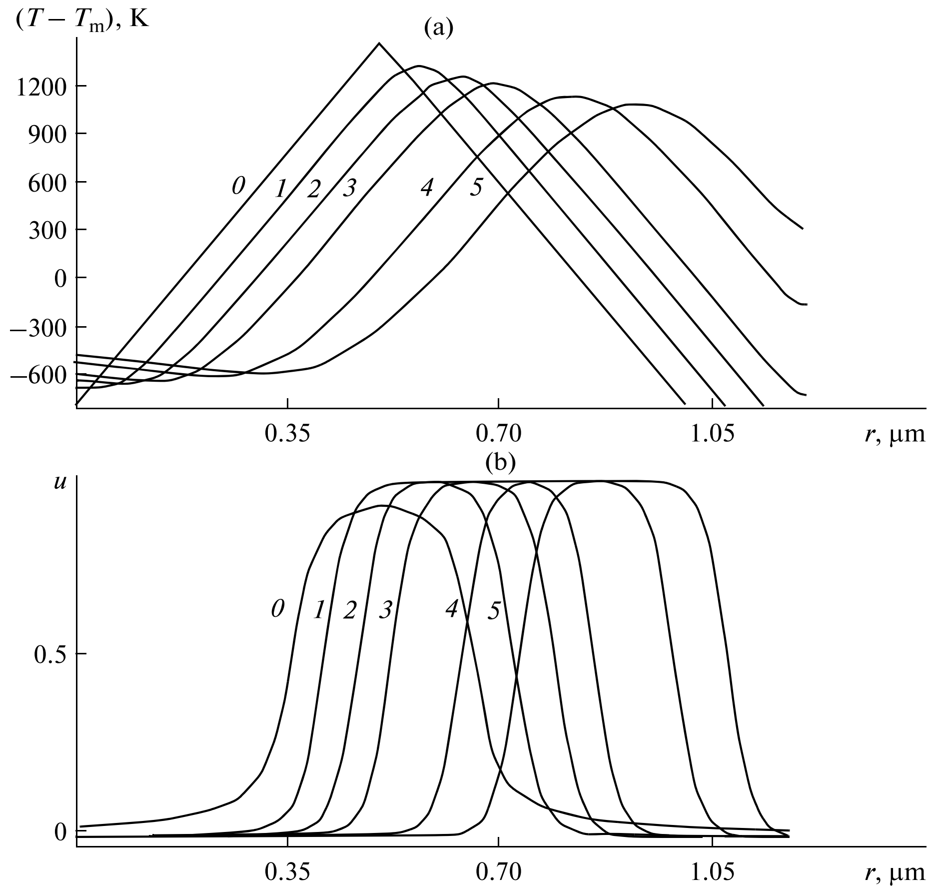

Fig. 5. Parametric family of (a) computed dependences of temperature and (b) the order function on the step number by *r*. Curve *0* corresponds to initial conditions, and curves *1–5* follow in the order of time increase (from the initial to the final).

formation of the liquid phase, which is described in detail in [2], is excluded from consideration, and we focus our attention on the further development of the temperature dynamics in time.

Heating of the cathode due to the Joule effect is taken into account using the introduction of the corresponding heat source into the right side of equation of heat conductivity (1). The Neumann condition is considered for function θ as the boundary condition to set (1) and (2) at the external boundary of the cone. The physical sense of this condition lies in the fact that the heat flow across the outer surface of the emitter operating in a vacuum is absent. As the difference scheme, when performing the numerical modeling, we use the two-dimensional analog of the longitudinal–transverse scheme in polar coordinates [7].

The parametric family of computed dependences of the temperature and order function on the step number by *r* (the radius of the cone section) is presented in Fig. 5. The analysis of these dependences shows that the region of the liquid phase, which is localized in the initial instant, is shifted with time towards larger radii, i.e., into the cathode depth. This fact can be governed by accounting for the surface tension on the curvilinear phase interface in the suggested physicomathematical model. In the geometric problem under consideration, notably in the cone, the surface tension prevents the motion of the phase front in the direction of decreasing the surface curvature, the minimal value of which is attained at the top. However, irrespective of the direction of the motion of the phase fronts, the temperature of the cathode top increases with time (Fig. 5). The rate at which the temperature of the top rises depends directly on current *I* and is caused by the Joule's heating.

As a result of the experimental investigation, in the process of the transfer of the emission current, the presence of a liquid phase in the cathode body (melting of the cathode by the conductivity current) is established. In addition, in a number of cases, the melt zone is localized and does not escape onto the top of the cathode In connection with this, the theoretical illustration of the experimentally observed effect of location of the melt in the middle part of the cathode is of greatest interest.

The results of the numerical modeling clearly indicate the action of two effects: (i) the surface tension at the phase interface prevents the escape of the phase front onto the top of the emitter, as a result of which, the melt region and temperature maximum shift into the cathode depth over time, and (ii) the heating of the cathode by the conductivity current flowing across it leads to increasing the temperature of the top. These facts are in good agreement with the experimental observations, according to which the top of the cathode is not subjected to plastic deformations with the take-off of currents lighter than 1 μA and melts at heavier currents. We note that when we stated the problem of numerical modeling, we had not taken into account the Nottingham effect [8] and other surface and bulk sources. However, accounting for only the effect of the surface tension at the boundary of the liquid phase with the mentioned geometry gives a result, which agrees well with experimental observations. The numerical experiment allows us to elaborate the mathematically substantiated recommendations on the optimization of base designs and the fabrication technology of emitters, cathode units, and electrooptical systems.

The results acquired in this study allow us to interpret the degradation processes of the field-emission cathode. In particular, the problem of selecting the optimal cathode configuration from the viewpoint of minimizing heating is reduced to the provision of the best heat removal from the middle and base of the autoelectronic emitter.

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