An impact of thermal electron energy on the field-electron emission from nanosized silicon tips

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***Abstract*— Thermal effects associated with the thermal energy of electrons play an important role in the process of field emission from a nanoscale silicon tip. To estimate the contribution of these effects, a self-consistent numerical calculation of the temperature of the semiconductor emitter, heated by the field-emission current, was carried out. It was experimentally obtained that the melting of the silicon field emitter occurs at currents less than 1 μA, for which the calculated temperature of the silicon tip varies only up to 420 K and does not exceed the melting point of Si. For this reason, we suppose that this effect can be caused by the sputtering of the anode material by hot field-emitted electrons that collect a high power density (~300 W/cm^2 at 1 μA) on the anode surface. It also can lead to the possible generation of self-sustained plasma in the space gap between anode and cathode. The considered thermal phenomena should be taken into account during the development and predictive modelling of vacuum nanoelectronic devices.**

Keywords—field-electron emission; nanoscale emitter; thermal effects; thermal degradation; emission current; vacuum nanoelectronics

I. Introduction

Nowadays, there is an increasing interest in the field of vacuum nanoelectronics, which is due to the current prospects for the technological realization of vacuum devices with a nanoscale vacuum channel based on field-electron emission [1]. These prospects are mainly attributed to the ability of vacuum nanodevices to operate at extremely high frequencies in harsh conditions, which is a challenge for modern solid-state devices that limits their performance. In this work we investigated the field-emission characteristics of silicon cathodes with a nanosized tip. It was found that the experimental values of the emission current noticeably differ from those theoretically calculated within the framework of the Fowler-Nordheim theory [2]. It is assumed that this difference can be due to ballistic thermal effects associated with an increase in thermal energy of the emitted electrons as a result of the partial penetration of the electric field into the near-surface region of the cathode, which contributes to the detected emission current. The need to take into account the thermal effects discussed above in the description of the field-electron emission is confirmed by the results of our experimental studies of the field emission from nanosized silicon tips, where thermal degradation of the cathode, accompanied by melting of the cathode emission region and the appearance of microdroplets on its surface, was observed at field-emission currents of less than 1 μA (Fig. 1).

To verify these assumptions, we developed self-consistent three-dimensional model that describes the field emission from silicon nanotips, taking into account the thermal phenomena associated with the penetration of an electric field into semiconductor. This, in turn, may lead to the changing the shape of the tip and provide an additional effect on the field-emission current, which is considered in this paper.

II. Theory and Computational Methods

A. *Electric field penetration into the silicon field emitter at nanoscale*

According to the Tsong's model [3], the electric potential $V_S(x,y,z) = -\varphi_S(x,y,z)/e$ responsible for the local band bending in the n-type (p-type) silicon field emitter due to the penetration of the electric field E_{vac} from vacuum into the near-surface layer of the semiconductor can be calculated by solving the Poisson equation in spherical coordinates:

$$\frac{d^2\eta_\varphi}{dr_\delta^2} + \frac{2}{r_\delta}\frac{d\eta_\varphi}{dr_\delta} = f\left(\eta_\varphi, N_a, N_d\right), \tag{1}$$

where φ_S is the potential energy of the electron, $\eta_\varphi = \varphi_S / k_B T$, $r_\delta = r/\delta$, $r = \sqrt{x^2+y^2+z^2}$ is the point's distance from the origin inside the field emitter, $N_{d(a)}$ is the donor (acceptor) concentration, $\delta = \left(\varsigma\varepsilon_0 k_B T_C / 2n_i e^2\right)^{1/2}$ is the Debye screening length of the semiconductor, ς is the dielectric constant of the semiconductor, ε_0 is the vacuum permittivity, k_B is the Boltzmann constant, T_C is the temperature of the emitter, e is the electron charge, n_i is the intrinsic carrier concentration in the semiconductor at given temperature. In the case of the fully ionized impurities, the function $f\left(\eta_\varphi, N_a, N_d\right)$ on the right side of (1) is determined by the simple expression:

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$$f\left(\eta_\varphi, N_a, N_d\right) = \frac{\Phi\left(\eta_\varphi^B, \eta_\varphi, \eta_\varepsilon^F, \eta_\varepsilon^v, \eta_\varepsilon^c\right) - 2\sinh\left(\eta_\varphi^B\right)}{2}, \quad (2)$$

where $\eta_\varepsilon^F = \varepsilon_F / k_B T_C$, $\eta_\varepsilon^{c(v)} = \varepsilon_{c(v)} / k_B T_C$, $\eta_\varphi^B = \sinh^{-1}\left(\left(N_a - N_d\right)/2n_i\right) = \varphi_B / k_B T_C$, $\varphi_B = \varepsilon_{Fi} - \varepsilon_F$, ε_{Fi} is the intrinsic Fermi level, ε_F is the Fermi level, $\varepsilon_{c(v)}$ is the bottom (top) of the (valence) conduction band, $\Phi = \Phi\left(\eta_\varphi^B, \eta_\varphi, \eta_\varphi^F, \eta_\varphi^v, \eta_\varphi^c\right)$ is the function determined through the half-order Fermi-Dirac integrals. To solve (1) numerically, we use the boundary condition in the bulk $d\eta_\varphi / dr_\delta\left(r_\delta \to -\infty\right) = 0$.

B. Thermal heating of a silicon tip by the field-emission current

In turn, the temperature of the silicon tip mainly due to the Joule heating by the field-emission current can be calculated from the self-consistent heat conduction equation:

$$\rho C_p\left(T\right)\frac{\partial T}{\partial t} - \nabla\cdot\left(\kappa \nabla T_C\right) = \rho_\varphi\left(E_{vac}\right) J_e^2\left(E_{vac}\right), \quad (3)$$

where ρ, κ are the volumetric mass density and the thermal conductivity of emitter material, $C_p\left(T_C\right)$ is the heat capacity of emitter material at constant pressure, $\rho_\varphi = \left(e\mu_T n_\varphi\right)$ is the resistivity of emitter material, $\mu_T = \mu_T\left(T_C, N_{a(d)}\right)$ is the carrier mobility, $n_\varphi = N_{d(a)} \exp\left(-\eta_\varphi\right)$ is the equilibrium carrier concentration for n-type (p-type) semiconductor [4], where $\eta_\varphi = \eta_\varphi\left(E_{vac}\right)$ is calculated from (1), and $J_e = J_e\left(\eta_\varphi\right)$ is the field-emission current density, which can be obtained from the quantum-mechanical calculations.

III. Results and Conclusion

The significant change in the shape of the silicon cathode during the field-emission from a nanometer silicon tip was experimentally observed, which is clearly seen in Fig. 1, where SEM images of the emitter are presented at the moments when the field-emission current was switched on and switched off.

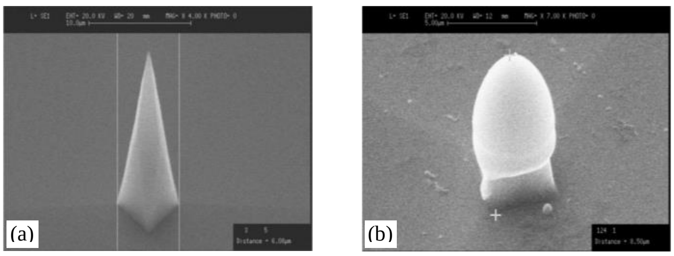

Fig. 1. SEM images of the Si cathode (a) before and (b) after field emission.

This process was accompanied by the melting of the silicon cathode (a decrease in the cathode height from 15 μm to 8 μm) with the appearance of microdroplets on its surface at currents less than 1 μA, which can be caused by thermal effects occurring during the electron emission. However, the results of numerical simulation of thermal heating of the silicon cathode confirm that the melting point for Si (1687 K) is not reached at these currents, when the cathode-anode distance is equal to 10 μm (Fig. 2a). At the same time, the significant power densities are achieved at the anode surface, taking into account the variation in the spot size area at different emission currents, as it is demonstrated in Fig. 2b. This feature can lead to the sputtering of anode surface by hot emitted electrons, which, in turn, induces the flow of high-energy ionized anode particles towards the emitter surface as an additional heat source. The threshold of emission current, providing the transition from field emission to self-sustained plasma generation in the microscale electrode gap [5], was also observed in our experiment, which can be caused by the anode sputtering.

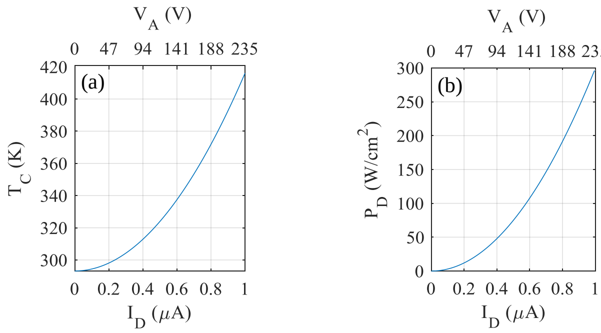

Fig. 2. (a) The maximum temperature of the silicon emitter and (b) the power density P_D of an electron beam incident on the anode surface versus the field-emission current I_D (anode voltage V_A).

Such thermal effects may play crucial role in the explanation of the experimental data of the emission current beyond Fowler-Nordheim theory [6] and can be taken into account for a detailed description of field-electron emission from nanoscale emitters, which opens the way towards predictive modeling of vacuum nanoelectronic devices.

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