Breakdown of vacuum electical insulation

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During the emission of electrons in a high current density ($j_e \gtrsim 4\times 10^6$ A/cm^2), the surface of the tip of a tungsten microcrystal becomes unstable and becomes an effective emitter of neutral atoms. The time required for the field ionization of an atom after desorption from the surface of a microcrystal is calculated. The results are used to develop some new ideas regarding the physical mechanism for the breakdown of vacuum electrical insulation.

The breakdown of vacuum insulation ("vacuum breakdown" for short) develops over a time $\lesssim 10^{-7}$ s, as soon as the potential difference across the electrodes exceeds a certain characteristic value for the given conditions.[1] This characteristic value is called the "breakdown voltage" V_b. During vacuum breakdown, a high-conductivity plasma channel forms in the vacuum gap, but the mechanism for the production of this plasma during vacuum breakdown remains unclear.[1,2]

Research on the plasma of vacuum breakdown has revealed the following:[1,3] (1) During vacuum breakdown, dense plasma formations appear locally at regions on the macroscopic surface of the cathode ("cathode bursts") and the anode ("anode bursts"). (2) A cathode burst forms first. Then, after a delay on the order of $\tau \sim 10^{-8}$ s, an anode burst appears opposite the cathode burst. (3) The average ion energy $\overline{E}_i$ in the plasma of a cathode burst is $\simeq$(3–5) eV and satisfies $\overline{E}_i \simeq \overline{E}_e$, where $\overline{E}_e$ is the

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average electron energy. (4) The velocity (v_k) at which the front of the cathode burst propagates depends on the cathode material and has values $v_k \simeq (1\text{–}3) \times 10^6$ cm/s.

Direct experiments[4,5] have also established that vacuum breakdown is initiated by distinct microscopic irregularities on the macroscopic surface of the cathode. These irregularities are microcrystals (whiskers) with a height on the order of a few microns. The prebreakdown emission current from the cathode surface can be approximated well as a function of the voltage V ($V < V_b$) by the Fowler–Nordheim equation.[1]

It thus follows from the results presented above that the most likely reasons for the initiation of vacuum breakdown (for the formation of a cathode burst) are processes occurring at the tip of a microcrystal and at the vacuum boundary of the microcrystal during intense electron emission. One such process is the heating of the tip of the microcrystal by the current of thermofield emission[6] as the result of Joule and Nottingham heat evolution.

To evalute the temperature (T_s) at the tip of the microcrystal, we solved a steady-state one-dimensional heat-conduction equation incorporating (for the first time) a factor reflecting the nonlocal nature of the scattering of hot holes. In a spherical coordinate system, for a conical model of a microcrystal, this equation is

$$\frac{d^2T}{d\rho^2} + \frac{2}{\rho}\frac{dT}{d\rho} + \frac{I\epsilon \exp\left[-\frac{(\rho-\rho_s-L)^2}{2D^2}\right]}{\sqrt{2}\pi^{3/2}e\kappa D \mathrm{tg}^2\alpha\rho^2} + \frac{I^2}{\pi^2 \mathrm{tg}^4\alpha\kappa\sigma\rho^4} = 0, \tag{1}$$

where I is the emission current, ϵ is the average energy transferred to the lattice of the microcrystal during the emission of one electron,[6] α is the vertex half-angle of the cone at the tip of the microcrystal, $\rho_s \equiv r_s/\tan\alpha$, r_s is the radius of the tip of the microcrystal, e is the charge of a proton, L is a characteristic average relaxation length for the energy of a hot hole, D^2 is a measure of the dispersion of L, κ is the thermal conductivity, and σ is the electrical conductivity. The boundary conditions on (1) are

$$T|_\infty = T_0, \quad \frac{dT}{d\rho}|_{\rho_s} = C, \tag{2}$$

where T_0 is the temperature at the base of the microcrystal, and C is a constant for a given value of I and a given value of the field (F_s) at the tip of the microcrystal.

Assuming that the maximum value of $T(\rho)$ corresponds to the point $\rho \simeq \rho_s + L$, and ignoring the T dependence of κ and σ, we find

$$C \simeq \frac{j_e\epsilon}{2e\kappa}\beta + \frac{j_e^2 L}{\kappa\sigma}, \tag{3}$$

$$T_s \simeq T_0 + \frac{j_e\epsilon\rho_s}{2e\kappa}\left(1 + 2\beta\frac{L}{\rho_s}\right) + \frac{j_e^2\rho_s^2}{2\kappa\sigma}, \tag{4}$$

where $\beta \equiv \mathrm{erf}(L/\sqrt{2D})$ and $j_e = I/\pi\rho_s^2\tan^2\alpha$. Imposing the condition that the flux of thermal energy is dissipated at the surface of the tip of the microcrystal with $T_s = \text{const}$, we find

$$\kappa C \simeq \Lambda n_s f \exp(-\Lambda/kT_s) + \delta T_s^4 + \frac{n_s Q^2 \nabla T D_s}{kT^2 r_s}, \tag{5}$$

where Λ is the average binding energy that binds an adatom with the surface of microcrystal, n_s is the surface density of adatoms, $f \simeq kT_s/h$ is the vibration frequency of the adatom, k is the Boltzmann constant, h is Planck's constant, δ is the Stefan–Boltzmann constant, Q is the heat of transport,[7] and D_s is the surface self-diffusion coefficient.

Calculations based on expression (4) show that T_s for a tungsten microcrystal with $r_s \gtrsim (0.3\text{–}0.4)$ μm, $T_0 \simeq 300$ K, $\epsilon \simeq 0.3$ eV (Ref. 6), and $\alpha \sim (1.5\text{–}5) \times 10^{-2}$ begins to rise significantly (in comparison with T_0) at $j_e \gtrsim 10^6$ A/cm^2. At values as low as $j_e \simeq 4 \times 10^6$ A/cm^2, its reaches $T_c \gtrsim (2000\text{–}2500)$ K.

It follows from (3)–(5) and the results of Refs. 8–11 that under the conditions $n_s = n_s(T_s)$ and $\Lambda = \Lambda(j_e)$ the right side of (5) is dominated at $j_e \gtrsim 4 \times 10^6$ A/cm^2 by the first term. This first term represents the energy flux carried away from the surface of the microcrystal by the evaporating adatoms. The flux density of evaporating adatoms is equal in order of magnitude of the flux density of emission electrons.

It can thus be concluded on the basis of these calulations that the surface of a microcrystal becomes unstable when the current density of the electron emission is high. At the same time, this surface becomes an effective emitter of neutral atoms.

After an atom is desorbed, after the time required to complete a hop of height[8,9] $h \lesssim 1000$ Å under the influence of the polarization force $\vec{\mathcal{F}} = (\alpha/2)\nabla F^2$ (α is the polarizability of the atom), this atom may be ionized, either by an emitted electron or by the strong electric field. One can show the probability for impact ionization is low in the initial stage of the desorption process, since the relation $\lambda \gg h$ holds, where λ is the mean free path of an electron with respect to impact ionization.

The probability for field ionization over a time t_i is

$$P_i(t_i) = 1 - \exp\left[-\frac{A\omega t_i S}{h} \exp\left(-\frac{2S}{\hbar}\right)\right], \tag{6}$$

where $A \sim 1$ is a dimensionless parameter, ω is the rate at which the electron collides with the potential barrier in the atom ($\omega \gtrsim 10^{16}$ s^{-1}),

$$S = \int_{z_1}^{z_2} \left[2m\left(I^* - \frac{e^2}{z} - ez\bar{F}\right)\right]^{1/2} dz, \tag{7}$$

m is the mass of an electron, I^* is the ionization potential of the atom in the ground or excited state, $\bar{F}$ is the average field at the surface of the tip of the microcrystal, and z_1 and z_2 are the coordinates of the turning points. Carrying out the integration in (7), we find

$$S = \frac{8}{3}\left(\frac{m^2 e^5}{\bar{F}}\right)^{1/4} \xi^{-3/2} \varphi(\xi), \tag{8}$$

where $\xi \equiv [2(e^3\bar{F})^{1/2}]/I^*$, $\varphi(\xi) \equiv (1+\xi)^{1/2}[E(k,\pi/2) - \xi\Phi(k,\pi/2)]$, $k \equiv [(1-\xi)]/(1+\xi)]^{1/2}$, and $\Phi(k,\pi/2)$ and $E(k,\pi/2)$ are the elliptic integrals of the first and second kinds. We note that the numerical values of j_e and T_s at which the surface of the microcrystal loses its stability according to the calculations above correspond[6] to a field $F_s \simeq \bar{F} \gtrsim 0.5$ V/Å. We then find from (6)–(8) that in this field the atoms desorbed in the ground and low-lying excited states (from $^5D_1$ to $^3P_0$; Ref. 12) are ionized with a probability $P \simeq 0.99$ over a time t_i between $\sim 10^{-10}$ s and $\sim 2\times 10^{-13}$ s.

A joint tunneling of electrons from bound states of atoms in the microcrystal and from free atoms desorbed from the surface of the microcrystal—a tunneling into vacuum in a strong electric field—could naturally be labeled "thermofield inization emission."

In a first approximation, the energy (W_i) of the ions bombarding the surface of the microcrystal during thermofield ionization emission, under the condition $V = \text{const}$, is

$$W_i \simeq \frac{1}{2M_i}\left[-\frac{e\hbar\bar{F}\ln(1-P_i)\exp(2S/\hbar)}{A\omega S}\right]^2, \tag{9}$$

where M_i is the mass of an ion. It follows from (7)–(9) that W_i can reach a few kiloelectron volts as the microcrystal is sputtered. During self-sputtering of crystalline targets by ions of these energies (W_i), the energy of the secondary particles (atoms and ions) corresponding to the maximum in the energy distribution is[13,14] $\sim$(2–5) eV, while the energies of the particles from the tail of the distribution function are $\sim 2\times 10^2$ eV (i.e., the velocities are $v \simeq 1.5\times 10^6$ cm/s in the case of tungsten). These characteristics of the secondary particles agree well with the data of Refs. 1 and 3 for an average ion energy $E_i \simeq$ (3–5) eV and for a velocity $v_k \simeq (1\text{–}3)\times 10^6$ cm/s of the expanding cathode burst.

We thus reach the conclusion that the production of the plasma of a cathode burst during the initiation of vacuum breakdown is the result of an instability and a self-sputtering of the surface of the tip of the microcrystal during intense electron emission.

It is also known[3,15] that the production of the plasma of the cathode burst is accompanied by a simultaneous and sharp increase (by a factor of 10^1–10^2) in the emission current (a microdischarge). According to the picture drawn here, a sharp increase in the emission current under the condition $V = \text{const}$ would be evidence that thermofield ionization emission is fundamentally unsteady.[11]

An important point is that the formation of a cathode burst is only a necessary condition—not a sufficient condition—for the occurrence of vacuum breakdown. The reason is that the amount of microcrystal mass which goes into the plasma of the cathode burst is exceedingly small, on the order of $\sim(10^{-10}$–$10^{-11})$g (Ref. 3) or even smaller. The formation of a plasma channel with a high conductivity during the development of vacuum breakdown requires that the plasma enter the vacuum gap as a result of the formation of both a cathode burst and an anode burst. Special experiments[1,16] have shown that an anode burst can form as a result of the electron current

from the surface of a microcrystal on the cathode and also as a result of an intense flux of electrons (or photons) from an external source (of electrons or photons). The minimum electron energy flux density which is dissipated at the anode should be[1] $\sim 2\times 10^7$ W/cm^2.

Taking these results into account, we conclude that the condition for the occurrence of vacuum breakdown as the result of a flux of electrons from a cathode burst is the condition of an electron-stimulated desorption of atoms (and ions) from the anode:

$$\frac{V_b j_A \tau}{n_{SA} r} \geq \Lambda_A. \tag{10}$$

Here j_A is the current density of the thermofield ionization emission at the anode, r is the dimensionless depth to which the electrons penetrate into the anode material, n_{SA} is the density of adatoms in the case of an intense electron flux, and Λ_A is the average binding energy of the adatom with the anode surface. For the typical values $\Lambda_A \simeq 2$ eV, $n_{SA} \sim 4\times 10^{14}$ cm^{-2} and $(V_b j_A)_{\min} \simeq 2.5\times 10^7$ W/cm^2 from (10).

From (10) we also find the known[1] empirical relation $V_b \simeq \text{const}\cdot d^{0.6}$, where d is the distance between the electrodes of the vacuum gap.

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