Field emission and explosive electron emission processes in vacuum discharges

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The article reviews the current state of studies of electrical breakdown and discharges in vacuum. The main attention is devoted to cathode and near-cathode phenomena, which form the physical content of fast processes in a vacuum discharge. The model of cathode initiation of a vacuum discharge as the result of field emission with high current density is analyzed. The phenomenon of explosive electron emission is described in detail. On the basis of ideas developed in study of explosive electron emission, nonstationary processes in vacuum breakdown and in the cathode spot of a vacuum arc are discussed.

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CONTENTS

1. INTRODUCTION

The phyiscal picture of electrical discharges in vacuum is rather complicated. In vacuum-discharge processes many physical phenomena appear which are not observed at all under other conditions. Among these are electron emission with current density at the cathode up to about 10^9 A/cm^2, high-current pulsed electron and ion currents, high-velocity plasma jets, micropinches with high particle temperature, acceleration of positive ions toward the anode, pulses of intense x-ray and ultraviolet radiation, and so forth.[1-15] These physical processes are the subject of numerous studies, since progress in understanding them contributes substantially not only to the development of the physics of electrical discharges but also to a number of quite different areas: emission electronics, plasma physics, particle-acceleration physics, radiation physics, and so forth. Technical interest in vacuum discharges is due, on the one hand, to the use of discharge processes in various electrical apparatus and, on the other hand, to the necessity of avoiding electrical breakdown in numerous devices operating under vacuum conditions.

The basic condition which assures the development of a vacuum discharge is the creation of a conducting medium in an evacuated gap. This medium may be in the form of plasma, vapor, desorbed gases, and microparticles which, as a rule, come only from the electrodes. The great diversity of experimental conditions, which cannot be very accurately controlled in space and time, has not permitted unambiguous information to be obtained on the role of various processes of a vacuum discharge. Studies of recent years have shown that in development of a vacuum discharge a fundamental role is played by field emission (FE) from the cathode, which then goes over to explosive electron emission (EEE). The purpose of the present article is to present up-to-date information on this question. Since the article is based to a substantial degree on the results of investigations by the authors, it reflects their point of view on the processes discussed, which in some cases is debatable or controversial.

2. INITIATION OF VACUUM BREAKDOWN BY FIELD EMISSION

The question of the role of field emission in initiation of vacuum breakdown has been discussed for a long time.[1,2,10] Even in early studies on vacuum discharges, the prebreakdown currents were assigned to field emis-

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sion. Then, however, it was established that appreciable prebreakdown currents appear at an electric field which is 2–3 orders of magnitude smaller than follows from the Fowler-Nordheim equation[1,10] (Fig. 1). This difference was explained by the existence of microprojections on the cathode, at which the electric field is enhanced by tens to hundreds of times, (Fig. 2). Electron emission, as a rule, occurs from just such microprojections and therefore is of a local nature.[1,10,16-18]

On increase of the field strength in the gap, the rise of the field-emission current density leads to heating up of the micropoint as the result of Joule heating and Nottingham heating.[1,2,19-21] At the same time the portion of the anode located opposite the micropoint is heated by the electron beam accelerated in the gap. It is usually assumed that heating of a local portion of one of the electrodes to some critical temperature (for example, the melting point) leads to development of thermal instability and as a consequence to an irreversible transition to breakdown. This approach has led to appearance of several varieties of hypotheses regarding the role of field emission in initiation of vacuum breakdown. According to some ideas, the role of field emission reduces to heating, evaporation, and ionization of vapor of the anode material by accelerated electrons, which creates a medium for development of breakdown and produces an enhancement of the field at the cathode.[1,22,23] According to other ideas, an important role in initiation of breakdown is played by heating of the cathode micropoints themselves by the field-emission current, which leads to development of thermal instability and transition to breakdown.[16-18,24,25] For this reason studies have appeared[19-21,23] in which attempts have been made to find theoretically the limits of realization of the cathode and anode breakdown mechanisms. In addition, field emission has come to be taken into account in hypotheses which associate breakdown with removal of microparticles from the electrodes.[1,26,27]

Experimental information accumulated in recent years shows that, regardless of the form of voltage applied to an evacuated gap and the duration of its action, the transition directly to breakdown and an arc is determined in the last analysis by the enhancement of the electric field of the cathode, the intensification of field-emission processes, and the transition to explosive electron emission. The influence of anode processes,

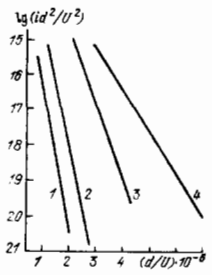

FIG. 1. Prebreakdown current flowing between clean parallel electrodes of tungsten, as a function of the voltage applied to the gap, plotted in the coordinates of the Fowler-Nordheim equation.[17] The interelectrode distance d has the following values in centimeters: (1)—0.005, (2)—0.0025, (3)—0.102, and (4)—0.406.

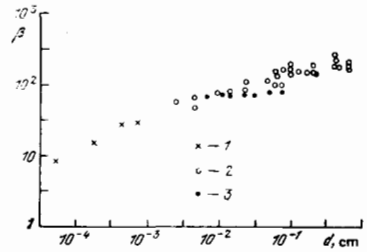

FIG. 2. Coefficient of field enhancement β at micropoints as a function of the length of the vacuum gap. 1—data of Ref. 22, 2—Ref. 17, 3—Ref. 21.

microparticles, and desorbed gases is important in the sense that they facilitate this process and reduce the electrical strength of vacuum insulation. However, cathode initiation of a vacuum discharge places a direct upper limit on the electrical strength. For this reason in this section we shall discuss the case of cathode initiation of breakdown by means of field emission. The role of other factors in initiation of breakdown will be discussed subsequently.

a) Heating of a cathode micropoint by field-emission current

Numerous experiments, including those described in the present work, have established the existence on the cathode surface of a set of micropoints which arise in electrical discharges or under the influence of electric fields. We shall consider a model situation consisting of a micropoint of cylindrical or conical shape of height h and radius of the emitting tip r_e on the surface of a massive cathode. On increase of the voltage across the evacuated gap an exponential rise will occur in the density of the current emitted by the micropoint in accordance with the Fowler-Nordheim equation.[1,2] On reaching a current density of the order 10^6–10^7 A/cm² as the result of Joule heating the tip of the point begins to be heated. The increase of the emitter temperature results in a transition from field emission to thermionic field emission, i.e., to a further increase of the current density. Thus, under certain conditions the interaction of the emission current density and the energy dissipation in the tip of the micropoint can lead to an irreversible rise in temperature of the latter, terminated by its explosive destruction.

The problem of heating of a micropoint of the cathode by field-emission current is described by the following system of equations[3]:

$$\left.\begin{aligned} &\rho c\frac{\partial T}{\partial t}=\nabla(\lambda\nabla T)-\frac{j c_e}{e}\nabla T+j^2\varkappa,\\ &T|_{bp}=T_0,\quad T|_{t=0}=T_0,\\ &\lambda\nabla T|_{eb}=-\frac{j_e}{e}\Delta\varepsilon; \end{aligned}\right\} \tag{2.1}$$

here ρ is the cathode-material density, c is the heat capacity, T is the absolute temperature, $c_e=\pi k^2T/2\varepsilon_F$, k is the Boltzmann constant, ε_F is the Fermi energy, $\varkappa(T)$ is the electrical resistivity, and λ is the thermal conductivity. The symbols $|_{bp}$ and $|_{eb}$ denote the boundary conditions at the base of the point and at the emission boundary. The latter boundary condition in Eq. (2.1) takes into account the fact that the average energy

brought in by conduction electrons from the interior of the cathode to the emission boundary is different from the average energy which is carried away by the emission electrons (the Nottingham effect). The emission-current density j_e and the quantity $\Delta\varepsilon$ depend in the following way on the emitting-surface temperature T_e (Refs. 28, 32, 33, 34):

$$\left.\begin{aligned} &j_e = j_0 \frac{\pi T_e}{2T_i}\sin^{-1}\frac{\pi T_e}{2T_i},\\ &\Delta\varepsilon = \frac{\pi^2}{2}\left(\frac{kT_e}{\varepsilon_F}\right)^2\varepsilon_F + 2kT_i\frac{\pi T_e}{T_i}\operatorname{ctg}\frac{\pi T_e}{2T_i}, \quad T_e < 1.2T_i,\\ &j_e = j_0\cdot 1.16\exp\left(0.31\frac{T_e^3}{T_i^3}\right),\\ &\Delta\varepsilon = \frac{\pi^2}{2}\left(\frac{kT_e}{\varepsilon_F}\right)^2\varepsilon_F + 2kT_i\left(1-0.93\frac{T_e^3}{T_i^3}\right), \quad 1.2T_i < T_e < 2.2T_i. \end{aligned}\right\} \quad (2.2)$$

In the present case j_0 is the field-emission current density at $T=0$, $T_i = 5.67\cdot 10^{-5}E/\sqrt{\varphi}$, T_i is the inversion temperature, E is the electric field strength at the cathode in volts/cm, φ is the work function in electron volts, and T_i is in degrees Kelvin.

The problem of heating of a point cathode was discussed for the first time by Dyke and his colleagures.[25] In their work they did not take into account the dependence $j_e(T_e)$ or $\varkappa(T)$ and set $\Delta\varepsilon = 0$. They obtained relations from which it is possible to find the maximum value of the emission-current density if the maximum permissible cathode temperature is specified. A number of workers[19,20,24-28,30-32] have attempted to improve on the results of Dyke *et al.*[25] The dependence of the cathode-material properties on the temperature were taken into account (mainly the dependence of the resistivity on temperature). Levine,[32] solving the stationary problem, first took into account the Nottingham effect. In Refs. 29 and 31 it was shown that a situation is possible in which there is no stationary solution. This circumstance permitted one to find the temperature at which thermal instability leading to cathode destruction develops.

The problem in its most rigorous formulation given by Eqs. (2.1) and (2.2) was solved in several papers[35] by Litvinov, Mesyats, and Shubin. For the stationary case the criterion was found for absence of thermal instability for a point cathode of cylindrical geometry:

$$j_0 h \leqslant \sqrt{\frac{\lambda}{\varkappa_0}}, \quad (2.3)$$

and for a conical geometry:

$$j_0 r_e \leqslant \frac{\sin\theta}{1-(r_e/r_0)}\sqrt{\frac{\lambda}{\varkappa_0}}. \quad (2.4)$$

Here r_0 is the radius of the base and θ is the half apex angle of the cone.

In the case in which the current density is sufficiently high ($j_0 \geqslant 10^8$ A/cm^2), heating of the cathode will occur very rapidly. Solution of the nonstationary problem (2.1) will permit one to obtain an expression relating the characteristic time of development of thermal instability (the delay time of the cathode explosion t_d) with the field-emission current density:

$$j_0^2 t_d \leqslant f\frac{\rho c}{\varkappa_0}. \quad (2.5)$$

The coefficient f varies weakly as a function of the cathode geometry. Change of the half-vertex angle θ in the range 0.1–0.8 rad changes f in the range from 0.75 to 2.35.[85] Equation (2.5) is in good agreement with the experimental results of Ref. 36.

If $j_0 \geqslant 10^9$ A/cm^2, then the cathode heating will occur so rapidly that it is necessary to take into account the fact that the relaxation time between the conduction electrons and the lattice is finite. This situation was analyzed in Ref. 3. In this case the criterion of development of thermal instability appears as follows:

$$j_{s0}^2 t_d \leqslant \frac{\rho c}{\varkappa_0}. \quad (2.6)$$

here $j_{s0} = env_{s0}$, n is the concentration of conduction electrons, and v_{s0} is the velocity of sound in the metal. Reference 37 numerically solved the nonstationary problem of heating by thermionic field emission current of a cathode in the form of a semi-ellipsoid of revolution. In Ref. 38 a similar attempt is described for a cathode with cylindrical geometry. The results of these studies confirm the validity of the criterion (2.5).

b) Influence of size effects on the thermal regime of the cathode

In solution of the thermal problems described above, use has been made of the kinetic characteristics of the cathode materials (λ, $\varkappa$) and their functional dependence, for example, on temperature, in the form in which they are known for massive samples. At the same time a number of experiments (for example Ref. 39) have used field emitters with linear dimensions of about 10^{-6} cm. Microemitters with such dimensions exist on flat cathodes and can arise dynamically in spark and arc discharges in vacuum (see Section 3). It is known[40] that at room temperature the electron mean free path in the metal is $L \approx 5\cdot 10^{-6}$ cm, and with increase of temperature L drops as T^{-1}. It follows from this that the process of dissipation and diffusion of energy in the emitter can be influenced by size effects. Here the kinetic coefficients are described with sufficient accuracy by the relations[40]

$$\lambda' = \lambda\left(1+\frac{L}{2r}\right)^{-1}, \quad \varkappa' = \varkappa_0\left(1+\frac{L}{2r}\right). \quad (2.7)$$

For the case of high current densities when the emitter is heated very rapidly and the effect of thermal conduction can be neglected, one obtains[41] the relation

$$(j_0^2 t_d)' \approx \frac{2r}{L_{cd}}(j_0^2 t_d), \quad (2.8)$$

where L_{cd} is the electron mean free path at the cathode destruction temperature T_{cd}.

For a stationary situation it is of interest to learn the limiting current densities which such microemitters can maintain. Analysis of this situation has led[40] to the expression

$$(j_0 h)' \approx \frac{2r}{L_{cd}}(j_0 h). \quad (2.9)$$

If we assume that the microprojection is close in shape to a truncated cone, then instead of h in Eq. (2.9) we must substitute the expression $r_e(r_0^2 - r_e^2)/2r_0^2\sin(\theta/2)$. Estimates on the basis of Eq. (2.9) show[41] that under the

conditions of the experiments of Ref. 39 the limiting densities of a stationary thermionic field emission current can reach values $\approx 10^{10}$ A/cm^2.

c) Initiation of breakdown under the conditions of superconductivity

Since there is no Joule heating of the micropoints under conditions of superconductivity, we might expect qualitatively that transition of the cathode to the superconducting state can raise the electrical strength of vacuum insulation substantially. However, in collection of current from a superconducting emitter the dissipation of heat at its tip as a result of the Nottingham effect is not excluded. In this case the solution of (2.1) leads to the expression (42)

$$j_0 r_e\left(1-\frac{r_e}{r_0}\right)\leqslant\frac{e\sin\theta}{\Delta\varepsilon}\int_0^{T_{cr}^*}\lambda\,dT, \qquad (2.10)$$

where T_{cr}^* is the temperature of the transition from the superconducting state to the normal state. Equation (2.10) determines the limiting field-emission current density j_0 which can be drawn from a superconducting cathode. In a real situation the limiting current density will be somewhat lower, since there is a critical magnetic field which decreases with temperature.[43]

Reference 44 obtained experimental data which show the influence of emission current on the critical parameters of a superconductor. Calculations by means of Eq. (2.10) permitted explanation of the data obtained in Ref. 44 by the influence of the Nottingham effect.[45]

Under pulsed conditions for evaluation of the delay time one can write

$$j_0^2 t_d\leqslant\left(\frac{e}{2}\int_{T_0}^{T_{cr}^*}\frac{\sqrt{\lambda c}}{\Delta\varepsilon}\,dT\right)^2. \qquad (2.11)$$

In this case c is the heat capacity of a unit volume of the superconductor.

Since the current density in the Fowler-Nordheim formula varies rapidly with the electric field strength, a perceptible change of the emission current is produced by small changes of the field. In other words, the limiting stationary prebreakdown fields for a superconductor cannot be substantially higher than those achieveable for a normal metal. Thus, Nottingham heating leads to the result that the use of superconducting electrodes provides practically no increase in the electric strength of a vacuum gap under stationary conditions.[46]

An interesting situation can arise if one prepares a pointed field emitter with a large angle θ from a pure type I superconductor. As was shown in Ref. 47, in this case the characteristic times of destruction of the superconducting state are in the range 10^{-8}–10^{-2} sec. One can hope that the Nottingham effect, which injects nonequilibrium excitations into the electron subsystem, will not immediately lead to decay of the superconducting state and that it will turn out to be possible to obtain under pulsed conditions emission currents which are supercritical with respect to (2.10) and (2.11).

We have carried out measurements of the delay time of initiation of pulsed breakdown under conditions of superconductivity (electrodes of Nb).[48] The results of the present measurements are shown in Fig. 3. It is evident that in the case of a superconducting cathode the delay time is increased significantly; this is especially noticeable at high electric fields. The data obtained are an experimental confirmation of the suggestion made above regarding the behavior of a superconductor in the presence of field emission with high current density ($\approx 10^9$ A/cm^2).

d) Influence of adsorbed gas on cathode-initiation of pulsed breakdown

A definite stimulating role in initiation of pulsed breakdown can be played by gas adsorbed on the cathode surface. For a field strength $E\approx 10^7$ V/cm field-stimulated desorption occurs.[1] If all atoms are desorbed, the gas concentration near the surface of the cathode is $n_a \approx N_0/V_a t$, where N_0 is the number of adsorbed atoms per unit surface and $V_a\approx 10^5$ cm/sec is the velocity of the atoms on desorption. From this formula it follows that in the presence of a monolayer of atoms ($N_0\approx 10^{16}$ cm^{-2}) in a time $t\approx 10^{-9}$ sec after application of the voltage a gas layer of thickness 10^{-4} cm and concentration $n_a\approx 10^{20}$ cm^{-3} is formed.

In order that this gas be able to influence the initiation of breakdown, it is necessary that it be ionized by means of electron impact ionization. For this to occur it is necessary to satisfy the condition $(n_a\sigma)^{-1}\ll V_a t$ or $N_0\sigma\gg 1$, where σ is the ionization cross section; $\sigma \leqslant 10^{-16}$ cm^2. If several monolayers of gas have been adsorbed on the cathode, the condition $N_0\sigma\gg 1$ is satisfied. However, if the field-emission current density is small, enhancement of the field at the cathode does not occur as the result of lack of ionization of the gas. For example, for tungsten at $E\approx 3\cdot 10^7$ V/cm the expected current density is $j_0\approx 10$ A/cm^2, so that for an emission area $S\approx 10^{-11}$ cm^2 the current amounts to $i\approx 10^{-10}$ A and the average time between the appearance of two electrons will be about 10^{-9} sec. The situation changes substantially when the electric field is sufficiently high but still smaller than the field at which explosive electron emission is excited. For an upper-limit estimate of the influence of the field of the ions we can neglect their loss as a result of departure to the cathode. Then the rate of ionization of the gas will be written in the form

$$\frac{dn_i}{dt}\leqslant\frac{N_0\sigma j_0}{V_a e}t^{-1}. \qquad (2.12)$$

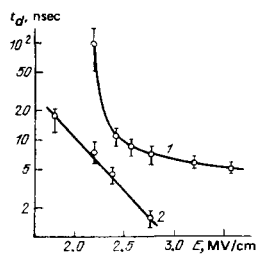

FIG. 3. Delay time of vacuum breakdown as a function of the average electric field strength in a gap formed by niobium electrodes with the cathode in the superconducting state (1) and in the normal state (2).

It follows from this that

$$n_1 \leqslant \frac{N_0 \sigma j_0}{V_a e} \ln \frac{t}{t_0}, \qquad (2.13)$$

where t_0 is an initial time equal in order of magnitude to $e/j_0 S$. The necessary condition for enhancement of the electric field in the cathode region is a significant excess of the ion concentration over the concentration of electrons, i.e., $n_1 \gg j_0/eV_e$. For this it is necessary to satisfy the condition

$$N_0 \sigma \frac{V_e}{V_a} \ln \frac{t}{t_0} \gg 1, \qquad (2.14)$$

which is well satisfied since $V_e/V_a \approx 10^3$.

For example, for a tungsten cathode at $j = 10^6$ A/cm^2 the electric field is $E \approx 6.5 \cdot 10^7$ V/cm. This field is insufficient for explosion of a point. If there is a monolayer of gas on the cathode, then already after a time $\approx 10^{-9}$ sec the concentration of ions at the cathode will amount to about 10^{20} cm^{-3}. Estimates of the electric field strength from Poisson's equation for this case give a value $E \approx 10^8$ V/cm which is sufficient for explosion of a point after a time $t_d \approx 10^{-9}$ sec.[3] Thus, presence of adsorbed gas on the cathode can lead to an effect equivalent to enhancement of the electric field by 2–3 times, and this occurs at external field strengths close to breakdown when the field-emission current density is high.

Thus, in Section 2 we have discussed the conditions of appearance of thermal instability of cathode micropoints due to the flow of the intrinsic thermionic field emission current on application of pulsed and quasistatic fields, with allowance for a number of factors, influence of which has been discovered experimentally. A quantitative comparison of the cathode criteria with experiment can be carried out, apparently, in a limited number of cases in which there is reliable control of the experimental conditions. In this respect a particularly complicated situation exists in study of breakdown at constant voltage, which we shall discuss below.

3. EXPLOSIVE ELECTRON EMISSION

The heating of a field-emitting point by its own current leads to appearance of a new type of electron emission—explosive emission (Fig. 4). Experimental observations have shown[3,4,11-15] that, after a time t_d relative to application of the voltage pulse at the cathode, luminous plasma microbunches appear—cathode flares, which expand into the vacuum with a characteristic average velocity $V = (1-3) \cdot 10^6$ cm/sec. The expansion of the flares is accompanied by an increase of the electron current in the gap. After the passage of an explosive-emission current pulse, erosion tracks are observed on the cathode. Spectral observations show that the cathode plasma bunches consist mainly of cathode material. Thus, in the process of explosive electron emission part of the cathode material is converted into plasma. In this section we shall discuss the main process characterizing explosive electron emission: the mechanism of cathode erosion and formation of elementary erosion tracks, the kinetic and emission characteristics of the plasma of cathode flares, possible mechanisms of passage of electrons through the metal-plasma phase-transition region, and also processes of interaction of the plasma with the cathode surface.

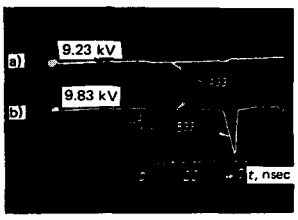

FIG. 4. Typical oscillograms of current from a tungsten field-emission cathode, which characterize the transition from field emission to explosive emission. At the left we have shown the heights of the rectangular voltage pulse of duration 40 nsec fed to the vacuum gap.

a) Behavior of cathode erosion and formation of microrelief of the cathode surface

Experimentally it has turned out to be easier to study cathode erosion by working with specially prepared points.[50-52] In this case by photographing a point in an electron microscope before and after the action of a pulse of explosive electron emission current it is possible to determine the change in shape and volume of the point and in this way to establish quantitative characteristics of the erosion process. In Fig. 5 we have shown profiles of points before and after the action of pulses of explosive electron emission current of various duration.[51] The velocity of the motion of the boundary of destruction of the point in the first nanoseconds is $\approx 10^5$ cm/sec, i.e., it is comparable with the velocity of sound in the metal. This directly indicates the explosive nature of the destruction process.

Let us investigate the mechanism of erosion of points. We shall begin with the emission-resistive model of cathode heating. Neglecting heat conduction, the system of equations (2.1) in the interior of a cathode of conical geometry is written in the following form:

$$\rho c \frac{\partial T}{\partial t} \approx \frac{i^2(t) \varkappa_0 T}{\Omega^2 r^4}, \quad T|_{t=0} = T_0, \quad \Omega = 2\pi(1 - \cos\theta). \qquad (3.1)$$

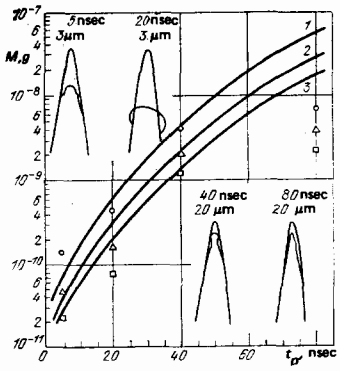

FIG. 5. Mass of metal M carried away from the tip of a molybdenum point as a function of the duration of the current pulse of explosive electron emission. $\theta = 4°$ (curve 1), 8° (curve 2), and 12° (curve 3). The curves are plotted in accordance with Eqs. (3.3). Also shown in the figure are the profiles of the points before and after the explosive electron emission current pulse. $U_0 = 20$ kV, $d = 0.2$ cm.

Solution of Eq. (3.1) will permit determination of the coordinate r_{cd} or the cross section $S_{cd}=\Omega r_{cd}^2$ corresponding to the volume of cathode heated to the state of destruction:

$$r_{cd}\approx\left(\frac{\varkappa_0\int_0^t i^2(t')\,dt'}{\Omega^2\rho c\ln(T_{cd}/T_0)}\right)^{1/4}, \tag{3.2}$$

where $T_{cd}=\varepsilon_c/c$ and ε_c is the specific heat of sublimation. The mass of cathode material carried away as the result of erosion is determined as follows:

$$M=\frac{1}{3}\rho\Omega r_{cd}^3=\frac{\rho}{3\Omega^{1/2}}\left(\frac{\varkappa_0\int_0^t i^2(t')\,dt'}{\rho c\ln(T_{cd}/T_0)}\right)^{3/4}. \tag{3.3}$$

The current density in the critical cross section does not depend on the cathode geometry and is determined by the constants of the cathode material and by the emission current:

$$j_{cd}=\left(\frac{\rho c\ln(T_{cd}/T_0)}{\varkappa_0}\,\frac{i^2(t)}{\int_0^t i^2(t')\,dt'}\right)^{1/2}. \tag{3.4}$$

It falls off as $t^{-1/2}$ for a nontranscendental dependence $i(t)$.

In Fig. 5 we have shown dependences $M(t_p)$ obtained experimentally and calculated according to Eq. (3.3) for points of molybdenum.[51] For $t_p\leq 40$ nsec there is satisfactory agreement of the theoretical and experimental values. For $t_p=80$ nsec the experimental values of the mass carried away are approximately an order of magnitude smaller than the calculated values. This difference is due to the fact that the appearance of explosive emission on the side surface of the point stimulated by the cathode plasma (this question will be discussed below) leads to a decrease of the current through the cross section S_{cd} and accordingly to a sharp decrease of the intensity of erosion of the vertex. In Fig. 5 we can see distinctly that at $t=80$ nsec a significant part of the mass carried away from the cathode is provided by erosion of the side surface of the point.

With due regard to the importance of the model experiments described, they do not provide an answer to questions associated with realization of explosive electron emission in massive cathodes. For characteristic sizes of the heat source on a plane cathode 10^{-5}–10^{-4} cm and current flow times of 10^{-9}–10^{-7} sec, realization of pure Joule heating is in doubt as a result of the increase of the role of heat outflow by conduction. References 53 and 54 used a method based on planned study of the regularities of the expenditure of the metal of conical and cylindrical "macrocathodes" of radius 10^{-3}–10^{-2} cm to determine the current density at a massive cathode and to analyze its energy regime. On the basis of observations of the morphology of the surface of cathodes in a scanning electron microscope (Fig. 6), they considered the geometrical pattern of the erosion process and found a relation between the rate of erosion of the cathode and the number of explosive-electron-emission current pulses. Comparion of this relation with the experimental dependences led to the following conclusions: 1) the elementary volume of metal removed from the cathode consists of the region of contraction of the current in

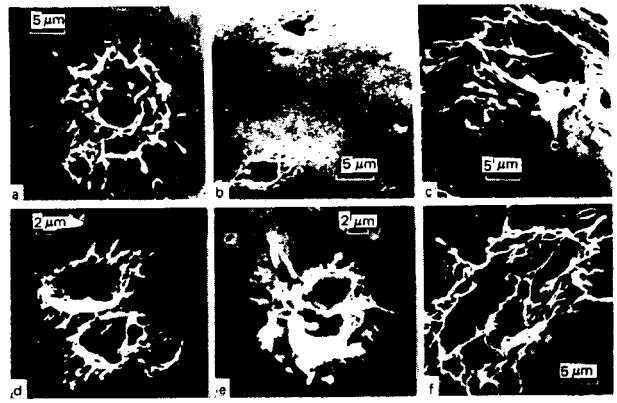

FIG. 6. Craters on the surface of a copper cathode which appeared after one pulse of explosive electron emission current. $U_0=30$ kV, $d=3$ mm, t_p in nsec = 20 (Fig. a), 50 (Fig. b), 100 (Fig. c), 300 (Fig. d), 1300 (Fig. e), and 5000 (Fig. f).

the form of a pinch with a solid angle $\Omega\leq 2\pi$; 2) the emission centers (EC) operate in parallel, and the density of the centers is about 10^6 cm^{-2}; 3) the current density in an emission center is $j\geq(3$–$5)\cdot 10^8$ A/cm^2. Analysis of the equations for the energy balance at the cathode and comparison with experimental data on erosion permitted the following conclusion to be drawn[54]: only realization of nonstationary Joule heating in emission centers, when it is possible to neglect heat outflow by conduction and the motion of the destruction boundary, will permit explanation of the experimental results. The process of functioning of an emission center is as follows.[52-54] The initial explosion occurs as the result of field emission[10] with a high current density (~10^9 A/cm^2), and then near it conditions are realized for appearance of a new emission center under the plasma, i.e., the erosion process consists of a series of successive microexplosions in the vicinity of the initial emission center.

Use of a scanning electron microscope to study the formation of the microrelief of the cathode surface during explosive electron emission has permitted new information to be obtained.[55-57] The elementary traces of the cathode-surface damage are microcraters (Fig. 6). In the case of a smooth initial surface, the microcraters are formed at defects (Fig. 6). With increase of the pulse duration to 100 nsec the crater diameter increased up to $(3$–$5)\cdot 10^{-4}$ cm. Further increase of t_p did not lead to an appreciable increase in the crater diameter, but a more complicated damage-zone structure began to appear, indicating a shift of the emission centers.

From the photographs it can be seen that craters are formed as a consequence of the ejection of liquid metal from local portions of the cathode surface. The liquid metal is crowded out of the craters nonuniformly and, freezing, forms deposits which are piled up on each other. Part of the metal is drawn out in the form of microcolumns, at the tips of some of which microdrops freeze. Removal of a microdrop leads to formation of a micropoint and a microparticle, and the radius of the tip of the micropoint frequently turns out to be less than $5\cdot 10^{-6}$ cm. The microrelief of the surface of cathodes

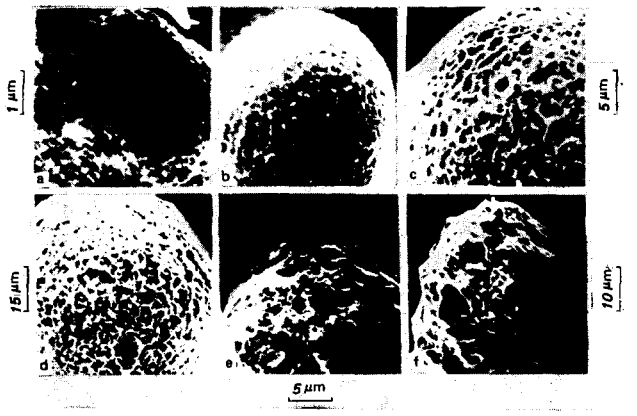

FIG. 7. Surface of the tip part of copper emitters (a–d, $N = 10^5$) and molybdenum emitters (e and f, $N = 10^4$). t_p in nsec is 1.5 (Fig. a), 5 (Figs. b and e), 20 (Fig. c), 50 (Fig. f), and 100 (Fig. d). $U_0 = 30$ kV, $d = 0.3$ cm.

subjected to repeated action of current pulses is shown in Fig. 7. It is evident that the surface has been formed as the result of a pileup of a large number of microcraters, that the nonuniformities become more regular, and that their characteristic size depends substantially on the pulse duration t_p. For $t_p = 1.5$ nsec the sizes of the irregularities amount to $(0.1–0.2)\cdot 10^{-4}$ cm, i.e., in working with pulses $t_p \approx 10^{-9}$ sec it is possible to obtain a well smoothed cathode surface.[55,56] In Fig. 8 we have shown the field enhancement coefficient β at micropoints as a function of t_p.

The drop fraction of erosion was investigated in Ref. 58. As can be seen from Fig. 9, the distribution curves of the drops in size have a maximum with a characteristic displacement toward the region of high dispersedness of the particles. The constancy of the position of the maximum with increase of t_p indicates that repeated cycles of creation and destruction of emission centers are occurring in accordance with the ideas described above. Drops are generated by the cathode for $t_p \geq 5$ nsec, and the drop fraction with increase of t_p approaches a value characteristic of quasistationary vacuum arcs (≈55% for copper according to Ref. 59). A region of melted metal appears at the place of grouping of emission centers. A pressure P_{cf} acts on the liquid metal surface from the direction of the plasma of the flare. The pressure P_{cf} amounts to about 10^{-9}–10^{10} erg/cm^3, and the pressure gradient is $VP_{cf} \approx 10^{13}$–10^{11} erg/cm^4. The action of this force can lead to appearance of nonuniformities on the liquid surface and to splashing of the liquid bath. The velocity of displacement of the liquid metal[60] is

$$V_{liq} \approx \sqrt{\frac{P}{\rho}}. \tag{3.5}$$

Setting the pressure $P = P_{cf} = n_{cf} k T_{cf}$ and $\rho = n_0 m_a$, we obtain

$$V_{liq} \simeq \sqrt{\frac{n_{cf}}{n_0}} V_{T_{cf}}. \tag{3.6}$$

In this case n_{cf} is the concentration of particles of the plasma of the flare, T_{cf} is the electron temperature of the plasma, n_0 is the concentration of particles of the liquid phase, and $V_{T_{cf}} = (kT_{cf}/m_a)^{1/2}$. Equation (3.6) assumes that the force of the plasma pressure substantially exceeds the forces of surface tension and viscosity. Estimates confirm this assumption. Setting $V_{T_{cf}} \approx (1–3)\cdot 10^5$ cm/sec and $n_{cf}/n_0 \approx 10^{-2}$–$10^{-3}$, we obtain $V_{liq} \approx (1–3)\cdot 10^4$ cm/sec. Experiments show that the emission of the drop fraction of the cathode erosion occurs with just this velocity.[61] The existence of a pressure on a cathode emission center $P \approx 10^{10}$ erg/cm^3 is proved by experiments in which appearance of a liquid phase was observed on a graphite cathode operating in the explosive electron emission regime.[62] The characteristic time of development of the erosion process in emission centers is $\leq 10^{-8}$ sec, and the displacement of the liquid metal occurs to a distance $(1–3)\cdot 10^{-4}$ cm.

After termination of the voltage pulse, the liquid micropoints begin to break up under the action of surface-tension forces and, on cooling off, solidify. Estimates show that eventually micropoints of height no more than a few microns are established on the cathode surface. This is in good agreement with the experimental data described above. The question of the forming of the cathode surface in vacuum discharges has been discussed also in Refs. 56 and 63. In our opinion the authors of these studies made a number of errors; in particular they did not take into account the necessity of outflow of the heat of the phase transition.

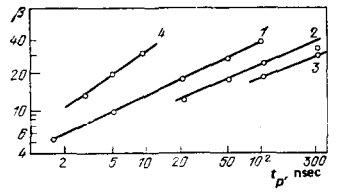

FIG. 8. Average electric field enhancement coefficient β at micropoints as a function of the duration of the pulses of explosive electron emission. Curves 1–3—Cu, Ref. 55. Curve 4—Mo, Ref. 56.

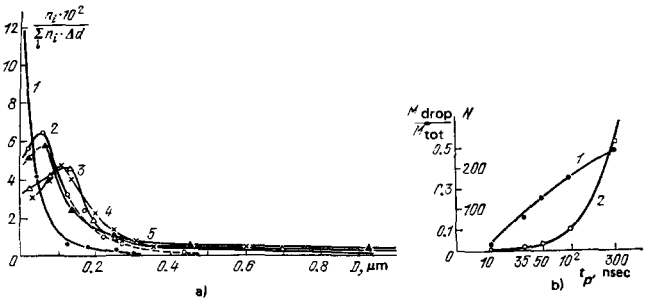

FIG. 9. a) Size distribution of drops leaving a copper cathode for t_p as follows: curve 1—10 nsec, curve 2—35 nsec, curve 3—50 nsec, curve 4—100 nsec, and curve 5—300 nsec; b) the drop fraction of the mass (1) and the number of particles (2) as functions of the duration of the explosive electron emission current pulses ($d = D$).

b) Properties of the cathode-flare plasma

Experiments studying the spectral characteristics of the radiation from the plasma of a cathode flare have shown that the composition of the flare includes ions of various charge multiplicities, neutral atoms, and free electrons.[64–66] The expansion of the cathode-flare plas-

ma into the vacuum with a characteristic average velocity $2\cdot10^6$ cm/sec corresponds to a kinetic energy of the heavy component 50–100 eV. Plyutto[67] suggested that the ions of the plasma in this case can be accelerated as the result of the existing gradient of the electron pressure. A formula has been obtained which permits estimation of the energy of an accelerated ion[68]:

$$\varepsilon_i = 1.5\bar{\varepsilon}_e \ln\left(\frac{n_{e0}}{n_e}\right), \tag{3.7}$$

where $\bar{\varepsilon}_e$ is the average energy of an electron in the region immediately adjacent to the cathode. Setting $\bar{\varepsilon}_e \approx 5$–$10$ eV and $\ln(n_{e_0}/n_e) \approx 3$–$10$, we find $\varepsilon_i \approx 50$–100 eV, which correspond to the experimental data. The authors of Ref. 69 also arrived at ideas of this type.

Analysis of the processes in the expanding plasma of a cathode flare[70] have permitted the following conclusions to be drawn. In the motion of the particles in the flare, elastic collisions are important and the conditions of applicability of a hydrodynamical discussion of the emission process are satisfied. Energy transfers from the electrons to the heavy component do not occur, since in each elastic scattering event there is exchange of a very small energy fraction equal to the ratio m_e/m_i.[71] The nature of the motion of the heavy component is close to adiabatic. The conditions of the motion of the electrons are close to isothermal. At high densities of the electric current flowing through the plasma of a cathode flare, Joule heating of the electron gas is possible. The conditions of electron heating have been realized in experiments.[66]

The motion of the peripheral layers of the flare plasma have an inertial nature as the result of the initially supplied energy. For estimation of the velocity of emission one can use the formula[72]

$$V \approx \sqrt{\frac{4\gamma}{\gamma-1}\varepsilon_0}, \tag{3.8}$$

where ε_0 is the initially supplied individual energy and γ is the index of the polytrope. By analogy with exploding wires[73] one can set $\varepsilon_0 = \delta\varepsilon_c$; δ is the coefficient of superheating and ε_c is the specific heat of sublimation. For Al, Cu, Mo, and W, $\varepsilon_c \approx (5$–$10)\cdot10^{10}$ erg/g, $\delta = 2$–5. Setting $\gamma = 5/3$, we obtain from Eq. (3.8) $V \approx 2\cdot10^6$ cm/sec. For Pb, $\varepsilon_c \approx 10^{10}$ erg/g and $V \approx (0.5$–$1)\cdot10^6$ cm/sec, which agrees with experiment.[3,4,11-14]

Analysis of the inelastic collision processes has shown that excitation and ionization of the heavy particles occurs mainly as the result of electron impact. According to spectral investigations, in the plasma of a flare there are singly, doubly, and triply ionized atoms.

c) Emission of electrons from the cathode-flare plasma into the vacuum

In the peripheral region of the cathode flare adjacent to the vacuum, the condition of quasineutrality cannot be satisfied. The characteristic parameter of the dimension of length which enters into plasma problems with consideration of space charge is the Debye radius $L_D = (kT_e/4\pi ne^2)^{1/2}$.

Estimates show that the inequality $L_D \ll V_{cf}t$ is satisfied, i.e., the process of formation of the emission boundary with separation of charges occurs in a very narrow region adjacent to the front of the cathode-flare plasma.

As the mechanism of emission from the flare plasma it is natural to choose thermionic field emission[74]:

$$j = \frac{4\pi m_e e k^2 T_e^2}{h^3}\exp\left(-\frac{e\varphi - \sqrt{e^3E}}{kT_e}\right), \tag{3.9}$$

where $e\varphi$ is the work function of the plasma and E is the strength of the extracting electric field. On the assumption that the electrons in the flare obey Maxwell-Boltzmann statistics, the following expression will be valid for the work function[74]:

$$e\varphi = kT_e \ln\frac{2(2\pi m_e kT_e)^{3/2}}{\bar{z}n_e h^3}. \tag{3.10}$$

Substitution of Eq. (3.10) into (3.9) leads to the formula

$$j = \bar{z}en_e\left(\frac{kT_e}{2\pi m_e}\right)^{1/2}\exp\left(\frac{\sqrt{e^3E}}{kT_e}\right), \tag{3.11}$$

which shows that a so-called thermal current leaves the flare plasma, since the electron concentration n_e is small and consequently the work function $e\varphi$ is small. The velocity of the electrons leaving the flare is $V_{T_e} \approx 10^8$ cm/sec $\gg V_{cf}$, i.e., the process of electron emission from the plasma front can be discussed using stationary concepts.

On leaving the cathode flare, the electrons move in vacuum, and their own space charge turns out to be the predominant influence on the nature of the motion. In other words, the 3/2-power law should be satisfied ($j_{3/2} \sim U^{3/2}$, where U is the applied potential difference) with the condition $j_{3/2} < j$.[74] This suggestion for plasma sources was first advanced by Flynn,[75] and it was used successfully for explosive electron emission processes in Ref. 76. Subsequently numerous experiments have confirmed this hypothesis (see also Section 4).[3,15,76-78]

In limitation of the electron current by its own space charge, three situations can arise. If the current density $j > j_{3/2}$, there is at the emission boundary an electric field which slows down the electrons and accelerates the ions; near it a virtual cathode is formed. The situation is similar to that which has been analyzed in Ref. 79. The effect of acceleration of ions (and of the emission boundary) can be estimated from the relation

$$m_i\frac{dV_{cf}}{dt} \leqslant e_i\sqrt{4\pi\bar{z}nkT_e}. \tag{3.12}$$

Estimates using (3.12) for specific experimental conditions[80] give $\Delta V_{cf} \leqslant 10^7$ cm/sec. For $j = j_{3/2}$ we can write for the current of explosive electron emission

$$i = \frac{e\dot{M}}{m_i V_{cf}}\left(\frac{kT_e}{2\pi m_e}\right)^{1/2}, \tag{3.13}$$

or in accordance with the results of Subsection a), taking into account that $V_{cf} = 2(\gamma-1)^{-1}\sqrt{\gamma kT_e/m_e}$:

$$i = e\frac{\dot{M}}{m_i}\left(\frac{m_i}{m_e}\right)^{1/2}\frac{\gamma-1}{2}(2\pi\gamma)^{-1/2}. \tag{3.14}$$

In the case when $j < j_{3/2}$, the electrons do not screen the emission boundary of the plasma and the ions are slowed down under the influence of the pressure of the electric field. The situation is similar to that which ex-

ists in stationary plasma sources of electrons.[81] The plasma in this case expands in effect into a medium with an opposing pressure $P_E = E^2/8\pi$. Choosing the limiting concentration value in accordance with the equation $kT_0 n_{1\text{lim}}(n_{1\text{lim}}/n_0)^{\gamma-1} = P_E$, we obtain for the expansion velocity[80]:

$$V'_{cf} = V_{cf}\left[1 - \left(\frac{P_E}{P_0}\right)^{(\gamma-1)/2\gamma}\right], \qquad (3.15)$$

where $V_{cf} = 2\cdot 10^6$ cm/sec and $P_0 \approx kT_{e0}n_0 \approx kT_{10}n_0 \approx 10^{19}$–$10^{20}$ cm$^{-3}\cdot 10^{-4}$ erg $\approx 10^8$–10^9 erg/cm^3. For typical experimental conditions $P_E \approx 10^6$–10^4 erg/cm^3 and $V'_{cf} \approx (0.9$–$0.7)V_{cf}$.

An experimental study of the formation of the emission boundary of a cathode-flare plasma was carried out in Refs. 77, 80, and 82. In Fig. 10 we have shown a typical oscillogram of the explosive emission current with characteristic bursts. In Ref. 82 it was suggested that at the moment of a current burst a plasma prebunch is pulled out of the main plasma of the cathode flare and acquires a high positive potential with respect to the flare. In Ref. 80 it was shown that the appearance of a plasma prebunch is due to a nonmonotonic radial distribution of the particle concentration in the flare as a consequence of the nonmonotonic nature of the dependence $M(t)$. This leads to appearance of peaks and valleys in the oscillograms of the emission current. Indeed, at the initial moment of time the emission ability of the plasma is high and the motion of the emission boundary occurs in accordance with Eq. (3.12). Then the saturation stage (3.14) sets in, which is replaced by the stage of motion with an opposing pressure (3.15). A denser plasma bunch follows the emission boundary, moving with a velocity V'_{cf}. The regime of motion (3.15) goes over into the regime (3.12), while the explosive emission current increases. Behind the plasma bunch there is a lower plasma density. If the extent and density of the bunch are such that the plasma behind the bunch turns out to be incapable of transmitting the collected current before the region of the bunch with higher density goes over to saturation, then a discontinuity with a high potential drop arises. The diode is converted into a triode with a grid—the plasma prebunch which has been extracted from the main flare. This leads to appearance of a current burst which exceeds the Langmuir limit. Experiments carried out with use of the probe technique have confirmed the appearance in the region near the cathode of a double layer with a high potential drop at the moment of a current burst.[83,84]

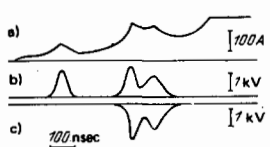

FIG. 10. Oscillogram of explosive electron emission current in a diode for $d = 1$ cm, $U_0 = 30$ kV (a) and the corresponding oscillograms of the potential of the plasma at a distance from the cathode $r = 0.4$ cm (b) and $r = 0.8$ cm (c).

d) Passage of current through the contact of the cathode surface with the plasma

Here we shall consider two questions: 1) The mechanism of emission of electrons from the cathode in the region of the phase boundary, and 2) the mechanism of formation of new explosive-emission centers beneath the cathode-flare plasma.

We can assume that in the explosive-emission process in the immediate vicinity of the zone of outflow of cathode material the concentration of particles will have a value 10^{20}–10^{22} cm^{-3}. In the general case of contact of a medium of this concentration with a solid, discontinuities of the thermodynamic parameters are possible, in particular a discontinuity of the chemical potential. In this case the principal quantities, which have the dimensions of length, are as follows: the Debye radius L_D which determines the characteristic scale of separation of the charges; the electron mean free path L_e; the quantum-mechanical wavelength of the electron $L_\hbar = \hbar\sqrt{2m\Delta\varepsilon_F}$, which characterizes the degree of damping of the wave function in passage through the potential barrier; $\Delta\varepsilon_F$ is the difference of the Fermi levels of the media in contact; $L\varepsilon_F = \varepsilon_F/(\partial\varepsilon_F/\partial x)$ is the characteristic length over which the chemical potential changes.

If $L\varepsilon_F \gg L_D$, then the transition region on the average is quasineutral, the chemical potential changes smoothly, and the electrical resistivity has an ohmic nature. In the case $L_e \ll L_D$ the discontinuity of the chemical potential is important. For $L_e \gg L_D$ we can use the methods of the theory of contact potential difference[85]; if $L_e \gg L_D$, then the Langmuir-MacKeown model[86] is applicable. If we have the condition $L_\hbar \geq L_D$, then the electric current has the nature of field emission from one medium into another. If the inequality $L_\hbar \ll L_D$ is satisfied, the current through the transition region is thermionic.

Analysis shows that for the region immediately adjacent to the destruction zone one has the condition $L_{\varepsilon F} \gg L_D$, i.e., this region has ohmic resistivity. References 87 and 88 studied the behavior of the electrical resistivity and the thermal conductivity as functions of the relative density $n/n_0 = 1$–10^{-4} for various values of the specific energy release ε_0. In our case the electrical resistivity can reach values 10^{-3}–10^{-2} ohm-cm, and the thermal conductivity λ can be in the range 10^{-3}–10^{-4} J/cm·sec·deg. These values of the kinetic coefficients make possible an increase of the specific energy release ($\varepsilon_0 \geq 10^4$ J/g) and provide an explosive nature of the erosion process. At such large specific energy releases the temperature in the emission zone reaches tens of thousands of degrees in a time of 10^{-9}–10^{-8} sec. This can provide a current density from the cathode of more than 10^8 A/cm^2 as the result of thermionic emission.

In Ref. 89 the authors suggested the possibility of resonant field emission from the metal into the plasma under conditions corresponding to explosive emission. Tunneling sub-barrier electrons can be scattered by ions of the cathode-flare plasma, and this leads to a rapid increase of the barrier transmission. Under certain conditions the emission can have a jet nature in which a large number of electrons are emitted through

each resonant ion.

Interaction of the plasma with the cathode surface leads to formation of new explosive-emission centers.[3,13,90] From analysis of the cathode surface (Fig. 6) it follows that new emission centers arise both in the immediate vicinity of the initial ones, leading to formation of a crater substructure, and at distances of tens of microns from them. In Ref. 84 the authors described model experiments in which a thin probe which could be moved to a short distance from the primary cathode flare or cathode spot was used to study the conditions of formation of emission centers on the probe with high time and spatial resolution. It was established that in a time t_d after immersion of the probe into the cathode plasma an explosive-electron-emission current appeared in its circuits. The appearance of micropoints on the probe did not lead to intensification of the process of emission-center formation under the plasma in subsequent discharges. In the spark-discharge stage ($di/dt \approx 5 \cdot 10^9$ A/sec) three regions of the distance x from the initial emission center were distinguished, which differ in the conditions of appearance of emission centers on the probe. In region I ($x \leq 10^{-2}$ cm) the probability of appearance of emission centers increased with decrease of x and with increase of di/dt. The most characteristic delay time under these conditions was $t_d \leq 10^{-8}$ sec. In region II ($x \geq 10^{-2}$–10^{-1} cm) emission centers appeared only on artificial creation of a negative bias U_{bi} on the probe relative to the plasma. In Fig. 11 we have shown the relation $t_d(x)$ obtained with $U_{bi} = -70$ V. In region III ($x \gtrsim 2 \cdot 10^{-1}$ cm) the emission centers appeared no earlier than the arrival of the plasma at the probe, but only at the moment when a spike appeared in the oscillogram of the discharge current. This moment corresponded to an increase of the potential of the boundary layers of the plasma in the probe region to several kilovolts. However, in regions I and II the plasma potential remained less than 50 V with oscillations of the current. For an arc discharge ($i = 10$–50 A) the conditions necessary for appearance of emission centers on the probe turned out to be close to those which existed in the spark-discharge stage in regions I and II, while in the region $x \gtrsim 10^{-1}$ cm no current appeared in the probe circuit.

Application of a transverse magnetic field to the spark discharge leads to the formation of new emission centers in the direction of the plasma drift in crossed electric and magnetic fields.[91] The emission centers arise triggered by the expansion of the plasma and increase of the current in the diode. The velocity of motion of the front of an emission center is about $3 \cdot 10^6$ cm/sec. Appearance of an emission center occurs at the moment of increase of the plasma potential over a given portion of the cathode to several kilovolts, i.e., formation of an emission center on the cathode in this case occurs in the same way as in a spark discharge without a magnetic field in region III. However, since in a transverse magnetic field the plasma expands not spherically symmetrically but into one half-space, the new emission centers arise in this direction. With the transition from the spark stage to the arc stage of the discharge, the "forward motion" of the emission centers is cut off and their "retrograde motion" begins with a velocity $\gtrsim 10^4$ cm/sec.

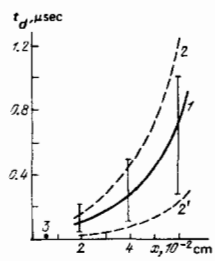

FIG. 11. Delay time in appearance of an emission center on a probe as a function of the distance x: 1—the experiment; 2 and 2'—calculated curves kept for $E_{br} = 5 \cdot 10^6$ and $1 \cdot 10^6$ V/cm.

In order to understand the reasons for formation of new emission centers, we analyzed the conditions in the near-cathode layer for various distances x from the initial emission center.[84,93] It was shown that the value of plasma concentration at which the electric field at the cathode reaches about 10^8 V/cm (for excitation of explosive electron emission in a time $\sim 10^{-9}$ sec) can exist only at a distance $x \approx 10^{-4}$ cm, i.e., essentially in the zone of the initial emission center. The characteristic size of the microinhomogeneities on the cathode should be much smaller than the value 10^{-5} cm, since only in this case will the field be enhanced. Size effects will facilitate realization of explosions.

A jump of the emission zone to the edge of the zone of melting, which results in formation of a crater substructure, can be due also to the process of drop formation. First, when the constriction between the drop and the point become sufficiently thin, the drop can be pulled off by the action of the current flowing to the drop.[93] Second, immediately after removal of the drop, a strong electric field capable of leading to an explosion arises between the drop and the tip of the liquid micropoint.[93,94]

Estimates show that for $x \gtrsim 10^{-3}$ cm the electric field at the micropoints cannot reach breakdown values $E_{br} \approx 10^8$ V/cm. The most probable mechanism of formation of new emission centers at these distances is breakdown of nonmetallic films and inclusions as a consequence of their charging by the ion current from the plasma.[84] The time of charging of a film (or inclusion) to breakdown voltage with a small outflow of charge is

$$t_d \approx \frac{\varepsilon\varepsilon_0 E_{br}}{j_i}, \tag{3.16}$$

where $j_i \approx e_i n V_{i0}$ is the density of ion current at the cathode and $E_{br} = 10^6$–10^7 V/cm is the breakdown strength of the electric field.[95] Since n is proportional to x^{-2}, the dependence $t_d(x)$ should have the form $t_d \sim x^2$. In Fig. 11 we have shown calculated dependences $t_d(x)$ for two possible values of E_{br}, which indicate satisfactory agreement with experiment. It was shown in Ref. 84 that the formation of new emission centers at large distances x in a spark discharge is due primarily to breakdown of nonmetallic films.

In conclusion let us set forth a number of basic propositions which follow from the data presented in Section 3. First of all we can consider proven the explosive

nature of the erosion process from the moment of beginning of the current rise in the gap due to the appearance of a cathode plasma. The rate of escape of the cathode plasma is determined by the energy stored in the cathode material in the regions of contraction of the current, both on the metal side and on the plasma side. The current density in the contraction region exceeds $(3-5)\cdot 10^8$ A/cm^2, and here Joule heat has the decisive influence in the energy balance at the cathode. However, immediately after the beginning of explosive destruction in the region of current contraction, a situation can be realized with a smooth transition of the particle concentration from metallic to "vapor" and "plasma", and the resistance of this transition region will have an ohmic nature. On the other hand, after a time of 10^{-9}–10^{-7} sec, depending on the magnitude and rate of rise of the current, the emission zone cools off as a consequence of decrease of the current density, and the rise of the electric field in the near-cathode region will lead to formation of new emission centers at the microinhomogeneities of the liquid phase forced out by plasma pressure. This is also facilitated by size effects and the process of drop formation. On a contaminated surface new emission centers appear under the cathode plasma by the mechanism of breakdown of nonmetallic inclusions and films. We note a further important aspect: the nonmonotonic nature of the generation of the cathode plasma, which follows from the essence of cathode processes, determines the presence of a phase of unstable collection of electron current, which is the cause of a number of non-stationary processes in a discharge gap.

4. FIELD EMISSION AND EXPLOSIVE ELECTRON EMISSION IN PULSED VACUUM BREAKDOWN

Studies of pulsed breakdown, especially with use of rectangular voltage pulses with a steep rise, permit one to trace most clearly the role of field emission and explosive emission phenomena in the initiation and development of a vacuum discharge. First, under these conditions it is possible to avoid the influence on the discharge of a number of slow processes (migration, diffusion, removal of microparticles, and so forth). Second, the possibility appears of a quantitative study of the time characteristics of the breakdown. Third, here it is possible to study breakdown in electric fields substantially higher than in static breakdown, which is extremely important also in practical aspects. Thus, use of the pulsed regime permits a clearer understanding of the breakdown mechanism.

The principal experimental results on study of the mechanism of pulsed breakdown of vacuum gaps have been obtained with use of high-voltage nanosecond technique and high-speed oscillography in combination with the technique of recording rapidly occurring processes.[3,4,9,11-15,96,97] On application to a vacuum gap of a voltage pulse with a rise time of about 10^{-9} sec the growth of the breakdown current does not occur immediately, but after a certain delay time t_d (Fig. 12). The time t_d decreases rapidly with increase of the electric field strength in the gap and depends very weakly on the duration of the field (Fig. 13). The current rise time

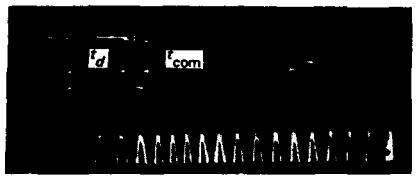

FIG. 12. Typical oscillograms of breakdown current of a vacuum gap by rectangular pulses of voltage with a nanosecond rise time. The small current peak at the left (the bias current) corresponds to the moment of arrival of the pulse at the vacuum gap. $d = 0.5$ mm, $U_0 = 50$ kV, and the electrodes are of copper. The calibrating sine wave has a period of 2 nsec.

t_{com} (the commutation time) is arbitrarily measured between the levels 10% and 90% of the height $i_0 = U_0/R$, where U_0 is the amplitude of the voltage pulse and R is the resistance of the discharge circuit. It has been established that the time t_{com} does not depend appreciably on the breakdown voltage of the electric field and rises linearly with the length of the vacuum gap (Fig. 14). Increase of the discharge current by an order of magnitude does not lead to a substantial change in the appearance of the oscillograms or of the dependence of t_{com} on d.[76] The ratio d/t_{com} for a large number of materials lies in the range $(1-3)\cdot 10^6$ cm/sec.

Electron-optical studies[9,96,98] have shown that the beginning of the current rise coincides with the appearance on the cathode of plasma bunches arising on explosion of cathode micropoints (Fig. 15). Thus, the current in the commutation stage (in the spark stage of the breakdown) is an explosive electron emission current. The growth of the current is due to the increase of the emitting surface of the cathode plasma, which is expanding into the vacuum with a velocity $V_{cf} \approx (1-3)\cdot 10^6$ cm/sec, depending on the cathode material, the time of escape, and the value of the explosive electron emission current. Electrons accelerated in the vacuum part of the gap bombard the anode, which leads to formation of an anode plasma. Initially its composition is determined by materials desorbed from the anode surface (gases, impurity vapors).[99] With increase of the temperature and transition to conditions of intensive evaporation, anode material vapor begins to dominate in the composition of the anode plasma.[64,66,100,101] As a result of the action of the electron flux on the anode, erosion of its surface and transport of anode material to the cathode occur,[96,102] which is many orders of magnitude greater than the inverse transport.[102,103] In the course of the action of the accelerated electrons on the anode, intense x rays arise, the duration of which is compar-

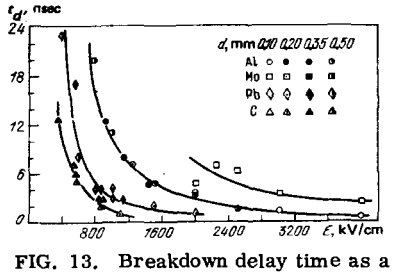

FIG. 13. Breakdown delay time as a function of the average electric field strength in the gap for various electrode materials.

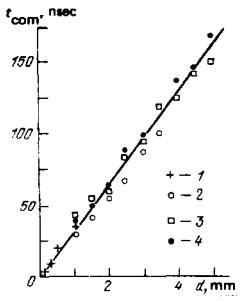

FIG. 14. Commutation time as a function of the length of the vacuum gap with electrodes of copper. U is as follows: (1)—40 kV, (2)—86 kV, (3)—130 kV, and (4)—164 kV.

able with the commutation time.[104,105]

The data which are available at the present time show that on the whole the scheme of development of pulsed breakdown does not depend on the length of the vacuum gap, the electrode material, or the vacuum conditions. This has permitted an unambiguous conclusion to be drawn regarding the breakdown mechanism.[3,4,9,11-13]

The breakdown delay time is due to delay of the explosion of micropoints on the cathode. According to Eq. (2.5),

$$t_d = \frac{j\rho c}{\varkappa_0 A^2 E^4 \beta^4} \exp \frac{2B}{\beta E}, \tag{4.1}$$

where A and B are the coefficients in the Fowler-Nordheim equation.[2] It follows from Eq. (4.1) that there is a very strong dependence of the time t_d on E. For example, if $E = 10^6$ V/cm, $\beta = 100$, and $\varphi = 4.5$ eV, then an increase of the field by 10% will lead to a decrease of the time t_d by almost 500 times. A good confirmation of this conclusion is obtained in the experimental results of Ref. 106 in the region $t_d \leqslant 10^{-6}$ sec. For $t_d \geqslant 10^{-6}$ sec field emission from micropoints already has a quasistationary nature, and additional factors can influence the initiation of breakdown (see Chapter 5).

For times $t_d = 10^{-9}$–10^{-8} sec the density of the pre-explosion thermionic field emission current exceeds 10^8 A/cm^2.[36] Here the current density is already limited by electron space charge in the region of the tip of the point[25]:

$$j = 2.33 \cdot 10^{-6} \frac{(\beta E)^{3/2}}{d_{eff}^{1/2}}, \tag{4.2}$$

where $d_{eff} \approx U/\beta E$ is some effective gap in which the space charge is concentrated ($d_{eff} \approx r_e$). When this is taken into account

$$t_d \approx \frac{j\rho c r_e}{5.4 \cdot 10^{-12} \varkappa_0 \beta^3 E^3}, \tag{4.3}$$

i.e., in the region of small delay times we have $t_d \sim E^{-3}$. This conclusion is confirmed experimentally.[96]

Studies of the regularities of the current rise in the spark stage of breakdown have shown that they are satisfactorily described on the assumption of current limitation by space charge in the vacuum part of the gap between the cathode plasma and the anode. Thus, in the case of use of a point cathode and a planar anode for the condition $V_{cf} t \ll d$ one obtains[15,78]

$$i(t) \approx 37 \cdot 10^{-6} U^{3/2}(t) \frac{V_{cf} t}{d - V_{cf} t}. \tag{4.4}$$

On appearance of a cathode flare on a planar cathode and under the same conditions[107] we have

$$i(t) \approx 44 \cdot 10^{-6} U^{3/2}(t) \left(\frac{V_{cf} t}{d}\right)^2. \tag{4.5}$$

When the flare radius $V_{cf} t$ becomes comparable with the gap length, we have

$$i(t) \approx 7.32 \cdot 10^{-6} U^{3/2} \left(\frac{V_{cf} t}{d - V_{cf} t}\right)^2. \tag{4.6}$$

From Eqs. (4.4), (4.5), and (4.6) one can draw the general conclusion that

$$i(t) = A_0 U^{3/2}(t) F_{cath}\left(\frac{V_{cf} t}{d}\right), \tag{4.7}$$

where F_{cath} is a function which depends on the shape of the cathode. If we take into account that $U = U_0 - iR$, we obtain from Eq. (4.7) $F_{cath}(V_{cf} t/d) = I(1-I)^{-3/2} A_0^{-1} U_0^{-1/2}$, where $I = iR/U_0$. If the discharge occurs between planar electrodes, then one can use Eq. (4.5). Assuming that one flare arises on the cathode, we have

$$\frac{V_{cf} t}{d} \approx I^{1/2}(1-I)^{-3/4} A_0^{-2} U_0^{-1/4}. \tag{4.8}$$

It follows from this equation, in accordance with the experiments, that the time of growth of the current to some value I is proportional to d/V_{cf} and depends only weakly on the applied voltage and the amplitude of the discharge current.

Under typical conditions of pulsed vacuum breakdown, heating of the anode by the electron flux occurs rather rapidly. The plasma which is formed near the anode is an efficient source of ions, which accelerate the rise of the current in the gap both as the result of compensation of electron space charge and as a consequence of the additional shortening of the vacuum part of the gap as the result of the contrary motion of the anode plasma.[4,12,96,108-110]

To consider the question of the heating and evaporation of the anode it is necessary to solve the thermal problem as was done in Ref. 11, with the only difference that the source of heat is not a surface source but a volume source. Analysis shows[66,112] that at first there is a rapid rise of the anode temperature, and then the temperature reaches some quasistationary value T_a^* which varies only slightly over a wide range of density of energy flow (10^8–10^{10} W/cm^2) as a consequence of the rise of the energy loss to evaporation. The temperature of the anode vapor is equal to the temperature of

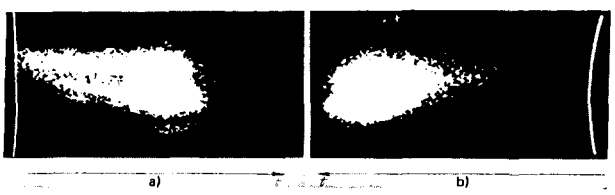

FIG. 15. Typical electron-optical chronograms of cathode luminescence (a) and anode luminescence (b) in a direction parallel to the electrode axis, recorded in pulsed breakdown of a 1.25-mm vacuum gap with indium electrodes. The origin of the sweep corresponds to the moment of beginning of the breakdown current rise.

the anode surface, since the energy transferred to the vapor by the accelerated electron flux is relatively small.[66] Thus, to determine the velocity of escape of the anode plasma one can use the concept of adiabatic expansion of a gaseous sphere into vacuum. For $\gamma = 5/3$ and for characteristic values $kT_e^* = 0.6-0.8$ eV, the value of V_{af} amounts to $(5-8)\cdot 10^5$ cm/sec, which is in good agreement with a number of experiments.[108,109,112-114] In some cases (Refs. 9, 114, and 113 where the electrodes are made of Bi or Pb) the energy dose delivered to the anode material by the electron beam exceeds by several times the heat of sublimation and, obviously, hydrodynamical conditions of escape are realized,[111] in which anode-plasma velocities $(1-2)\cdot 10^6$ cm/sec are reached.

In spite of the fact that almost all of the energy in a breakdown is dissipated at the anode, formation of the anode plasma is a secondary process due to the existence of explosive electron emission. Since the anode plasma arises with a delay relative to the beginning of explosive electron emission current, and, as a rule, $V_{ef} < V_{af}$, the role of the anode plasma becomes important only in the final phase of filling of the gap by a conducting medium.

The ideas described above regarding the mechanism of development of breakdown permit one to explain and calculate the parameters of the x-ray pulse in tubes of the diode type.[115] In particular, it has been shown that the duration of the x-ray flash and the radiation dose are proportional to the length of the gap.

5. ROLE OF FIELD EMISSION AND EXPLOSIVE ELECTRON EMISSION IN INITIATION AND DEVELOPMENT OF VACUUM BREAKDOWN AT CONSTANT VOLTAGE

The problem of the mechanism of electrical breakdown in vacuum on application to the gap of a slowly increasing or constant voltage is one of the most controversial questions. This is due in large degree to objective causes. Indeed, in extended application of voltage, a large number of different processes occur simultaneously on the electrodes and in the gap, among which it is difficult to distinguish those directly responsible for the initiation and subsequent development of breakdown. It will be possible to overcome these difficulties only by carrying out studies with use of apparatus possessing high time and spatial resolution, and also high sensitivity.

To investigate the mechanism of development of vacuum breakdown at constant voltage we have carried out a series of experiments[98,104,116,117] at the Institute of High Current Electronics, Siberian Division, USSR Academy of Sciences, including study of breakdown current oscillograms, the regularities of x-ray production, electrode erosion, and the space-time pattern of development of the luminescence which accompanies breakdown. Studies have been carried out for various electrode materials for gap lengths ≤ 1 mm. Analysis of the oscilligrams has shown that the nature of the rise of current is practically the same for constant and pulsed voltages, and the absolute values of the current rise times are also very similar (Fig. 16). The dependences $t_{com}(d)$ have a linear nature. In Table I we have given the ratios d/t_{com} for various electrode materials.[98]

Study of the nature of the current growth in the initial phases of breakdown is of significant interest for understanding the mechanism of initiation and development of breakdown. By connecting the input of a high-speed oscillograph to a nonpotential electrode, we have obtained oscillograms of the rise of the current with high amplitude resolution (Fig. 17).[98,104] In this figure the dashed line shows the behavior of the explosive electron emission current as a function of time according to Eq. (4.5). It is easy to see the good resemblance of the experimental and theoretical dependences $i(t)$.

Observation of electrode erosion by the interrupted-discharge method (the electrical length of the storage line was less than the time t_{com}) showed that, as in pulsed breakdown, there is an appreciable transport of anode material to the cathode. This is explained by the action on the anode of the intense electron flux. For $d = 0.5-1.0$ mm the beginning of rapid erosion of the anode is delayed relative to the beginning of the current rise by 10–20 nsec. The cathode material has the main influence on the time t_{com}. This was proved by experiments in which electrodes of various materials were used.[98] In the first discharges, when there was little transported anode material on the cathode, the time t_{com} was determined by the cathode material. With increase of the number of breakdowns the cathode was more and more covered with anode material, and the time t_{com} gradually approached the value characteristic of the anode material.

Experiments[98,104] have also established a complete analogy with pulsed breakdown in the characteristics of the x rays emitted by the anode during the current rise. As in pulsed breakdown, the duration of the x-ray flash is approximately equal to the time t_{com} and is proportional to the gap length (Fig. 16).

Space-time studies of the kinetics of breakdown at constant voltage have been carried out by means of photoelectric and electron-optical techniques.[98,116] Even with detection of the integrated radiation and with the maximum sensitivity of the photoelectric apparatus it was not possible to detect luminescence in the gap for the 100 nsec before the beginning of the current rise. With accuracy ~10^{-9} sec the luminescence initially ap-

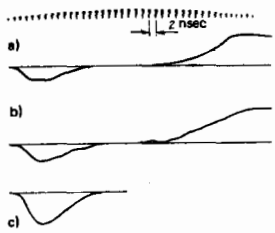

FIG. 16. Oscillograms of the pulse of x rays (left) and breakdown current (right) of a gap of length 0.5 mm at constant voltage (a) and pulsed voltage (b); (c) calculated shape of x-ray pulse.

TABLE I.

Material	Bi	Cd	In,Pb	Sn	Zn	Ti, Ni	C	Cu	Al, Mo	W	Nb	Ta
$d/t_{com}\cdot 10^{-6}$, cm/sec	1.1	1 3	1.35	1.5	1.6	1.9	2.0	2.5	2.6	2.7	3.0	3.5

peared at the cathode simultaneously with the current rise. Luminescence at the anode lagged behind the beginning of the current rise on the average by 10 nsec ($d = 0.7$ mm, electrodes of Cu). If we assume that the delay of the luminescence from the center of the gap is due to the propagation of the luminous medium from the cathode, then its velocity is about $2\cdot 10^6$ cm/sec. Photography by means of an image tube (Fig. 18)[1)] (Refs. 98, 117) confirmed in its entirety the pattern of luminescence development obtained by the photoelectric technique. The difference from pulsed breakdown lies only in the fact that in breakdown at constant voltage there is only one cathode flare. This is understandable, since with a slow increase of the voltage the appearance of several explosive-emission centers simultaneously is unlikely.

Study of the moment of appearance of electrode-material vapor by the method of detecting the resonance radiation of atoms by a photoelectric technique has been carried out also by Davies and Biondi.[118,119] As a whole the results of these studies are consistent with the data of Refs. 98 and 116. However, the use of electrodes of mixed materials in order to learn what kind of electrode plays the most important role in initiation of breakdown is in our opinion incorrect from the methodological point of view, since in each discharge there is a preferential transport of anode material to the cathode. In this respect the statement of the authors that the initial appearance of anode-material vapor near the cathode simultaneously with the beginning of the current rise is due to evaporation in flight of an anode microparticle is not sufficiently justified.

Thus, studies of the development of breakdown at constant voltage carried out with high time resolution show unambiguously that the irreversible destruction of the vacuum insulation in this case also is due to excitation at the cathode of explosive electron emission. This conclusion makes the search for the causes of initiation of the vacuum arc in a static breakdown better defined and more goal-oriented. In our opinion, these causes must be looked for only in association with processes leading to enhancement of the electric field at the cathode and, as a consequence, to excitation of explosive electron emission.

Under conditions of ultrahigh vacuum and high purity of the electrodes, on the assumption that there is no influence of microparticles or evaporation of the anode, excitation of explosive emission involves only development of thermal instability of cathode micropoints.

[1)]In Ref. 98 a scheme was developed for controlling the timing rates of an image amplifier directly by the breakdown current. This scheme excludes the instrumental dead time, which is of fundamental importance for study of the kinetics of static breakdown.

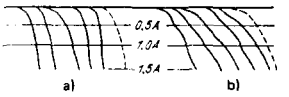

FIG. 17. Experimental (solid) and calculated (dashed) oscillograms of the initial phase of the breakdown current between electrodes of molybdenum (a) and indium (b).

Here, in accordance with the data of Section 2, the value of the critical electric field strength $E_{cr} = \beta E$ should not change with the gap. Constancy of $E_{cr}(d)$ was established experimentally for the first time by Alpert and his colleagures[17] (Fig. 19), and subsequently confirmed by other groups.[119-122] The values of E_{cr} determined experimentally for an extensive set of materials are in the range $(5-10)\cdot 10^7$ V/cm and agree satisfactorily with the theory.[19,20,25,30-32,35] According to the calculations (see Section 2) the limiting densities of the field-emission current for a large number of metals are 10^7-10^8 A/cm^2. This means that the critical breakdown strengths of the electric field for electrodes of various metals should not differ substantially, since they have similar values of the work function.

The work of Alpert *et al.*[17] made a substantial contribution to proof of the cathode mechanism of breakdown initiation at constant voltage. However, an argument against this mechanism is the so-called "total-voltage effect"—the decrease of the breakdown field strength with increase of the breakdown voltage (correspondingly, also of the gap length). At the present time there are a number of experimental data which permit qualitative explanation of this effect while not refuting the role of explosive electron emission in development of the vacuum discharge.

1. The total-voltage effect and the decrease of prebreakdown currents with increase of gap length can be due to the presence of adsorbed gases and vapors on the electrode surfaces. In the presence of surface contaminations, the surface migration of atoms of the cathode material and adsorbate to the region of strong electric field is greatly facilitated, and this leads to growth of the microemitters and development of breakdown. A significant portion of the energy necessary for activation of the migration process is provided as the result of bombardment of the cathode by ions formed in ionization of the residual and adsorbed gases by the electron beam.[123,124] The total-voltage effect can be due to the fact that with increase of the voltage (or gap) the energy and number of the ions produced from the adsorbate increases; correspondingly there is an intensification of the processes of the microemitters becoming

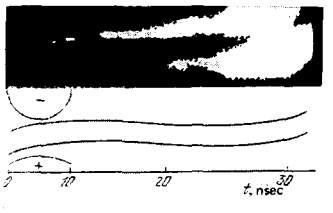

FIG. 18. Electron-optical chronogram of luminescence in breakdown at constant voltage. Copper electrodes, $d = 0.7$ mm.

more pointed and being cleansed of adsorbate (usually adsorbate atoms are electronegative), the frequency and amplitude of oscillations of the prebreakdown current increase, and this finally leads to an increase in the breakdown probability.[10,125,126] In Ref. 126 it was shown convincingly that the total-voltage effect can be reduced to a substantial degree as the result of producing the cleanest possible experimental conditions.

2. The total-voltage effect can be due to the presence on the cathode surface of dielectric films and inclusions. Dielectric films in the form of islands are formed on contaminated electrode surfaces under the action of discharge processes; here the prebreakdown electron current becomes appreciable already at a mean field ~10^4 V/cm.[127] The appearance of this conduction is due to emission of electrons from dielectric islands as a consequence of their self-charging, which leads to enhancement of the electric field at the cathode and in the dielectric.[127] On reaching a field strength ~10^6 V/cm, breakdown of the film occurs, which initiates explosive electron emission. With increase of the ion energy, the ion-electron emission coefficient increases[74] and the conditions for self-charging of the islands are improved. Consequently an increase of the gap length requires less than a proportional increase of the breakdown voltage.

3. On extended application of voltage to the gap, the anode becomes also a supplier of microparticles.[1] References 128 and 129 on achieving an average field ~10^5 V/cm observed removal of microparticles from a polished anode surface which left in it valleys of micron size. Most such valleys were localized at places where foreign inclusions were present, which were located mainly along grain boundaries or near them. Nonmetallic particles deposited on the cathode may become active in initiation of breakdown.

Experiments with metallic particles artificially introduced into the gap have proved convincingly the existence of the polarity effect: the breakdown took place only in those cases when the particles started from the anode and collided with the cathode.[129,130] Little and Smith[129] concluded that inelastic impact of a particle on the cathode leads to formation of effective micropoints of melted metal under the influence of ponderomotive forces. Although these authors[129] did not analyze the further development of the breakdown, the results of their work, which are particularly clear in the case when a transverse magnetic field was used to deflect the electron beam, prove convincingly the cathode mechanism of initiation and development of breakdown.

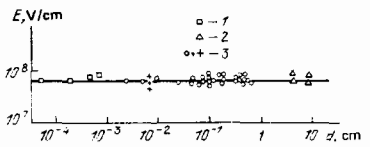

FIG. 19. Critical electric field strength at micropoints as a function of the length of the vacuum gap in the case of clean electrodes of tungsten. 1—data of Ref. 22, 2—Ref. 25, 3—Ref. 17.

In order that the impact of a particle on an electrode be inelastic, its velocity must exceed some value $V_p^* \approx (2\sigma_{lim}/\rho)^{1/2}$ determined by the tensile strength σ_{lim} of the particle and the target.[60] If a particle of radius r is torn out of the anode, its velocity at impact on the cathode will be[131]

$$V_p^* = \sqrt{\frac{9.87\varepsilon_0\beta_a U^2}{r\rho d}}. \tag{5.1}$$

β_a is the enhancement coefficient of the electric field at the anode at the place of removal of the particle. Hence the minimum breakdown voltage necessary for inelastic impact with formation of micropoints is

$$U_{min} = \sqrt{\frac{\sigma_{lim} rd}{4.94\varepsilon_0\beta_a}} \sim \sqrt{d}. \tag{5.2}$$

Analysis shows[131] that for $\beta_a = 1$ and $d \geq 0.1$–1 cm (copper electrodes) the known experimental data can be explained by formation of micropoints on impact onto the cathode of particles of radius $r \leq 1$ μm. If one takes into account that in a real situation β_a can be substantially greater than unity and that the particles can be in a heated (melted) state, then the mechanism considered turns out to be acceptable even for particles of larger size.

In the case of particles of dimensions tens of microns or more the velocity acquired by them in the gap is insufficient for inelastic impact. However, on approach of such a particle to the cathode to a distance less than r, the electric field between the cathode and the particle can increase by several orders of magnitude in comparison with the average field.[1,131,132] If opposite the particle there is a micropoint ($r_0 \approx 10^{-6}$ cm, $\beta \approx 5$), then the electron current emitted by it can heat the bombarded portion of the particle surface even to a temperature of intensive evaporation.[131] In Ref. 131 it is assumed that in this situation as the result of ionization of the vapor a microplasma bunch arises which plays the role of igniting the discharge. Thus, a microparticle by itself is not the direct initiator of the breakdown; it creates either cathode micropoints on inelastic impact or an igniting spark, the plasma of which excites and maintains explosive electron emission. In addition to the total-voltage effect, the approach considered here explains the dominant influence of anode material on the static breakdown voltage,[133] since there is a correlation between σ_{lim} and U_{lim}, and also the reduction of U_{lim} with increase of the size of the particles.[134] For realization of breakdown with participation of a microparticle, an extended flow of an appreciable prebreakdown current is not required at all, since the time from the moment of impact of the particle on the cathode to the explosion of the micropoint or the time of formation of an igniting spark will be extremely small.

Summing up what has been said, we can conclude that the enhancement of the electric field at the cathode during extended maintenance of the electrodes in a strong electric field will depend on many processes. All these processes produce conditions favorable for excitation of explosive emission. After excitation of explosive electron emission the development of breakdown at constant voltage occurs in the same way as for pulsed breakdown.

6. EXPLOSIVE ELECTRON EMISSION AND THE CATHODE SPOT OF A VACUUM ARC

Processes in a cathode spot are extremely complicated and in many respects are still not understood.[10,135-137] Up to the present time the principal attention has been devoted to development of stationary models of a cathode spot based on solution of a closed system of equations for the cathode, the near-cathode layer, and the plasma,[136,138] or on finding regions of existence of a solution which determine regions of possible values of the parameters of a cathode spot.[137] However, stationary models have not explained such experimental facts as the rapid displacement of the spots, fluctuations of the arc voltage, and the existence of multiply charged ions. In these models the roughness of the cathode surface and the inhomogeneities of its chemical composition have not been taken into account. Analysis of the stationary energy balance in a cathode spot on refractory metals[139,140] has shown that over the entire temperature range possible in reality for a cathode surface under a spot, the energy carried away by emitted electrons is much greater than the energy brought in by ions. As a result it has been concluded[139] that an important role is played by a volume heat source, which turns out to be more intense than the surface heat source for a current density in the spot $j \geqslant 10^8$ A/cm^2,[141-143] when one can expect that phenomena of the explosive type, observed in studies of the transition of field emission to an arc and studies of vacuum breakdown, will have a nonstationary nature. In addition, numerous estimates of the strength of the electric field at the cathode under a spot give a value close to that at which vacuum breakdown is initiated. For just these reasons the results of studies of rapidly occurring processes in vacuum breakdown, and subsequently studies of electron emission, have attracted considerable attention by physicists occupied previously with study of the cathode spot.[56,57,63,94,136,137,144,145]

On the basis of studies of processes in vacuum breakdown and explosive electron emission and the phenomenological association of them with processes in the cathode spot, we have repeatedly expressed the opinion that explosive emission phenomena can have decisive significance in the functioning of the spot.[3,13,53,146] Since the state of cathode-spot research as a whole is reflected in the literature,[135-137] we shall dwell only briefly on the new data which characterize the nonstationary nature of the processes in a cathode spot.

a) Crater formation

Daalder[147] studied the craters left on the cathode after burning of a vacuum arc and established that in a certain range of currents which depends on the cathode material a direct proportionality is observed between the average value of the crater radius and the current (Fig. 20). This result is explained satisfactorily in the framework of the nonstationary Joule model of cathode heating described in Section 3. Assuming that the cathode spot at a given location dies out at the moment of time at which heat outflow by conduction begins to play a role, $r_{cr} \approx (\lambda t/\rho c)^{1/2}$, with inclusion of Eq. (3.2) we

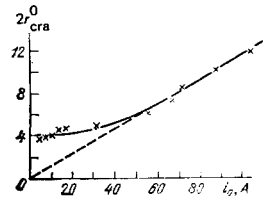

FIG. 20. Average radius of craters on a copper cathode as a function of the arc current.

can determine the final size of the crater on a flat cathode[148]:

$$r_{cr} = \frac{1}{2\pi}\sqrt{\frac{\varkappa_0}{\lambda \ln (T_{cr}/T_0)}}\, i. \qquad (6.1)$$

An expression close to Eq. (6.1) was obtained by Daalder.[147] The value of the ionic component of cathode erosion calculated by him with this approach agrees satisfactorily with the results of experimental study of the ionic component of the plasma generated by the cathode spot.[68,149]

b) Spot motion

Recently investigators have initiated observations of erosion tracks left by a single spark or arc discharge of duration 10^{-7}–10^{-6} sec on a clean and smooth initial surface of cathodes of refractory materials, obtained by melting the tip of a wire in ultrahigh vacuum.[57,93] In Fig. 21a it is possible to count more than ten clearly expressed individual craters. We can assume that the emission zone stayed in one place for less than 10 nsec. The photographs presented convincingly confirm the nonstationary nature of the processes in a cathode spot. If there are no impurities on the cathode surface, the emission centers in no case travel further than the region of melting and, as a rule, are formed at the edge of the craters. As can be seen from Figs. 21b and c, the cathode spot is not attached to the grain boundaries of the microcrystals of molybdenum, and this indicates that regeneration of microprojections at the crater edges affects the jumping of the spot. Consequently, a cathode spot creates craters and micropoints which are not only the consequence of its functioning, but also a necessary condition for its further existence.[10,55,94]

The data shown in Fig. 21 indicate once again with what caution it is necessary to approach a determination of the current density in a cathode spot. If the current is divided by the area of the entire erosion track, the

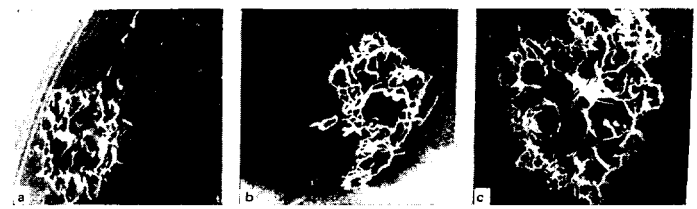

FIG. 21. Autographs of cathode spots. a) Tungsten cathode, $t_p = 100$ nsec, $i = 30$ A (Ref. 93); b and c) molybdenum cathode, $t_p = 500$ nsec, $i = 80$ A. c) $i = 200$ A (Ref. 57). Scale: in part a, 1 cm represents 6 microns; in parts b and c 1 cm represents 25 microns.

current density turns out to be $\approx 2\cdot 10^7$ A/cm^2 for $t = 100$ nsec and falls to about $2\cdot 10^6$ A/cm^2 at $t = 500$ nsec, although it is quite obvious that the true current density is substantially greater.

The random motion of rapidly moving cathode spots (spots of the first type[136,145]) can be explained by the appearance of emission centers as the result of breakdown of nonmetallic inclusions and films on the cathode surface,[84,150] and not by explosion of micropoints as was suggested previously.[145] In fact, at a distance of tens of microns from the initial emission center (the characteristic distance between the fragments of a spot) for realization of the mechanism of breakdown of inclusions and films less severe conditions are required in the near-cathode layer. As was shown in Ref. 84, the minimum probe current and the duration of its flow are of the same order as in the case of fragments of a cathode spot of the first type. Spots of the first type arise only on an uncleaned cathode surface.[50] After cleaning a cathode by arc discharges in ultrahigh vacuum, cathode spots become rather immobile in spite of the presence on the cathode of a large number of micropoints of various sizes formed in discharges.[150]

The spontaneous formation of new cathode spots observed in spark discharges ($di/dt \geq 10^8$ A/sec; see Refs. 135 and 151–153) evidently also occurs by the mechanism of breakdown of nonmetallic films.[84] The process considered is greatly intensified in comparison with an arc discharge as a consequence of the charging of the peripheral layers of the plasma to a high potential. Here the maximum observable velocity of motion of the front of the spots ($\approx 2\cdot 10^6$ cm/sec; see Ref. 153) is determined by the velocity of expansion of the cathode plasma.

The direct motion of cathode spots in spark or arc discharges in vacuum with high velocities apparently also cannot be associated with explosion of micropoints on the cathode,[84] since after passage of a spot there remains a track consisting of individual craters located at distances of tens of microns from each other[147]: the same distance is observed between the luminous fragments of a cathode spot.[145]

c) Inertial properties of the emission of a cathode spot

One of the methods which makes possible investigation of nonstationary phenomena in an arc discharge is the method of detection of transition processes on a sudden change of the arc current. By studying the reaction of an arc to a current jump ($di/dt \approx 10^7$ A/sec), Kesaev[135] and later Paulus *et al.*[154] reached the conclusion that the duration of the transition stage is determined exclusively by the inertial property of cathode processes. In Ref. 155 the reaction of an arc to a current jump with $di/dt \approx 2\cdot 10^{10}$ A/sec was studied with use of high-speed detection of the discharge current and transition voltage, and with probe diagnostics of the plasma potential. At the moment of the current jump a transition spike of voltage was observed on the electrodes, the duration of which t_{tr} increased in direct proportion to the gap length d ($V_{tr} \approx d/t_{tr} \approx 2\cdot 10^6$ cm/sec). For $d = 0.5$–4 mm the arc current increased without inertia (Fig. 22a). For $d = 4$–8 mm the current lagged behind the rise of the applied voltage pulse (Fig. 22b), and the nature and time of its growth to the level i_2 recalled the commutation characteristics of a vacuum spark. In such cases the amplitude of the transition voltage reached 2–10 kV. However, the potential of the plasma at a radius ≤ 0.5 mm from the point of ignition always remained less than 100 V.

The results obtained in Ref. 155 show that emission centers can provide high rates of growth of the current without a substantial increase of the cathode fall, and the interia in formation of new emission centers does not exceed 10^{-9} sec. In addition, it follows from Ref. 155 that there is a dominant role of processes in the plasma column in the transition stage of the discharge. Indeed, the current i_1 in a cross section S of the plasma column is determined by the expression $i_1 = en_1 V_{dr} S$, where V_{dr} is the drift velocity. The new value of plasma concentration $n_2 \gg n_1$ which is established after a time t_{tr} should correspond to a new current level $i_2 \gg i_1$. However, for $d \leq 4$ mm the new current value is established practically without inertia, which can be explained only by an increase of the electron drift velocity V_{dr}.

In its dynamics the transition process occurs as follows. At the moment of the current jump a certain increase of the potential drop near the cathode (by tens of volts) produces intensification of emission processes in existing emission centers and the explosive appearance of new centers. This process is accompanied by generation of a denser plasma corresponding to the new current level. Between the new, denser plasma and the initial plasma there arises a double electrical layer which moves with the velocity of the cathode plasma $V_{cf} \approx 2\cdot 10^6$ cm/sec. Probe measurements confirm the picture of motion of the layer. For $d \geq 4$ mm the concentration of the initial plasma near the anode is so small that between the newly formed plasma and the anode in a time $\leq 5\cdot 10^{-8}$ sec a vacuum gap appears as a consequence of the rapid rise of the thickness of the double layer.

Analysis of the data of Ref. 155 permits a number of conclusions to be drawn.

a) The lower limit $(di/dt)_{cr}$ at which the process of filling of the gap with plasma still succeeds in following the rate of rise of current, and the transition voltage does not differ substantially from the near-cathode drop, can be estimated from the expression

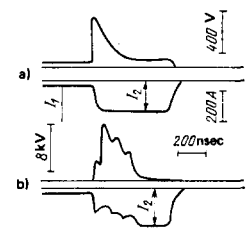

FIG. 22. Oscillograms of discharge current (lower traces) and voltage in the gap (upper traces) characterizing processes for a jump of arc current. a) $d = 4$ mm, b) $d = 6$ mm.

$$\left(\frac{di}{dt}\right)_{cr} \approx \frac{i_{thr}}{t_{tr}} \approx \frac{i_{thr} V_{tr}}{d}, \quad (6.2)$$

where i_{thr} is the threshold arc current. In application to Ref. 154 ($d = 5$ mm, $V_{tr} \approx 1.2 \cdot 10^6$ cm/sec) we have $(di/dt)_{cr} \approx 6 \cdot 10^6$ A/sec.

b) The lower limit $(di/dt)_{cr}$ at which one can already note the inertial nature of the emission of the cathode spot can be estimated as follows:

$$\left(\frac{di}{dt}\right)_{cr} \approx j \frac{dS_{cf}}{dt} = j \cdot 4\pi V_{cf}^2 t. \quad (6.3)$$

For an explosive emission current density $j = 5 \cdot 10^8$ A/cm^2 and a characteristic time $t = 10^{-8}$ sec the steepness of the current is $(di/dt)_{cr} \approx 10^{14}$ A/sec.

c) The duration of the voltage spikes of the arc at currents close to threshold is determined by the dynamics of variation of the conductivity of the plasma column. The fact of correlation of voltage spikes and the motion of the plasma jets from the cathode in an arc discharge was established in Ref. 147.

In conclusion we note that at the present time a number of contradictory ideas have accumulated regarding the role of explosive emission processes in cathode spots of vacuum arcs. For example, Mitterauer[144] considers that explosive electron emission completely determines the essence of processes in a cathode spot. According to Ref. 94, explosive electron emission is a necessary initiating act in functioning of the cathode spot, but the role of explosive processes increases in the transition to refractory metals, and also with increase of the arc current. Ekker[137] has pointed out that processes in a cathode spot can be a superposition of explosive electron emission and ordinary thermionic field emission accompanied by quasistationary evaporation of metal atoms, the relation between the explosive and nonexplosive processes depending on the specific conditions of the experiment. It is quite possible that the functioning of nonstationary cathode spots with current density $j \geq 10^8$ A/cm^2 will lead with time to substantial heating of a portion of the cathode surface and to a transition to a quasistationary spot with a current density $\approx 5 \cdot 10^5$ A/cm^2 and a spot temperature $\approx 4 \cdot 10^3$ K.[138] Further research is necessary to answer this question unambiguously.

7. DISCHARGE IN VACUUM ALONG A DIELECTRIC SURFACE

An electrical discharge along the surface of a dielectric in vacuum is interesting not only in its physical aspect, but also has great practical significance.

The presence of a dielectric in a vacuum gap substantially influences the discharge process. An especially important role is played by processes at the cathode-dielectric contact.[147] On application of an electric field, luminescence appears at this contact and electron emission begins. The voltage at which luminescence and electron emission appear is reduced with increase of the permittivity of the dielectric and the field strength at the cathode, and depends on the configuration of the cathode and dielectric at the cathode contact.[157] In study of a pulsed discharge it has been established that the electrical strength is affected by the angle of inclination of the insulator surface to the normal to the cathode.[158] The flashover voltage turns out to be greatest for an angle $\varphi = 45°$.

An electron-optical study of the development of a pulsed discharge along the surface of a ceramic placed in a uniform electric field showed[159] that, several nanoseconds after application of voltage, luminescence appears at the edge of the cathode, which propagates to the anode. For a field $E = (1-2) \cdot 10^5$ V/cm the velocity of propagation of the luminescence along the dielectric is $(1-6) \cdot 10^7$ cm/sec. With the advance of the luminescence, the current between the cathode and anode increases (sometimes up to tens of amperes). It has been established that this current has a purely electronic nature.[159,160] When the luminescence reaches the anode, the discharge current rises rapidly (in a time $\approx 10^{-9}$ sec) to a value limited by the resistance of the discharge circuit; at the same time the brightness of the luminescence increases rapidly, both in the region of the contact and in the region of the discharge channel in the dielectric.[159,160]

The mechanism of the discharge along a dielectric surface in vacuum has still been inadequately studied. We shall mention only certain processes which in our opinion are important.

a) The initiating role is played by field emission from the cathode at the location of the cathode-dielectric contact. At this contact there always are microgaps of width δ, and on the cathode there are microprojections with a field-enhancement coefficient β. If $\varepsilon\delta \ll d$, where ε is the permittivity, then the field at the microprojections at the cathode contact will be

$$E_{cath} \approx \varepsilon\beta E_0, \quad (7.1)$$

where $E_0 = U/d$ is the average field in the dielectric. Consequently for large values of ε we should expect a significantly greater field enhancement at the cathode than in the case without a dielectric. This facilitates a reduction of the breakdown voltage with increase of the permittivity of the insulator.

b) An important influence on the discharge process is exerted by secondary electron emission from the dielectric.[156-159] Part of the electrons from the cathode contact hit the dielectric and eject secondary electrons. If the secondary emission coefficient is $\gamma_e > 1$, then the dielectric surface will turn out to be positively charged. This will create conditions of attraction of additional electrons from the cathode contact and will lead to further rise of the positive charge. However, the rise of the surface charge cannot be unlimited, since subsequent electrons will be attracted to the dielectric more rapidly than they can acquire the necessary energy which provides the large coefficient γ_e. In this case the value of γ_e will drop, the growth of the charge will be cut off, and dynamic equilibrium will be established. The electrons will migrate in jumps along the dielectric, and here their energy will be determined not by the applied voltage, but by the length of one link of the chain. For example, for a voltage between electrodes of 10 kV the maximum energy of the electrons does not

exceed 50 eV.[161] Electron-optical studies of a pulsed discharge have shown[162] that the electric field near the cathode is enhanced, and near the anode it is weakened. The process of charging of the dielectric surface propagates from the cathode to the anode with a velocity $\approx 10^9$ cm/sec.

c) A significant influence on the development of the discharge is exerted by gas adsorbed on the dielectric surface. The idea of the role of adsorbed gas, first expressed in Ref. 159, was rapidly accepted.[163,165,166] Knowing the predischarge current i, the velocity of propagation of the luminescence V, and its geometrical dimension L, one can determine the relation between the number of electrons and the number of adsorbed molecules entering the discharge zone.[159] The rate of arrival of electrons in the discharge zone is $dN_e/dt = i/e$, and that of molecules is $dN/dt = N_0 VLm$, where N_0 is the number of molecules per cm^2 of a monolayer and m is the number of monolayers. For example, for several nanoseconds before quenching of the anode luminescence, $i \approx 1$ A, and therefore $dN_e/dt \approx 10^{19}$ electrons per second. For N2, O_2, CO_2, H_2O, and other molecules with allowance for the roughness of the surface, $N_0 \approx 10^{15}$–10^{17} cm^{-2}.[167] For $V = 3 \cdot 10^7$ cm/sec, $L = 0.1$ cm, and $m = 1$, we have $dN/dt = 10^{21}$–10^{23} molecules per second. Consequently, even for a monomolecular layer for each electron there are 10^2–10^4 gas molecules.

These molecules are pulled off the dielectric surface in the predischarge phase mainly as the result of electron-stimulated desorption. The desorption coefficient in this case is high ($\approx 10^2$ molecules per electron[165]). Let us estimate in order of magnitude the density of gas at the dielectric surface in the process of electron-stimulated desorption: $n \approx \gamma i/eV_0 VtL$, where V_0 is the velocity of the desorbed molecules and t is the time. If $V_0 \approx 10^5$ cm/sec and $t \approx 10^{-9}$ sec, then under the conditions of the experiment of Ref. 159 $n \approx 10^{18}$ molecules/cm^3, which corresponds to a gas pressure of the order 10^4 Pa in a gas-layer thickness $\approx 10^{-4}$ cm. In this gas layer a discharge can develop. Thus, even a monolayer of gas can provide conditions for development of a discharge along the dielectric. This amount of gas is held on the surface of any dielectric regardless of the vacuum conditions. Apparently for this reason in a number of experiments no relation was observed of the characteristics of surface breakdown with the residual gas pressure, on the one hand, and with the properties of the dielectric on the other hand.[1]

d) In the concluding stages of the discharge an important role is played by explosive electron emission. With extremely high electric fields at the cathode (for example, if the cathode has the shape of a point) it can arise directly in a time of about 10^{-9} sec after application of voltage,[168] as occurs in an ordinary pulsed vacuum discharge. In the process of formation of the discharge, explosive electron emission arises as the result of enhancement of the electric field in the cathode region, on the one hand as a result of positive charging of the dielectric, and on the other hand as a consequence of drift of positive ions to the cathode. In this way one can explain the appearance of electron current up to tens of amperes even before complete breakdown of the gap.[160] In the final phase of the discharge, explosive electron emission provides the formation of the cathode spot of the vacuum arc.

8. CONCLUSIONS

In this review we have devoted the main attention to the role of emission phenomena in electrical discharges in vacuum. We have shown that field emission and the explosive electron emission excited by it play a fundamental role in initiation and the subsequent development of a vacuum discharge up to the arc phase. On the basis of a number of experimental and theoretical studies carried out mainly in recent years, we have presented proofs that, under conditions of real experiments, various additional processes (for example, heating and evaporation of the anode, desorption and adsorption of gases and vapors, migration and diffusion of atoms, ion bombardment, impact of microparticles, and so forth) lead eventually to enhancement of the electric field at the cathode and intensification of field emission, and thereby make possible the excitation of explosive emission and the transition to breakdown at electric fields less than in the case when these processes do not occur.

It must be noted, however, that study of emission processes and their role in a vacuum discharge is far from complete. The great diversity of experimental conditions hinders considerably the identification of the most general and fundamental aspects of the phenomenon. Of the greatest value here are studies with use of the newest methods of analysis of surfaces and nonstationary processes on electrodes and in the gap. In the final analysis, investigations of this type will permit one to trace in detail in what way various processes, to some extent mutually related, lead to enhancement of the electric field at the cathode and to the transition to explosive emission.

Also presenting undoubted interest is the further study of nonstationary processes at the cathode in an arc discharge, since this will permit one to establish more definitely the role of field emission and explosive electron emission in the functioning of cathode spots of vacuum arcs.

The very phenomenon of explosive electron emission contains a great deal which is still to be learned. Since the state of the cathode material in the region of the metal-plasma phase boundary remains unknown, only qualitative ideas are expressed regarding the mechanism of passage of electrons through the phase boundary. Here we must point out also the objective difficulties in study of this phenomenon. First, the extent of the regions in which the processes under investigation occur is extremely small, and the electric field strength, the particle temperature and concentration, and the corresponding gradients are extremely high. Second, here we are dealing with a situation in which the four states of matter are concentrated in region a few microns in size and in which intense emission and erosion processes are occurring simultaneously. Third, the processes considered are clearly nonstationary and have a

cycle with a time scale in the range 10^{-9}–10^{-8} sec. It appears to us that progress in further understanding of explosive emission can be achieved both by theoretical analysis of the phenomenon with inclusion of the achievements in the field of study of the state of matter at high energy densitiies, and by experimental study of the characteristics of a single explosive-emission cycle.

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