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Abstract

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INVESTIGATION OF THE TEMPORAL CHARACTERISTICS OF THE TRANSITION OF FIELD EMISSION INTO A VACUUM ARC

(Presented by Academician B. P. Konstantinov on 22 V 1969)

In works ⁽¹⁾ it was shown that, when the density of the field-emission current is increased to $\approx 5 \cdot 10^7$ A/cm², after a time of the order of 10^{-6} sec destruction of tungsten microtips occurs as a result of the avalanche-like increase of current caused by Joule heating of the emitter. In work ⁽²⁾ the assumption was made that the process of emitter destruction may have a character analogous to the electrical explosion of thin wires. Recently, interest in investigations of this kind has grown considerably in connection with the fact that the explosion of microinhomogeneities on the cathode is one of the most probable mechanisms of initiation of vacuum breakdown ⁽³⁻⁵⁾. In works ^(6, 7) it was proved by direct experiments, for pulse durations less than 10^{-7} sec and vacuum-gap lengths up to 1 mm, that the development of the breakdown process in fact begins at the cathode.

It is of interest to investigate the process of emitter explosion at field-emission current densities considerably larger than in ⁽¹⁾, and also to trace in detail the change of current from the beginning of the explosion to complete bridging of the gap by plasma. Increasing the current density leads to a decrease in the time to explosion; therefore, in order to obtain limiting large current densities ($> 10^9$ A/cm²), voltage pulses with a front $\tau_\phi \approx 10^{-9}$ sec ⁽⁸⁾ and duration τ_i from 5 nsec to 4μ sec were used. The circuit of the pulse generator is described in ⁽⁹⁾. The current flowing through the vacuum gap was measured at different stages of the phenomenon with a resolution no worse than 10^{-9} sec. The sensitivity in current recording was $7 \cdot 10^{-2}$ A.

All investigations were carried out on tungsten single-crystal tips obtained by the usual method of automatic electrolytic etching ⁽¹⁰⁾. The radii of the emitters were determined by the Hensel and Drechsler method and were $5 \cdot 10^{-6}$ — $3 \cdot 10^{-5}$

Figure 1

Figure 1: Figure 1

cm. The cone angle did not exceed 15° . All measurements were carried out in sealed-off devices at a pressure of $5 \cdot 10^{-9}$ torr.

Investigations of the explosion process were carried out under the following conditions. 1. With $\tau_i = 4\mu$ sec, the voltage was increased in steps of less than 1% up to the value U_k , at which explosion occurred. With a sharp rise of the current at the moment of explosion, oscillographs switched on in the waiting mode were triggered. 2. With $\tau_i = 4\mu$ sec, in order to increase the current density, an overvoltage was created across the gap, i.e., the amplitude of the pulse U was deliberately greater than U_k . 3. To investigate explosion at limiting large current densities, pulses of duration $5 \cdot 10^{-9}$ sec were used. The general picture of the current variation in the vacuum gap before and after explosion of the emitter is shown in Fig. 1.

In explosions without overvoltage (Fig. 1A), four phases can be clearly distinguished on the current oscillograms. I is the pre-explosion phase, in which heating of the emitter occurs by its own field-emission current. The critical prebreakdown current densities are $(3 \div 5) \cdot 10^7$ A/cm²,

which is in complete agreement with the results obtained earlier^(1, 4, 11, 12). Phase II of the transition is associated with the explosive destruction of the emitter (Fig. 1 B, C). It is important to note that in this phase the current in the gap rises sharply, by approximately two orders of magnitude in a time of $(2 \div 5) \cdot 10^{-8}$ sec. The sharp increase of the current at this stage, by approximately two orders of magnitude,

Fig. 1. A—Schematic representation of the various stages of the transition of field emission into a vacuum breakdown; B and C—oscillograms of the current through the vacuum gap after the explosion of the field-emission emitter

corresponds to the estimates made in (1). Following the rise of the current in phase II, it is possible to detect a stage in which the current changes comparatively slowly (phase III, Fig. 1 B, C). Such a character of the change in the conductivity of the gap in phases II and III may be due to the fact that, at the moment of destruction of the tip during the transition of the solid body into plasma, the effective surface emitting electrons increases and contributes to the growth of the current in the gap. An estimate of the velocity of expansion of the plasma after the emitter explosion gives a value of $(2 \div 3) \cdot 10^6$ cm/sec, almost equal to the velocity of motion of the cathode flare in the development of breakdown in vacuum between macroelectrodes⁽⁶⁾. Phase III on the current oscillogram (Fig. 1 A) is apparently due to the emission of electrons from the plasma clot in the process of its crossing the vacuum gap⁽¹³⁾. The growth of the current in phase IV occurs after the vacuum gap has been bridged by plasma.

Figure 2

Figure 2: Figure 2

Fig. 2. Oscillograms of the field-emission current in the pre-explosion period at extremely high fields and current densities. $\tau = 5$ nsec, $j = 4.2 \cdot 10^9$ A/cm², $E_{\max} = 1.2 \cdot 10^8$ V/cm

Under overvoltage, the character of the current rise in the vacuum gap changes substantially. Such a clear subdivision into stages as indicated above cannot be made. It may be expected that the duration of stage III is sharply reduced, and phase II merges directly with phase IV. An attempt was made to measure the rate of change of the current dI/dt for various overvoltage coefficients $\gamma = U/U_k$. From analysis of the oscillograms it follows that the initial rate of current rise (phase II, $\gamma = 1$) is $5 \cdot 10^7$ A/sec. With an increase in overvoltage up to $\gamma = 1.5$, the value of dI/dt rises sharply, reaching values of 10^9 A/sec. With a further increase in overvoltage, the development of breakdown occurs on the front of the voltage pulse in times of less than 10^{-9} sec, which is beyond the resolution of the apparatus used.

A more thorough study of tip explosion was carried out under the action of voltage pulses with a duration of 5 nsec. In this case a prebreakdown spontaneous change of the current was found at an unchanged voltage at the peak of the pulse (Fig. 2), analogous to that observed earlier in the microsecond range (^{1,11,12}). The presence of this effect made it possible to determine the physical delay time of breakdown as the time before explosion of the tip, t_3 .

With a slight change in the field strength E (from $1.05 \cdot 10^8$ to $1.2 \cdot 10^8$ V/cm), the current density changes from $6 \cdot 10^8$ to $2.1 \cdot 10^9$ A/cm², while the time t_3 decreases from 5 to 1.5 nsec (Fig. 3). At the same time the amplitude of the voltage pulse increases by 11%. A further increase in the amplitude of the voltage pulse by 1% led to explosion of the tip on the front of the pulse with a delay time $t_3 < 10^{-9}$ sec; in a time $< 10^{-9}$ sec the current in the vacuum gap rises to 50–60 A, which corresponds, at least, to a current-rise rate $dI/dt = 5 \cdot 10^{10}$ A/sec. The largest current densities before explosion (phase I, Fig. 1A) at $\tau_i = 5$ nsec amount to $(2 \div 5) \cdot 10^9$ A/cm². For the specific case shown in Fig. 2, the current density at the beginning of the pulse is $j_1 = 2 \cdot 10^9$ A/cm², and at the end of the pulse $j_2 = 4.2 \cdot 10^9$ A/cm². The large magnitude of the relative increase of the current in the preexplosion phase is noteworthy. As was shown (^{11,12,14}), at $\tau_i = 4$ μ sec the relative change of the current $\Delta I/I_{cr}$ is $(30 \div 50)\%$. At $\tau_i = 5$ nsec this quantity is $(100\text{—}120)\%$, which may indicate either substantially higher emitter temperatures or a shift of the electron energy spectrum. It is important to note that the effect of spontaneous current rise, if explosion does not occur, is completely reversible.

Fig. 3. Breakdown delay time, measured before the moment of emitter explosion. **I**—as a function of the electric-field strength, **II**—as a function of the

Fig. 3 graph

Figure 3: Fig. 3 graph

logarithm of the current density (the numbers 4, 5, 6, 7 give values taken from works ^(1,11,12,15), respectively; points 1, 2, 3, 4 are plotted on the basis of the data obtained in the present work).

The general trend of the change in the explosion delay time as a function of the current density and the field strength at the emitter tip can be obtained from an analysis of the experimental data of the present work, as well as of works ^(1,11,12). The resulting curves of the dependences $\lg t_3$ on E and $\lg t_3$ on j are given in Fig. 3. To determine the field strength at the emitter tip, a parabolic approximation was used.

In conclusion it should be noted that an attempt was made to construct the Fowler–Nordheim curve $\lg I - 1/U$ for $\tau_i = 5$ nsec. It was found that, in a certain interval of applied voltages $\Delta U = (1.5 \div 2)$ kV, at densities $j = 1 - 2 \cdot 10^9$ A/cm², the emission current changes only very weakly. The latter may mean that the emission current in this region of field strengths and current densities tends toward saturation.

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