INFLUENCE OF THE COLD CATHODE MATERIAL ON THE OPERATING MODE OF THE PULSE HIGH – CURRENT VACUUM DIODE IN A MICROSECOND RANGE

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The material of the cold cathode has significant influence on the operating mode of the pulse high-current electron accelerators in the microsecond range. The most effective is the application of graphite cathodes. In this case it is possible to optimize the activity of the diode and to obtain a beam with limiting parameters: pulse duration current and energy values [1, 2]. The high-current beam is formed at the expense of development of explosive electron emission, and its duration is determined by the time of switching with anode and cathode plasma plumes of the accelerating gap [3]. The retraction rate of a cathode plasma is ~ $(1\text{-}2)10^4$ m/s and, practically, does not depend on the material type. Therefore, it is difficult to explain the advantages of using graphite cathodes within existing models. In comparison with other materials, the specific heat of sublimation ~ 6×10^7 J/kg can promote only qualitative explanation of the established experimental facts.

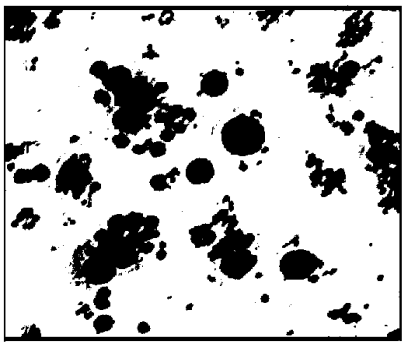
A characteristic of an electrical breakdown in vacuum is the availability of a drop fraction of the cathode material in a discharge channel (aerosol microparticles). The length of the drop fraction increases with increasing pulse duration and after several hundreds of nanoseconds it comes asymptotically close to the value determined in the research on quasi-stationary vacuum arcs of low pressure (~ 50 - 80 %) [4 - 7]. In refs. [8, 9] the assumption is made that the aerosol particles have the characteristic size about of a length of Fermi-electron free run in the material of a cathode. The drop fraction seems to play a decisive role in the processes taking place in a vacuum diode during formation of high-power microsecond electron beams [9, 10].

The present work is aimed at the description of experimental results on the drop fraction of high-power electrical vacuum discharge and analysis of processes, which take place in cold cathodes working in microsecond range of pulses, and also on the influence of the material of a cold cathode on the operating mode of the pulse high-current vacuum diode.

1. EXPERIMENTAL STUDY OF THE DROP FRACTION OF CATHODE MATERIAL UNDER EROSION

An accelerator of direct operation was used for the investigations [11] with the following parameters of the beam: energy ~ 1.5 Mev, current ~ 15 kA, pulse duration ~ 5-15μs. The high- voltage pulse source was a Marx-generator. The cylindrical vacuum chamber of the diode had the dimensions: width 1.1 m, diameter 0.7 m, the distance between the cathode and anode varying in limits of 10-30 cm. Flat cathodes made from various materials: Cu, Al, W, C (graphite), with diameter of 5cm were used. The magnetic insulation of the diode was not used.

The microdispersion fraction resulting from cathode erosion was investigated. The particles were collected on a thin glass plate covered with a coal film of a thickness 10^{-6}cm, which were installed in the field of the anode; exposure time was more than 100 pulses of a beam. Then they were investigated in the electron microscope "Tesla-613" with accelerating voltage ranging from 50 up to 70 kV. The microscope resolving power allowed to attain a precise image of particles of about 3nm. A typical picture of the dispersion fraction resulting from cathode erosion for Al is shown in Fig. 1.



|50 nm|

Fig.1 Microdispersity fraction of yields of cathode erosion for Al

The spherical form, practically, of all particles testifies to their origin from a liquid phase. The statistical analysis of particles has allowed to obtain histograms of cumulative distribution functions depending on the sizes, $F(D)=\Delta N/N\Delta D$, where ΔN is the number of particles with diameter D, $D+\Delta D$; N is the full number of particles. ΔD equals 5nm, N = 120 - 200 particles. The processing of histograms by the method of least squares has allowed to obtain the cumulative distribution function represented in fig. 2 for Cu, Al, W.

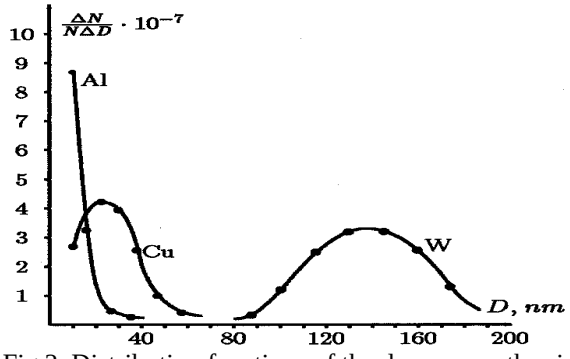


Fig.2. Distribution functions of the drops upon the sizes for Al, Cu, W

From fig. 2 it follows that the maximum of a cumulative distribution function for copper lies in the diameter range of about 20-25 nm, for aluminum it is about 10 nm, for tungsten - 140 nm. For graphite a similar analysis is impossible, since the size of graphite particles more than by three order of magnitude exceeds the size of metal particles, and their registered quantity

is not enough, that does not allow performing statistical analysis.

2. EVALUATION OF THE MICROPARTICLE SIZE AND ENERGY RATIOS

Mean length of free Fermi-electrons in metals can be determined from the well-known ratio:

$$\langle \lambda_F \rangle = \frac{Ed}{\pi n_0 kT} \qquad (1),$$

where n_0 is the concentration of free electrons in metal, which was determined from the value of Hall constant Rx, d is the lattice constant, E- the elastic modulus, k- the Boltsman constant, T- the absolute temperature. The indicated characteristics of materials were taken from [12] and calculated values are listed in the following table.

Table

Cathode matherial	T=293K	$T=T_m$		
	$\langle \lambda_F \rangle$, nm	T_m, K	$\langle \lambda_F \rangle$, nm	$W\cdot 10^{-11}$, J/m^3
C Graphite	$1.76\cdot 10^5$-$9.47\cdot 10^3$	4020	12800-700	3.54
Al	20.7-5.5	933.5	6.5-1.7	1.23
Cu	40-16.6	1357	8.6-3.6	2.58
W	174-51.4	3660	13.9-4.1	5.23

From a comparison of the computed $\langle \lambda_F \rangle$ and the sizes of particles measured experimentally (shown in fig. 2) it follows that a sufficient correlation between these sizes takes place, and the debris of thermal explosions is formed already at low temperature T~ 293 K.

The energy stored in unit of volume of a microedge before the explosive period is determined from a ratio [13].

$W = 0.55\ \pi^4\ \rho\ cT_m \qquad (2),$

where ρ- is the density, c- the specific heat, and T_m-the melting temperature. The dependence of W on the type of material is also shown in the table. It is important to note that before the explosive period, the volumetric energy density in the cathode material some times exceeds the specific energy sublimation for all materials without exception. However, as it is shown experimentally (by the filing of drops in the anode region), the internal energy in them is not concentrated in a random motion of atoms and molecules, since otherwise it would have resulted in an intense sublimation.

The most probable form of that high internal energy of drops can be electrostatic, which value is determined by the following ratio:

$$W_q = n\frac{q^2}{2C} = \frac{1}{\frac{4}{3}\pi r^3}\frac{q^2}{2\times 4\pi\varepsilon_0 r} = \frac{3q^2}{32\pi^2\varepsilon_0 r^4} \qquad (3).$$

Here n is the number of drops per unit volume, C- the capacity of a drop, r- its radius, q- the charge of a drop, ε_0 is the electrical constant. As follows from the assessments, the charge q can be high enough (1000 and more of elementary charges). It is natural, that in this condition, the drops continue to emit electrons, giving the contribution to a common current of the diode. However at a heat equal T_m, at the expense of tunnel effect, the charge exchange of a drop is possible and an acquisition by it of a positive potential $\varphi \approx kT_m/e$, e is the charge of an electron. The presence of positively charged drops in a close proximity of the cathode, obviously, can determine the issuing characteristics of the latter. This fact was also marked in ref. [9].

The minor part of internal energy of a drop is spent against the forces of surface tension of liquid metal:

$$W_\sigma = n4\pi r^2\sigma = \frac{1}{\frac{4}{3}\pi r^3}4\pi r^2\sigma = \frac{3\sigma}{r} \qquad (4),$$

where σ is the surface tension. The evaluation of W_σ shows that its value is almost two order of magnitude less than the full internal energy W before explosive period of material.

3. CONDITIONS DETERMINING THE ORIGIN OF THE DROP FRACTION DURING ELECTRIC EXPLOSION OF CONDUCTORS AND MICROEDGES

The following processes stipulate the formation of a drop fraction in the high-current vacuum discharge. As have been shown in the last study of dynamic phase transformations in microsecond electric conductor explosion, the heavy evaporation of a material takes place only at the initial stage of the impulse. In a consequent instants, the growth of a current in the conductor results in high internal pressure, which stops the evaporation process, since the boiling temperature strongly depends upon pressure. After that, there is a process of a thermal retraction of material [14]. Actually, the pressure along the radius of the conductor varies as follows:

$$P \approx P(a,t) + P(0,t)\left(1 - \frac{r^2}{a^2}\right) \qquad (5),$$

where a is the radius of a conductor, t is the time. Thus, the pressure grows towards the axis of a conductor. In turn $P\ (0,\ t) \sim \mu_0 I^2/(2\pi a)^2$, where I is the current in a conductor, μ_0- the magnetic constant. With increasing current and allocation of energy, the whole conductor transforms in a liquid phase and then boils. However the evaporation takes place only in a part, in which the condition of the liquid-gas phase transition is satisfied. This condition is determined by the Clapeyron- Clausius equation. With reference to a conductor of round cross-section [14] it takes a form:

$$\frac{dT_b}{dP} < \frac{a^2}{r^2 P(0)\alpha} \qquad (6).$$

Here α is the temperature coefficient of the extension of liquid metal, T_b – the temperature of boiling. As follows from (6) the liquid – vapor phase transition is possible

only in the area, in which the gradients of pressure given by dT_b/dP are not so great. In particular, this condition is not satisfied at the surface of a conductor at $r \sim a$, and the high internal pressure results in the explosion of a liquid envelope. Note that at a current density ~10^{11}A/m^2, a~10^4m^2 , the pressure in the axis of a conductor can achieve 10^8 N/m^2, while the pressure at the surface equals the atmospheric one 10^5 N/m^2. The processes due to the heating by the current and a consequent explosion of microedges are similar. The difference consists only in that microedges have variable cross-section, and the current across it, which is defined by the Fauler-Nordgeim law, is amplified at development of the electron explosive emission.

4. MECHANISM OF ENTRY A VAPOR AND CATHODE PLASMA IN INTERELECTRODE GAP OF VACUUM DIODE AND INFLUENCE OF CATHODE MATERIAL ON PARAMETERS OF ELECTRON BEAM. CONCLUSION

Based on the analysis of dynamic phase transformations in electrical conductors and edges of explosion it is possible to offer the following mechanism of the entry of a vapor and cathode plasma in the accelerating gap and of the influence of the material of cold cathode on the beam parameters.

At passing of an auto electron current through microedge, the heating, boiling and evaporation of a surface layer take place. The thickness of an evaporated layer is insignificant and can be determined from a simple ratio $\delta = P(a)a/2P(0)$. With the above mentioned diameter of a conductor, the current makes ~$5\cdot10^{-8}$m^2. It indicates that at the given stage, the quantity of the vapor going in ambient conductor or edge space, is insignificant. For obtaining high-power microsecond electron beams we use extended accelerating gaps (tens cm and more) with a developed surface of electrodes. Taking into account isotropic character of retraction of the vapor it is possible to conclude that the plasma, forming as a result of ionization by electrons, can not supply gap's switching. The main body of an edge material fails due to a thermal explosion and retraction of microscopic particles. The sizes of scattering particles are about the length of free run of Fermi-electrons in a cathode material. The internal energy concentrated in drops exceeds sublimation energy, therefore they continue to evaporate intensively. From a table it follows that diameter of graphite particles is more than three order of magnitude exceeds the diameter of metal. Therefore the total area of smaller-sized particles exceeds the area larger ones by three orders of magnitude (it is possible to show, provided that masses of the particles are identical). Consequently, quantity of the vapor which is let out by metal particles, exceeds the quantity of the vapor which is let out graphite by three orders of magnitude. Therefore it is obvious that in diodes with developed geometry of the graphite cathode, plasma practically is not enough for switching of accelerating gap. For this reason, the use of graphite cathodes allows to receive the high-currents beams with large pulse duration – up to tens of μs and more. The pulse duration is in this case determined by the time of motion of the anode plume to the cathode. Besides the drops in the immediate proximity of the cathode can gain a positive charge and influence the issuing processes.

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