PRIMARY AND SECONDARY PROCESSES OF EXPLOSIVE ELECTRON EMISSION

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The phenomenon of explosive electron emission (EEE) consists in an intense emission of an electron current as a result of a transition of the material of the cathode from the condensed phase to a dense plasma, due to heating of local regions by the inherent emission current [1-6]. The discovery of EEE has made it possible not only to approach an explanation of many physical processes in vacuum and gas discharges and in electric arcs, but also to build new electronic sources of large currents, whose use in quantum electronics, shf electronics, pulsed x-ray techniques, etc., has led to a real revolution, since, in a majority of cases, it has been possible to increase the pulsed power of the radiation by many orders of magnitude. Scientific investigations in the field of EEE, as well as investigations of processes in diodes with EEE, the successful development of the technology of powerful nanosecond pulses in relativistic electron bunches, have made it possible to develop a new direction in electronics, i.e., strong-current electronics. Explosive electron emission is a complex phenomenon. It includes processes leading to the creation of a phase transition, processes taking place at an interface between a metal and a plasma, and its interaction with an electron current. EEE is characterized by a large density of the plasma (not less than 10^{20} cm^{-3}) in the cathode part of the emission zone, its strong inhomogeneity in small volume ($\sim 10^{-6}$-10^{-3} cm^{-3}), the brevity of its flow processes (10^{-10}-10^{-8} sec), a large density of the current at the cathode (10^7-10^8 A/cm^2), etc. This phenomenon has several stages, of which the main stages are processes of the initiation of EEE, and primary and secondary processes.

1. Initiation of EEE. The process of initiation of EEE consists in creating an original metal–plasma phase transition at the cathode, which will assure an electron current capable of then maintaining this transition independently. To effect such a transition it is necessary to create a large concentration of energy in a microvolume of the cathode, to assure the explosion of this volume. Therefore, such an emission has been called explosive. A large concentration of energy in a microvolume can be set up in different ways (the impact of a fast microparticle on the cathode, a focused laser beam or a beam of ions, etc); however, the most frequently encountered and widely used for the initiation of EEE is autoelectronic emission (AEE).

An important parameter characterizing EEE is the dependence of the lag time of the explosion t_l of a section of the cathode on the current density j of the AEE. Experimental [7] and theoretical investigations lead to the dependence

$$\int_0^{t_l} j^2(t)\,dt = \text{const}.$$

For tungsten const = $4 \cdot 10^9$ A^2/cm^4 [7]; therefore, to obtain $t_l = 10^{-9}$ sec, it is necessary to have $j \approx 10^9$ A/cm^2, which is achieved with an electrical field $E \approx 10^8$ V/cm. Such a high intensity of the electric field can be obtained at the tip of a specially built thin microemitter. However, an explosive emission arises also with the use of flat electrodes, where the mean intensity of the field $E > 10^5$ V/cm. This is explained by a considerable reinforcement of the field and a lowering of the work function of the local regions of the cathode, which is due to the presence of microscopic protrusions on any flat surface of the cathode, as well as dielectric films and inclusions, and adsorbed gases [9].

For a quantitative estimation of the effect of microprotrusions, use is made of the concept of the reinforcement of the electrical field β. In the case of simple geometrical forms of the protrusions (a semiellipsoid, a sphere on a thin base, a cylinder with a spherical tip, etc.), with $\beta \gg 1$ the reinforcement coefficient of the field [9] $\beta = \alpha h/r$, where h and r are the height and radius of the tip of a protrusion. The coefficient α for different cases is equal to 0.4-1. It has been shown in a large number of measurements that, at a flat cathode, EEE arises after a time $t_l \approx 10^{-9}$ with a field $E \geq 10^5$ V/cm. Consequently, the presence of

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$\beta = 10^3$ must be assumed. However, a large number of observations do not always lead to the observance of microprotrusions with values of h/r corresponding to such values of β. The most frequently observed values are $\beta = 10\text{-}100$.

This contradiction is explained by the combined effect of micropeaks and dielectric films and inclusions, which appears, specifically, as a strong effect of contaminants of the cathode on the lowering of the electrical strength of vacuum gaps. The number of dielectric contaminants, e.g., is of the order of $10^{-8}\text{-}10^{-7}$ Γ/cm^2, which, with a specific weight of the contaminants of 1-10 Γ/cm^3, corresponding to less than a monoatomic layer, already leads to an appreciable lowering of the vacuum strength [10]. Their effect on the initiation of EEE is due to the formation of islands, whose role manifests itself in a lowering of the work function of sections of the cathode, as well as in "self-charging," leading to an additional lowering of the electrical field at the cathode [10]. Such "self-charging" can also occur due to anode ions and ions of residual gases, as well as due to processes in the dielectric itself (shock ionization over the thickness and in the pores of an island, the arrival of electrons from the dielectric in the vacuum, the photoeffect, etc.). The surface charging of an island up to the intensity of the field 10^6 V/cm leads to its breakdown, which initiates EEE. A detailed investigation of processes initiating EEE was made in [4].

2. Primary Processes. The explosion of a microsection of the cathode, the formation of a cathode plasma, and effects bringing about the emission of electrons from a primary emission center will be called primary processes. Since primary and secondary cathode processes are due to a considerable extent to the properties of the cathode plasma and the interaction between the emitting electrons and the cathode, we shall examine these questions in more detail.

After the explosion of a microsection of the cathode, a so-called cathode flare is formed, which consists mainly of the plasma and the vapors of the material of the cathode. The distribution of the concentration of the plasma in a cathode flare is nonuniform. The concentration of the plasma immediately at the cathode is $\sim 10^{20}$ cm^3 [5]; it then decreases along the radius of the flare. The mean concentration of particles in the plasma with a current of ~100 A, after a time of from 5 to 20 nsec, falls from 10^7 cm^{-3} to $5 \cdot 10^{15}$ cm^{-3} [5]. An important characteristic of a cathode plasma is the velocity of its flight into a vacuum. A large number of experimental investigations have shown that, in the initial period of time $t < 10^{-7}$ sec, the velocity of the flight of the plasma for a majority of metals is $(1\text{-}3) \cdot 10^6$ cm/sec [11]; it then decreases considerably, by at least an order of magnitude. The velocity of the plasma in the initial stage is satisfactorily explained within the framework of a model of adiabatic flight, proposed in [6] and developed in [12]. A more attentive study of the process of the flight of a cathode plasma in the initial period points to a need to take account of heating of the plasma by Joule heat, since, in the first place, the conductivity of a cathode plasma is considerably less than the conductivity of the metal; in the second place, after an explosion, there is a weak rise in the electron current. Evaluations show that estimation of the heating of a plasma taking account of the conductivity using the classical formulas [13] leads to an electron temperature of 10-20 eV.

For calculation of the current of the EEE, the "3/2 law" can be used, taking account of the configuration of the plasma [14, 5]. In general form, without taking account of relativistic effects and of the intrinsic field of a bunch of electrons, the relationship for determination of the electron current is written in the form [5]

$$i/u^{3/2} \cdot = F(vt/d), \tag{2.1}$$

where u, d are the difference in the potentials and the distance between the cathode and the anode; v, rate of expansion of the plasma. For example, for the case where a flare is formed at the tip of a sharp cathode with $vt \ll d$,

$$F(vt/d) = Avt/d,$$

where $A = 37 \cdot 10^{-6}$ AB$^{3/2}$ [15].

During the process of the flight of the plasma, its concentration will be lowered. When the concentration of the plasma has been lowered to such a degree that the thermal current transmitted by it is equal to the current according to the "3/2 law," the velocity of the motion of its boundary is slowed, as occurs in steady-state plasma sources of electrons [16]. This leads to a slowing of the rise of the current in comparison with (2.1). Under these conditions, the electron current will be equal to the thermal flow of the plasma. Such conditions of EEE have been called saturation conditions. In an experiment with a vacuum gap (sharp cathode—flat anode) with a length of 2 cm with a voltage of 30 kV, the concentration of the plasma under saturation conditions with $j \approx 10$ A/cm^2 was ~10^{11} cm^{-3} and, with j = 1 A/cm^2, ~10^9 cm^{-3}.

The character of the growth of the current corresponds to the picture described above if the saturation current is not lower than ten amperes. With smaller currents (on the order of an ampere), the saturation phase can end in breakaway of the current. The current at which this breakaway occurs is greater the greater the time of the functioning of the explosive emission. Process of the take-off of the electron current with EEE and of generation of a plasma at the cathode are interconnected. The greater the current, the higher the temperature of the plasma. Therefore, there exists a threshold current, below which there is no emission of electrons from the plasma [17].

If the density of the current withdrawn from the plasma attains values of the order of 10^2 A/cm^2, then, instead of saturation conditions, unstable EEE conditions set in, which are characterized by chaotic excursions on the oscillograms of the EEE current, whose amplitudes are 2-3 times greater then the current according to the "3/2 law," and the duration is ~10^{-8} sec. Therefore, the initial conditions of the expansion of the plasma and the limitation of the EEE current by the charge of the electrodes will be called stable conditions. At the same time as the excursions under unstable conditions, the density of the axis of the bunch rises by 5 times or more. At the moments of excursions of the current, there is an acceleration of a certain number of positive ions of the cathode plasma toward the side of the anode. The energy of these ions attains 0.3-1.0 MeV with a difference in the potentials of 80-3000 kV [18].

One of the important special characteristics of unstable EEE is a short-term rise in the pontential of the peripheral sections of the cathode plasma during the time of the excursions of the current [19]. The existence of this effect is again convincingly shown in [20] with measurement of the potential of the plasma using floating probes. There are several reasons for the existence of this effect. In the first place, with a rise in the electron current of the EEE, a moment may arise when the number of electrons emitted by the plasma in a vacuum will be greater than the number which enter the plasma from the cathode, which leads to charging of the plasma. In the second place, the potential of the plasma can rise due to the ohmic drop of the voltages in it. In addition, in [21], the connection between the excursions of the potential of the cathode plasma and the electron current of the EEE, with nonuniformity of the arrival of the material of the cathode in the plasma, is demonstrated.

One of the main problems in primary processes is the mechanism of the emission of electrons from the cathode into the plasma. If it is taken into consideration that the density of the electron current at the cathode is on the order of ~10^8 A/cm^2 [5], the temperature of the plasma is ~4-5 eV [22], the electric field in the cathode layer should be $(0.6\text{-}1)\cdot 10^8$ V/cm. Holographic and interferometric measurements [23, 24] showed that, at a distance of ~10^{-2} cm from the tip of the cathode, the concentration of the plasma attain 10^{19} cm^{-3}, which does not contradict the evaluations made above.

We note that, with the impact of ions at the surface of the cathode, the potential barrier, through which an electron must tunnel, can take on a complex configuration during the act of emission. In particular, there is the possibility of a case with two or more tunnel barriers, separated by potential walls. Under these circumstances, there is a possibility of resonance tunneling, where the resultant transparency coefficient is close to unity. An interesting approach is developed in [25]. Examining the emission of electrons into a plasma, the authors considered subbarrier collisions between tunneling electrons and ions of a plasma. This leads also to an effect of resonance tunneling, favoring the development of large current densities.

3. Formation of New Emission Centers. One important secondary process is the formation of new centers of EEE at the cathode under the action of the plasma of a primary flare. Observation of the structure of the electron current in a diode with flat electrodes showed that, in the process of EEE, in the immediate vicinity of the primary center of the emission new centers arise [26]. It was then shown by direct experiments that, with expansion of the plasma over the surface in the cathode in the presence of an external electric field, new emission centers develop with interaction between the plasma and the cathode. The new emission centers

can be formed both in the immediate vicinity of old centers at a distance of not more than 10^{-4} cm, and at a considerable removal from them. Here, new emission centers were formed at a distance $r < 10^{-2}$ cm, and then with $r > 0.2$ cm [20]. In the interval between them, there was a zone where new emission centers practically did not develop.

To explain the mechanism of the development of new emission centers, let us examine more attentively the conditions at the cathode-plasma interface. The intensity of the electric field E in the precathode layer and its thickness L in the case of conditions without collisions are determined from the expressions [28]

$$E = E_i(eU_c/kT_i)^{1/4}, \quad L = L_i(eU_c/kT_i)^{3/4},$$

where $E_i = (4\pi n_i kT_i)^{1/2}$; $L_i = (kT_i/4\pi n_e e^2)^{1/2}$; U_c, cathode drop; n_i, T_i, concentration and temperature of the ions of the plasma. Here, $v = 2 \cdot 10^6$ cm/sec; $kT_i = 5$ eV, and the value of U_c is equal to the cathode drop in a vacuum arc. We shall estimate the concentration of the plasma from the entrainment of mass, assuming that $n_{i,e} \sim 1/r^2$ [12], where r is the radius.

With $U_c = 15$ V, the field $E = 10^8$ V/cm, required for the start of EEE, can be achieved with $r \approx 10^{-4}$ cm, i.e., immediately in the zone of the emission. It is obvious that it is precisely this fact which brings about the appearance of new emission centers in the craters of the primary emission centers [29].

Under these conditions, a new emission center due to the explosion of points can arise only with small values of r, if the reinforcement coefficient of the field $\beta = 100$, i.e., with a height of the point of $h \approx 100r$. However, an appreciable reinforcement of the field can be achieved only with points whose dimensions $h \ll L$ since the cathode plasma screens points of large dimensions. Under these circumstances, the dimension of the cathode radius of the points will be not more than 10^{-7} cm. Under these conditions, a considerable role starts to be played by dimensional effects, leading to a situation in which the electrons are scattered at the boundaries of an emitting protrusion [30]. The critical current density needed for the breakdown of such a microprotrusion decreases by $2r_c/\lambda$ times, where λ is the length of the free flight path of an electron interaction of the temperature of the breakdown of the cathode. This circumstance facilitates the development of new centers of EEE beneath the plasma. However, the probability of the appearance of new centers of EEE below the plasma due to the direct explosion of points is obviously possible only in a zone adjacent to an emission center.

One probable mechanism of the formation of emission centers in this region is the charging of the dielectric inclusions and films at the cathode, due to a flow of ions from the plasma and their subsequent breakdown. Along the charging of a dielectric, there may be a flow of charge away from it through a volumetric resistance or of charges over the surface of the dielectric. The intensity of the field is determined from the relationship $E(t) = j\rho[1 - \exp(-t/\rho\varepsilon_0\varepsilon)]$, where ρ is the specific resistance of the dielectric; ε_0 and ε are the dielectric constant and the dielectrical permeability; $j = en_iv_i$ is the current density. With $t/\rho\varepsilon_0\varepsilon \ll 1$, we obtain the obvious linear dependence

$$E \approx jt/\varepsilon\varepsilon_0.$$

From the investigation of the breakdown of thin dielectric films, it is well known that the breakdown takes place at the points of microprotrusions at the cathode. With $E > 10^6$ V/cm, the lag time of the breakdown is $<10^{-9}$ sec. Consequently, the charging time of the film up to the breakdown voltage with a small leakage is written in the form

$$t_l \sim \varepsilon_0\varepsilon E/en_iv_i. \tag{3.1}$$

It can be proposed why new emission centers develop at small and great distances r from a primary emission center. Since $n_i \sim 1/r^2$, then, in accordance with (3.1), the time $t_l \sim r^2/v_i$. Therefore, with small values of r, the breakdown of the film and the appearance of new emission centers take place due to the high concentration of the plasma, and, with large values of r, due to a sharp rise in the potential of the boundary layers of the plasma and an increase in v_i. The latter is confirmed by the coincidence of the moment of the appearance of a new emission center and of an excursion of the potential of the plasma, measured by a probe method [20].

The imposition of a transverse magnetic field leads to the creation of new emission centers at the surface of the cathode [32]. Experiments carried out in a coaxial diode with a disk-type cathode at whose edge the appearance of a primary emission center was artifically initiated showed that the multiplication of emission centers takes place in the direction of the drift of the plasma. Using probes, installed at different distances from the point of installation of the primary emission center, the velocity of the motion of the boundary of the formation of new emission centers was determined; it amounted to $(2\text{-}3) \cdot 10^6$ cm/sec. It was established that new emission centers appear with a growth of the current in the diode and an increase in the potential of the peripheral sections of the plasma (up to kilovolts). In this case, there is charging by the ionic current, and a breakdown of the dielectric films and inclusions, which initiates the development of new emission centers.

4. Shielding Effect. In a secondary EEE process, there are effects favoring the appearance of new emission centers, and effects which prevent them. The latter are explained by the fact that the appearance of any kind of emission center leads to the development and growth of an electron current. The space charge of these electrons lowers the electrical field in the region adjacent to the emission center. Even an insignificant lowering of the field leads to a substantial decrease in the current of autoelectronic emission from micropoints, which inhibits the spontaneous development of new emission centers. This effect appears clearly in a diode with a multipoint cathode. In these diodes, the usual number of exploding points is less than their total number. For example, if there are two cathodes, in the first there are 0.16 cm^2 per one point, and in the second 1.25 cm^2. Under these circumstances, the decrease of the distance between the anode and the cathode from 100 to 40 mm leads to a rise in the number of exploding points in the first case from 1 to 4%, and, in the second case, from 25 to 60%.

For an evaluation of the shielding effect, the influence of the space charge on the electrical field of adjacent points was calculated. At the tip of a point with a height a let there be a plasma ball of radius $r = vt$, from which the current is taken off according to the "3/2 law." The problem was solved self-consistently taking account of the space charge. Calculations showed that, with $r = a/100$, at a point with the coordinates $x = a$, $\sqrt{y^2 + z^2} = a/2$ the potential of the field decreases by 21% and, with $r = a/3.5$, by 65%.

One possibility for decreasing the shielding effect consists in the use of a magnetic field. Electrons from the cathode plasma of an emission center are emitted in different directions; therefore, the area on the cathode where the space charge of the electrons appears will be great. A magnetic field acts as an electron bunch, and decreases this area. For example, experiments with a coaxial diode showed that, with a pulse length of 5 nsec, a diameter of the cathode d = 15 mm, and a potential of the cathode of 500 kV, a growth of the magnetic field from 0 to 30 kOe leads to an increase in the number of new emission centers from 3-5 to 50 or more. In this case, the possibility of the appearance of emission centers due to the drift of the plasma was excluded, since, in the time of a pulse, the plasma moves no more than 0.1 mm.

LITERATURE CITED

1. G. A. Mesyats, "Investigations of the generation of powerful nanosecond pulses," Dissertation in competition for the scientific degree of Doctor of Physical and Mathematical Sciences, Tomsk (1966).
2. G. N. Fursei and P. N. Vorontsov-Vel'yaminov, "Qualitative model of the initiation of a vacuum arc," Zh. Tekh. Fiz., 37, No. 10 (1967).
3. S. P. Bugaev, A. M. Iskol'dskii, G. A. Mesyats, and D. I. Proskurovskii, "Electro-optical observance of the initiation and development of the breakdown of a short vacuum gap," Zh. Tekh. Fiz., 37, No. 12 (1967).
4. G. N. Fursei, "Investigation of an autoelectronic emission in extremely strong electrical fields under the conditions of a transition in a vacuum arc," Doctoral Dissertation (1972).
5. G. A. Mesyats and D. I. Proskurovskii, "Explosive emission of electrons from metallic points," Pisma Zh. Eksp. Tekh. Fiz., 13, 7-10 (1971).
6. G. S. Mesyats, "The role of fast processes in vacuum breakdown," in: Proceedings of Tenth International Conference on Phenomena in Ionized Gases, Invited Papers, Oxford (1971).
7. G. K. Kartsev, G. A. Mesyats, D. I. Proskurovskii, V. P. Rotshtein, and G. N. Fursei, "Investigation of the time characteristics of the transition of an AEE to a vacuum arc," Dokl. Akad. Nauk SSSR, 192, No. 2 (1970).

8. E. A. Litvinov, G. A. Mesyats, and A. F. Shubin, "Calculation of a thermoautoemission, preceding the explosion of microemitters under the action of pulses of an autoelectronic current," Izv. Vyssh. Uchebn. Zaved., Fiz., No. 4 (1970).
9. I. N. Slivkov, Electrical Insulation and a Discharge in a Vacuum [in Russian], Atomizdat, Moscow (1972).
10. F. G. Zheleznikov, "The mechanism of emission processes, bringing about the conductivity of vacuum insulation," Zh. Tekh. Fiz., 48, No. 6 (1978).
11. S. P. Bugaev, E. A. Litvinov, G. A. Mesyats, and D. P. Proskurovskii, "Explosive emission of electrons," Usp. Fiz. Nauk, 115, No. 1 (1975).
12. E. A. Litvinov, "Kinetics of a cathode flare with EEE," in: Powerful Nanosecond Pulses of Sources of Accelerated Electrons [in Russian], Nauka, Novosibirsk (1974).
13. L. Spitzer, Physics of a Completely Ionized Gas [Russian translation], Mir (1965).
14. G. A. Mesyats and D. I. Proskurovskii, "Growth of the current with the pulsed probing of short vacuum gaps," Izv. Vyssh. Uchebn. Zaved., Fiz., No. 1 (1968).
15. G. A. Mesyats and E. A. Litvinov, "The volt—ampere characteristic of a diode with a sharp cathode under conditions of the explosive emission of electrons," Izv. Vyssh. Uchebn. Zaved., Fiz., No. 8 (1972).
16. Yu. E. Kreindel', Plasma Sources of Electrons [in Russian], Atomizdat, Moscow (1977).
17. G. P. Bazhenov and S. M. Chesnokov, "A minimal EEE current," Izv. Vyssh. Uchebn. Zaved., Fiz., No. 11 (1976).
18. E. D. Korop and A. A. Plyutto, "Acceleration of the ions of a cathode material with a vacuum probe," Zh. Tekh. Fiz., 40, No. 12 (1970).
19. E. D. Korop and A. A. Plyutto, "Potential of the plasma of a cathode flare in the initial stage of a vacuum breakdown," Izv. Vyssh. Uchebn. Zaved., Fiz., No. 4 (1973).
20. D. P. Proskurovskii and V. F. Puchkarev, "Formation of new emission centers at the cathode in the process of the cumulation of an electric current in a vacuum," Zh. Tekh. Fiz., 49, No. 12 (1979).
21. G. P. Bazhenov, O. B. Ladyzhenskii, S. M. Chesnokov, and V. G. Shpak, "Probe diagnosis of fluctuations of the potential of a plasma in diodes with an explosive emission," Zh. Tekh. Fiz., 49, No. 1 (1979).
22. R. B. Baksht, S. P. Bugaev, V. P. Stas'ev, and E. A. Litvinov, "Investigation of the formation of a high-current spark by the method of high-speed interferometry," Teplofiz. Vys. Temp., No. 6 (1976).
23. R. B. Baksht, A. P. Kudinov, and E. A. Litvinov, "Investigation of a precathode plasma in the initial stage of a vacuum discharge," Zh. Tekh. Fiz., 43, No. 1 (1973).
24. L. P. Mix, I. G. Kelly, G. W. Kuswa, D. W. Swain, and I. N. Olsen, "Holographic measurements of the plasma in a high-current field emission diode," J. Vac. Sci. Technol., 10, No. 6 (1973).
25. I. M. Livshits and B. E. Meierovich, "Resonance autoelectron emission from a metal to a plasma," Dokl. Akad. Nauk SSSR, 249, No. 4 (1979).
26. G. P. Bazhenov, "Experimental investigation of the explosive emission of electrons," Dissertation in competition for the scientific degree of Candidate of Physical and Mathematical Sciences, Tomsk (1973).
27. G. A. Mesyats, "Electron explosive emission and electrical discharge in vacuum," in: Proceedings of the Sixth Symposium on Discharges and Electrical Insulation in Vacuum, Invited Papers, Swansea, United Kingdom (1974).
28. V. I. Rakhovskii, Physical Principles of the Commutation of an Electrical Current in a Vacuum [in Russian], Nauka, Moscow (1970).
29. D. I. Proskurovskii and E. B. Yankelevich, "Dropwise fraction of the erosion of the cathode with EEE," Radiotekh. Elektron., 24, No. 1 (1979).
30. E. A. Litvinov and A. A. Starobinets, "Limiting currents of an autoelectron emission," Zh. Tekh. Fiz., 47, No. 10 (1977).
31. R. A. Vorob'ev and V. A. Mukhachev, The Breakdown of Thin Dielectric Films [in Russian], Sov. Radio, Moscow (1977).
32. G. A. Mesyats, D. I. Proskourovsky, and V. F. Puchkarev, "On effects resulting in appearance of new emission centers of explosive electron emission," in: Proceedings of Eighth International Symposium on Discharge and Electrical Insulation in Vacuum, Albuquerque, USA (1978).