EXPLOSIVE EMISSION ELECTRONS FROM METALLIC NEEDLES

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Metallic needles are widely used as sources of electron current pulses of 10^3 - 10^5 A. It is customarily assumed that the emission of the electrons from the needles at such currents is due entirely to field emission. Our investigations have shown that the appearance of large electron currents is preceded by an electric explosion of the tip of the needle and the formation of a plasma as a result of resistive heating by the field-emission current. This was first demonstrated with explosions of microscopic needles on the surface of a flat cathode in vacuum as an example [1]. The plasmoids produced thereby were called cathode flares (CF). If the electric field at the tip of a tungsten needle is $E > 1.2 \times 10^8$ V/cm, then the delay of the explosion of the needle is $t_d < 10^{-9}$ sec [2]. The explosions and the spark discharges produce on the tip of the needle microscopic projections, on which the current is increased by approximately one order of magnitude, and $t_d < 10^{-9}$ sec at a tip field $\sim 10^7$ V/cm. In the case of a bulky cathode, the field at the microscopic needle increases by hundreds of times [3], and therefore $t_d \simeq 10^{-9}$ sec for a macroscopic field on the order of 10^6 V/cm [1].

We investigated the phenomena that occur in the case of the electric explosion of a needle located in vacuum at a distance d = 0.05 - 1.0 cm from a flat anode. We used in the experiments square-wave generators with voltage amplitude U_0 = 10 - 500 kV, rise time ∿1 nsec, and internal resistance 60 - 150 ohm. The pulse duration was 5 - 50 nsec and was always shorter than the time delay of the start of the evaporation of the anode [4]. The electron current reached several kiloamperes.

We determined the longitudinal and transverse velocities of the boundary of the electron emission from the CF. For needles of W, Mo, and Cu, both velocities were $v \simeq 2 \times 10^6$ cm/sec, indicating that the CF expands spherically. The same follows also from photographs of the CF glow (Fig. 1), obtained as before [1] with the aid of electron-optical apparatus. Within a time $\sim 10^{-7}$ sec the velocity v remains constant and depends little on the applied voltage.

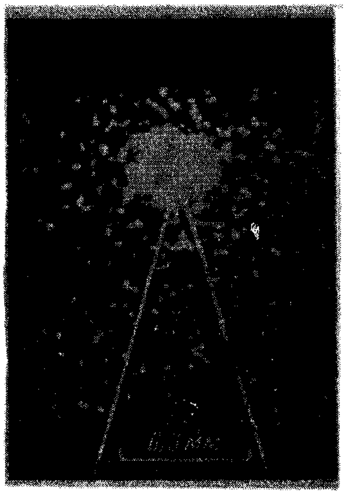

Fig. 1

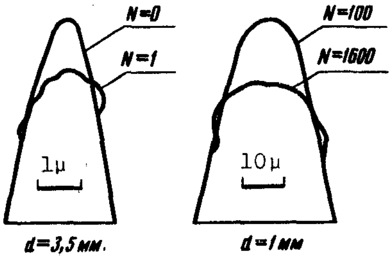

Fig. 2

Fig. 1. Photograph of CF obtained 2 nsec after arrival of the pulse front; exposure duration 3 nsec, U_0 = 35 kV, d = 2 mm.

Fig. 2. Profiles of the tip of a needle after application of N pulses of amplitude U_0 = 30 kV and duration 10 nsec.

We investigated the flow of metal from a molybdenum needle to the CF by photographing the needle in an electron or an optical microscope before and after the application of short pulses. With increasing number N of the pulses, the radius of the needle r increased as a result of metal erosion (Fig. 2). At $r \gtrsim 10\mu$, the amount of metal carried away in one pulse becomes practically constant and almost independent of the needle cone angle. In the range U_0 = 10 - 50 kV and at currents 20 - 100 A, the rate of flow of metal into the CF amounts to $(2 - 3) \times 10^{-3}$ g/sec. Under the same conditions, the electrons are emitted into the CF from a needle area $\sim 10^{-6}$ cm^2, and the average current density is $\bar{j} = (1 - 5) \times 10^7$ A/cm^2. The average concentration of the particles in the plasma within a time from 5 to 20 nsec decreases from $\bar{n} \simeq 10^{17}$ cm^{-3} to $\bar{n} = 5 \times 10^{15}$ cm^{-3}.

According to the measurements, during the time of the pulse the number of electrons carried across the gap is larger by 1 - 3 orders of magnitude than the number of particles in the CF. It can be assumed that the emission of the electrons from the cathode to the plasma is due to field emission induced by the field produced on the plasma boundary as a result of the separation of the charges during their thermal motion:

$$E = \frac{kT_e}{e\ell_D} = 1{,}25 \cdot 10^{-5} \sqrt{nT_e}\,, \qquad (1)$$

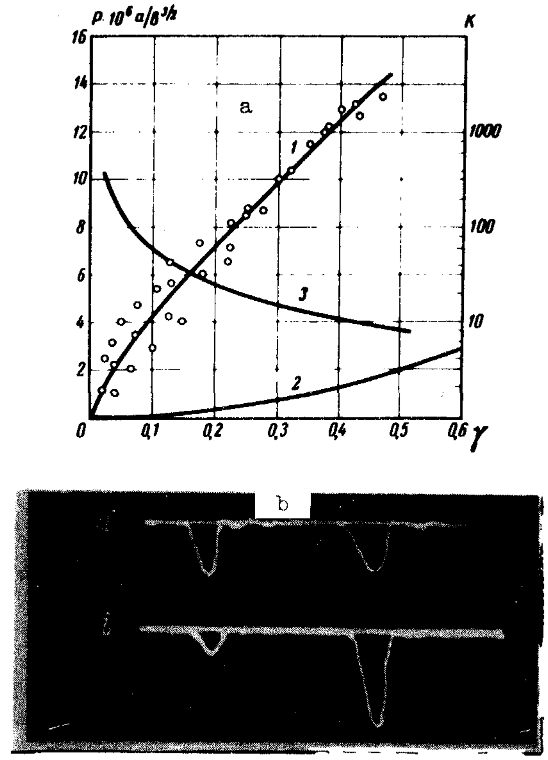

Fig. 3. a) Plot of $P(\gamma)$ obtained under the following experimental conditions: d = 0.1 cm, U_0 = 20 kV; d = 0.2 cm, U_0 = 160 kV; d = 0.4 cm, U_0 = 80 kV; d = 0.6 cm, U_0 = 160 kV, d = 0.2, 0.4, 0.6, 0.8, and 1.0 cm, U_0 = 240 and 300 kV.

where T_e is the electron temperature in deg K, ℓ_D is the Debye screening radius, n the particle concentration in cm^{-3}. When $\bar{j} = (1 - 5) \times 10^7$ A/cm^2, the electric field at the cathode, according to the field-emission equation, should be $(6 - 6.8) \times 10^7$ V/cm for molybdenum. The electron temperature in the CF plasma is $T_e \simeq 5 \times 10^4$ °K [4]. According to (1), the plasma concentration in the immediate vicinity of the cathode should be of the order of 10^{20} cm^{-3}.

If the area of electron emission from the CF is given approximately by $\pi v^2 t^2$, and the distance between the plasma front and the anode by d - vT, then, taking into account the limitation by the space charge, the current is

$$i(t) = 2{,}33 \cdot 10^{-6} U^{3/2}(t) \pi \gamma^2 k(\gamma)\,, \qquad (2)$$

where U(t) is the gap voltage, k a correction for the action of the field in the case of a bounded emission surface [5]; this correction depends on $\gamma = vt/(d - vT)$. It follows from (2) that the perveance of the electron beam $P = i/U^{3/2}$ should be uniquely determined by the value of γ. The results of an experimental investigation of the perveance are shown in Fig. 3a (curve 1) under the assumption that $v = 2 \times 10^6$ cm/sec. The same figure shows a plot of

$P(\gamma)$ calculated for $k = 1$ (curve 2). It is easy to see that the use of the "two-thirds" law, which does not take into account the bounded character of the emission surface, gives an electron current that is smaller by 1 - 2 orders of magnitude ($k(\gamma)$ - curve 3).

It follows from Fig. 3a that an appreciable increase of the perveance of the electron beam can be attained by first filling the gap partially with the plasma of the CF. This can be done by applying two voltage pulses with a certain pause between them. Application of the first short pulse produces the CF, and the second is the working pulse. The results of one of the experiments with two pulses of 5 nsec duration are shown in Fig. 3b. Although the amplitudes of both voltage pulses are approximately equal (U_0 = 30 kV), the amplitude of the electron current is 4 times larger for the second pulse (~85 A). The maximum attained current ratio was 8.

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[1] G.A. Mesyats, Doctoral dissertation, Tomsk, 1966; S.P. Bugaev, G.A. Mesyats, and D.I. Proskurovskii, Dokl. Akad. Nauk SSSR 196, 1067 (1969) [Sov. Phys.-Dokl. 14, 605 (1969)].

[2] G.K. Kartsev, G.A. Mesyats, D.I. Proskurovskii, V.P. Rotshtein, and G.N. Fursei, ibid. 192, 309 (1970) [15, 475 (1970)].

[3] D. Alpert, D.A. Lee, E.M. Lyman, and H.E. Tomaschke, J. Vacuum Sci. and Technol. 1, 35 (1964).

[4] G.A. Mesyats, E.A. Litvinov, and D.I. Proskurovsky, Discharges and Electrical Insulation in Vacuum, Proc. of the IVth Intern. Symp., p. 82, Waterloo, Canada, 1970.

[5] I.I. Levitov, Dokl. Akad. Nauk USSR 85, 1247 (1952).

INFLUENCE OF SUPERCONDUCTING TRANSITION ON THE INTERNAL FRICTION OF TANTALUM

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We have studied low-frequency internal friction of tantalum, using samples in the form of thin foils measuring 0.1 × 2 × 10 mm. The measurement of the internal friction (Q^{-1}) was based on a procedure developed in [1] and modified because the investigated sample was placed in a helium cryostat. The sample was cantilever-mounted on a holder, and the free damped flexural oscillations produced after excitation were registered. The oscillation frequency could be varied from 50 to 2000 Hz and the relative deformation was $\varepsilon = (2 - 3) \times 10^{-6}$. The relative error in the measurement of the internal friction at helium temperatures did not exceed 0.5%. The temperature was measured with manometric and capacitive [2] thermometers accurate to 0.02°K.

Figure 1 (curve 1) shows a plot of Q^{-1} obtained with a sample annealed at 1500°C for 0.5 hours in a vacuum of 2×10^{-5} Torr. A very sharp and tall maximum was observed at the temperature of the transition to the superconducting state. The width of the maximum at the base did not exceed 0.25°K.[1]. The temperature of the maximum does not change when the sample oscillation frequency is altered. In order to ascertain tentatively the nature of the maximum observed by us, we measured the internal friction in a magnetic field

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[1] There were many similar investigations of Q^{-1} (see the review [3]), but the peak was never observed, apparently as a result of the insufficient accuracy of temperature measurements and as a result of the use of bulky samples.