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Modification of the cathode material around the explosive electron emission centers in the spark stage of vacuum breakdown

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On the basis of numerical calculations estimates for the fields of mechanical stresses around the explosive electron emission centers of the cathode during the development of pulsed vacuum breakdown are given. Expansion of material due to conduction loss was taken into account. It is shown that the sizes of regions with broken crystalline structure is much larger than the corresponding of explosive emission centers.

Keywords: vacuum breakdown, explosive electron emission, mechanical stresses.

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It is known that vacuum breakdown goes through a spark stage that involves the emergence of explosive electron emission centers (EEECs) on the cathode surface [1]. Each elementary EEEC is associated with a local erosion region (a microscopic crater and an expanding plasma cloud formed by the material ejected from this crater). When the size of a growing a crater reaches a level of several tenths of a micrometer or several micrometers, further melting and evaporation of metal is difficult. Therefore, the spark stage of vacuum breakdown may be sustained only under the condition of nucleation of daughter EEECs near parent centers [1]. Crater erosion of the cathode is not the only effect induced by a vacuum spark. Modified material zones, which are hidden from direct observation and are not related to material melting, develop around craters and affect the probability of emergence of new EEECs under the influence of subsequent breakdown pulses [2,3].

In the work [4] have examined cathode crater erosion of single-crystalline copper after vacuum-gap breakdown (anode was made of tungsten and tantalum) by a triangular 200 kV voltage pulse with a rise time of 20 ns and a fall time of 10 ns. With this short-pulse breakdown interrupted at the start of the spark stage, several compact clusters of craters with a size on the order of several micrometers and several individual craters several tenths of a micrometer in size formed on the single-crystalline copper cathode surface. Modified material zones, which were identified by selective electrochemical etching, turned out to be significantly larger than the corresponding marks of crater erosion. It was hypothesized that the cathode material is modified by thermomechanical stresses developing in the vicinity of EEECs.

In the present study, the dynamic equation of an isotropic elastic medium in an axially symmetric approximation with respect to a cylindrical coordinate system $\{r, z\}$ is used to estimate the mechanical stress σ fields in the near-surface volume of a copper cathode heated by a pulsed current flowing through a EEEC. It was assumed initially that the heating zone is much smaller in scale than the critical stress zone. Accordingly, temperature dependences of the elasticity modulus and the Poisson ratio were neglected, and their values corresponded to initial temperature $T = 293$ K. In contrast, the temperature dependence of resistivity of copper was taken into account. The entire computational domain was a cylinder with its radius and height being equal to 0.2 mm. The upper base of this cylinder ($z = 0.2$ mm) was assumed to be fixed, thermally stabilized at $T = 293$ K, and grounded; the remaining part of the computational domain surface was free, thermally insulated, and under „floating potential“, which depended on the geometry of current spreading in the material. Estimates and trial calculations demonstrated that radiation heat losses have

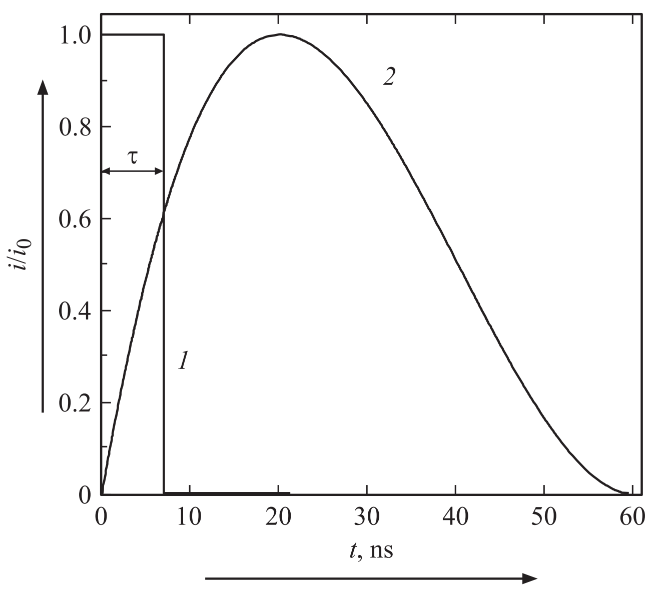

Figure 1. Shapes of current pulses, which are normalized to amplitude values i_0, in modeling of an individual EEEC (*1*) and an EEEC cluster (*2*).

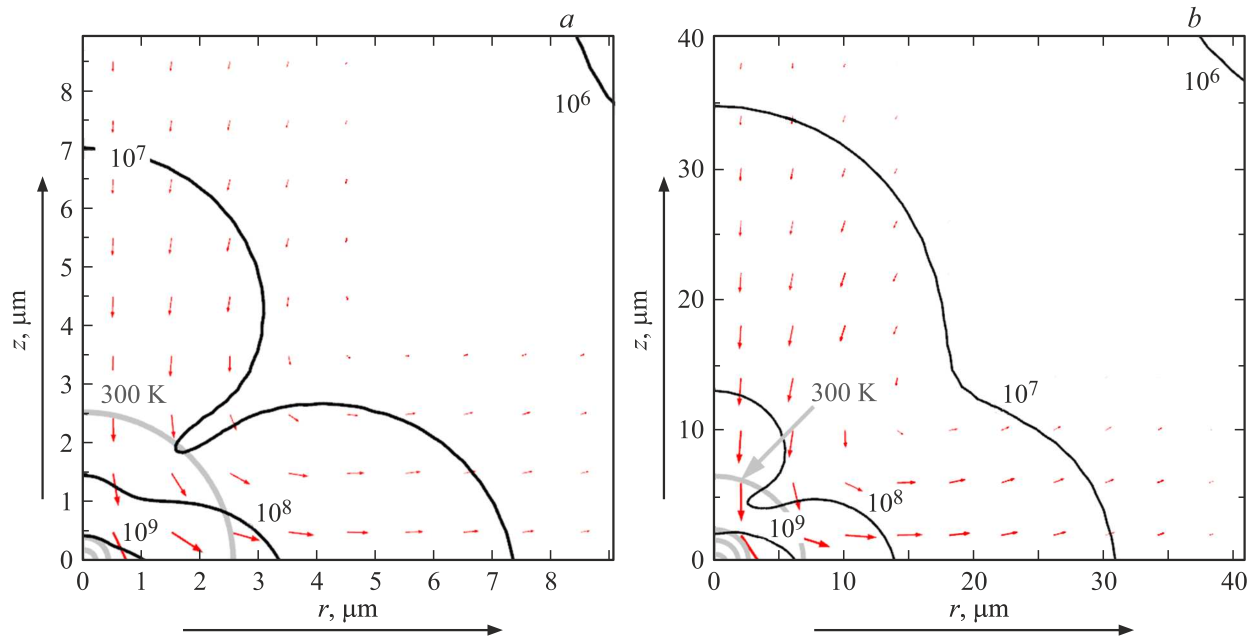

Figure 2. Calculated effective mechanical stress (black isolines annotated in Pa) and temperature (gray isotherms; 300, 1376, 2836, and 8000 K) fields for an individual EEEC at $t = 7$ ns (a) and an EEEC cluster at $t = 40$ ns (b). Arrows denote the strain vector directions.

almost no effect on the results. It was assumed that current enters the metal around the center of the lower base ($r = 0$, $z = 0$) uniformly in a circle with radius $R \sim 0.1-1\,\mu$m („current spot").

It was assumed in modeling of an individual EEEC that current i persists within $t = \tau = 5-10$ ns, which corresponds in the order of magnitude to the EEEC lifetime [1] (Fig. 1, curve *1*). When the evolution of a single EEEC cluster was modeled, it was assumed that the time dependence of current $i(t)$ corresponds in shape to the current waveform measured in vacuum-gap breakdown by a triangular pulse (Fig. 1, curve *2*). I.e. it was believed that the total current is at all times divided proportionally between EEEC clusters.

Trial calculation runs were performed first. The amplitude of current density j_0 increased from one run to the other as long as the maximum temperature reached the critical temperature of copper at any time point. When the temperatures had become equal at a certain point, the obtained result was considered to be the final one.

Figure 2, a presents the results of calculation of the effective mechanical stress field at the end of the action of an individual EEEC with parameters $R = 0.1\,\mu$m, $j_0 = 4.7 \cdot 10^{13}$ A/m^2 (current amplitude $i_0 = 1.48$ A), and $\tau = 7$ ns on the radial-axial section plane. Von Mises averaging was used in plotting the stress field:

$$\sigma_M = \Big\{\big[(\sigma_{xx} - \sigma_{yy})^2 + (\sigma_{yy} - \sigma_{zz})^2 + (\sigma_{xx} - \sigma_{zz})^2 + 6(\sigma_{xy}^2 + \sigma_{yz}^2 + \sigma_{zx}^2)\big]/2\Big\}^{1/2},$$

where σ_{ij} are components of the stress tensor. The length of arrows corresponds to an arbitrary logarithmic strain vector scale. Certain isotherms are shown in gray. The outer isotherm corresponds to a temperature of 300 K (7 K above the initial temperature), while inner isotherms represent melting (1376 K) and boiling (2836 K) temperatures [5].

Let us assume in our estimation that plastic strain occures in a region with stress $\sigma_M \geqslant 10^8$ Pa (the yield point for pure annealed copper is $7 \cdot 10^7$ Pa [5]). It can be seen from Fig. 2 that the radius of the contour of this region on the electrode surface ($z = 0$) is an order of magnitude greater than the radius of the melt zone, and the contour itself is located at near-room temperatures. When the current is interrupted, the temperature at the current spot drops sharply. At the same time, provisional yield boundary $\sigma_M = 10^8$ Pa continues to expand within 1 ns due to the redistribution of strain in wave processes and reaches a radius of $3.3\,\mu$m. Stresses above 10^8 Pa on the cathode surface vanish at $t = \theta = 12$ ns (the provisional moment of stress relief).

Figure 2, b presents the results of calculation for an EEEC cluster at $R = 1\,\mu$m, $j_0 = 7.5 \cdot 10^{12}$ A/m^2 (current amplitude $i_0 = 23$ A), and a time of 40 ns, which corresponds to the maximum temperature of the material. Isotherms corresponds to the temperatures indicated above. The 8000 K isotherm of the critical temperature of copper is also shown. The radius of the plastic strain zone on the cathode surface is stabilized at $12-15\,\mu$m; it starts to contract 100 ns after the onset of a current pulse. The provisional moment of stress relief on surface $z = 0$ is at $\theta \approx 170$ ns.

Thus, the obtained calculated data confirm the earlier estimates of current density in EEECs ($\sim 10^{12}-10^{13}$ A/m^2 [1])

and demonstrate that the cathode material is subjected to breaking stresses in the non-heated region, which is much larger in size than an EEEC. Since these stresses correspond to EEEC plasma pressure levels $10^8 - 10^9$ Pa [1], they should affect both the dynamics of evolution of an individual EEEC and the spread of explosive emission activity along the cathode surface at the spark stage of breakdown. It has been observed directly in experiments that mechanical phenomena at the cathode (propagation of sound, plasticity, cracks) may become the key factors governing the vacuum spark development in rigid single-crystalline materials, such as doped silicon [6].

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Conflict of interest

The authors declare that they have no conflict of interest.

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