10. A. P. Bykovets and V. B. Repin, "Experimental study of the formation of vortex rings at the open end of a pulse chamber," Fiz. Goreniya Vzryva, No. 1, 78-84 (1980).
11. A. P. Bykovets and V. B. Repin, "Experimental study of the structure of pulse chamber exhaust," in: High-Speed Photography and Metrology of Fast-Acting Processes, Abstracts of Tenth All-Union Scientific-Technical Conference [in Russian], VNIIOFI, Moscow (1981), p. 126.
12. V. V. Furduev, Electroacoustics [in Russian], Gostekhizdat, Moscow-Leningrad (1948).
13. L. Van Wijngaarden and J. H. M. Disselhorst, "Resonant gas oscillations in open pipes," Arch. Mech., 31, No. 1, 115-124 (1979).
14. R. G. Galiullin, I. P. Revva, and G. G. Khalimov, Theory of Thermal Self-Excited Oscillations [in Russian], Kazan State Univ. (1982).
15. E. R. G. Eckert and R. M. Drake, Heat and Mass Transfer (2nd ed.), McGraw-Hill, New York (1959).
16. I. M. Ryzhik and I. S. Gradshtein, Tables of Integrals, Series, and Products, Academic Press (1966).
17. A. V. Lykov, Theory of Heat Conduction [in Russian], Vysshaya Shkola, Moscow (1967).

STUDY OF PHYSICAL PROCESSES IN A SPARK DISCHARGE

V. I. Obukhov

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Temperature and energy balance are calculated for a breakdown channel in a solid dielectric.

Electrical breakdown of solid dielectrics is accompanied by liberation of heat in the discharge gap and scattering of energy into the surrounding medium. Scintillation of the breakdown channel, beginning at the moment of its formation and lasting until the end of the discharge, indicates that the matter within the channel is at a high temperature. Data on temperature and the components of energy balance in the stage of discharge formation in solid dielectrics are not available in the literature, while at the stage of discharge completion available data are scarce.

To measure the diameter of the discharge channel and the energy liberated therein, the apparatus described in [1] was used. Specimens were prepared from rock salt single-crystals. The interelectrode distance d = 1 cm. Breakdown was produced by square voltage pulses with an amplitude of 80 kV in a nonuniform field with positive polarity of the discharge point. The capacitor system used had C = 2400 pF, L = 1.85 μH, and braking resistance R_r = 150 Ω. The discharge was produced in the crystallographic direction (110), with a breakdown channel length l = 1.4, d = 1.4 cm.

Comparison of voltage u(t) and current i(t) oscillograms taken under identical conditions for breakdown of several tens of specimens showed good agreement. Typical u(t) and i(t) oscillograms are shown in Fig. 1.

The pulsed breakdown goes through two stages.

1. Discharge Formation. The time for this stage is shown in Fig. 1 by the segment t_f. It begins at the moment corresponding to the static breakdown voltage U_{st}, and ends with an abrupt drop of voltage across the specimen. In the beginning of breakdown development, electron avalanches develop and transform into a streamer which melts an incomplete breakdown spark channel into the specimen. The streamer propagates from one electrode to the other at a rate of the order of 10^6 cm/sec. By the end of the stage the current density passing through a channel of diameter 1 μm increases to 10^5 A/mm^2. The formation stage is completed by the full extension of the streamer across the gap.

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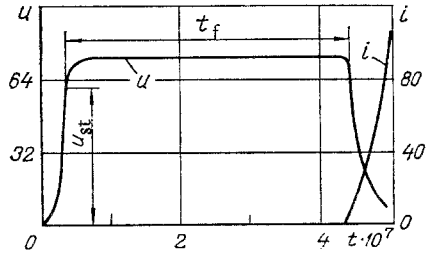

Fig. 1. Typical voltage and current oscillograms for breakdown of NaCl single-crystals. U = 78 kV; C = 2400 pF; L = 1.85 μH; l = 1.4 cm; R_r = 150 Ω; u, kV; i, A; t, sec.

2. Discharge Completion. After the discharge gap is bridged by the streamer, the current density and energy liberation in the channel increase abruptly, reaching maximum values after a time of the order of $(1\text{-}3)\cdot 10^{-8}$ sec. In the last moments the channel resistance falls to values comparable to the braking resistance included in the discharge circuit, and the rate of energy liberation decreases.

To qualitatively estimate the particle density in the breakdown channel, a quartz spectrograph [2] was used to take the spectrum of radiation in the discharge gap of specimens made of rock salt single-crystals.

The spectrum was continuous, and energy distribution over the spectrum was close to that of an incandescent reference lamp with tungsten filament. The plasma radiates a spectrum more characteristic of a solid than a gas. Under these conditions the channel can be considered as a black body, and its radiation, that of an ideal black body. It can be assumed that at the moment of streamer generation and formation of the incomplete breakdown channel the particle density within the channel is close to that in the solid: 10^{22} cm^{-3}. For further calculations the density of NaCl molecules in the channel will be taken as $n_0 = 10^{22}$ cm^{-3}. The incomplete breakdown channel has a radius of 1 μm. It develops due to heating of material to the fusion point by the streamer. Thermal dissociation and ionization processes develop simultaneously. The free electrons formed by ionization of Cl^- acquire energy from the external electric field. Energy exchange between ions and electrons leads to an increase in the channel plasma temperature and scintillation. The temperature growth hinders the processes of heat transfer and radiation.

With consideration of the processes described above, the energy balance in the breakdown channel can be written in the form

$$W = \int_0^t uidt = W_h + W_f + W_D + W_I + W_t + W_c =$$

$$= V\left[\gamma c T_f + \gamma L_f + \alpha n_0 W_d + x n_0 W_i + \frac{3}{2} kT n_0 (x+2) + \frac{2}{m+1}\Delta\gamma c T\left(1 + \frac{1}{m+2}\Delta\right)\right]. \quad (1)$$

To describe the dependence $\alpha = f(T)$ we use data presented in [3]. The basic types of particle which can exist in the plasma channel are ions and atoms of chlorine and sodium, and free electrons. The rate of copper atom migration from the electrodes into the depths of the channel is 100 cm/sec, and at the times under consideration, of the order of hundreds of nsec, such atoms may be neglected. The density of dissociated Na^+ and Cl^- ions up to the time of their ionization is equal to the density of NaCl molecules: $n_{Na^+} = n_{Cl^-} = n_0$.

The density of free electrons produced by ionization of Cl^- ions and the density of Cl atoms is equal to: $n_{Cl} = n_e = n_0 x$. The density of Cl^- ions during the process of their ionization $n_{Cl^-} = n_0(1 - x)$. The total density of particles in the channel $n = n_0(x + 2)$. The number x of Cl^- ions in the discharge formation stage can be determined by using an expression for the current flowing through the incomplete breakdown channel,

$$I = \frac{Erv\varepsilon}{1.8\cdot 10^{12}} = 0.9\cdot 10^{-3} A.$$

TABLE 1. Results of Numerical Calculation of Temperature and Energy Balance W Components, 10^4 J

No.	$t\cdot10^8$, sec	$r\cdot10^4$, cm	$x\cdot10^4$	α	Δ	W_h	W_f	W_D	W_I	W_t	W_c	W
1	1	6	20	0,94	$1,5\cdot10^{-2}$	45	17	84	0,022	33	4,3	183
2	1,5	8	12	0,7	$1,5\cdot10^{-2}$	85	32,6	117	0,25	58	7,5	300
3	3	12	5	0,6	$1,5\cdot10^{-2}$	156	60,5	188	0,16	93	12,4	510
4	3,3	15	1	0,2	$1,5\cdot10^{-2}$	275	106	110	0,06	140	17,7	650
5	3,7	18	0,4	0,028	$1,5\cdot10^{-2}$	414	158	23	0,024	182	23	800
6	20	0,5	0,2	$4,4\cdot10^{-9}$	0,95	0,32	0,12	$1,1\cdot10^{-9}$	$1,4\cdot10^{-5}$	0,047	0,49	0,98[5]

The breakdown electric field intensity E in NaCl single-crystals has a value of $1.6\cdot10^6$ V/cm; $\varepsilon = 5.62$ is the dielectric permittivity; $v = l/t_{fo} = 3.5\cdot10^6$ cm/sec is the mean velocity of electron displacement along the electric field in the channel. The discharge time was determined from voltage oscillograms. Since the current $I = evxn_o\pi r^2$, then

$$x = \frac{0.27\cdot10^7}{13.3\cdot10^{10}} = 2\cdot10^{-5}. \tag{2}$$

It was shown in [1] that in a powerful spark discharge the time required for equalization of the temperatures of individual plasma components comprises $(0.1\text{-}1)\cdot10^{-8}$ sec. Therefore, the plasma can be considered as an equilibrium system and characterized by an equilibrium temperature. If as a first approximation we consider the channel plasma as an ideal gas with equation of state

$$P = nkT, \tag{3}$$

then the degree of ionization x of the Cl^- particles can be determined from Sach's equation.

Substituting for the pressure P in Sach's equation the expression Eq. (3) and the value $W_i = 3.82$ eV, we obtain an expression valid for values $x \leqslant 0.1$, $T = 15{,}000°K$:

$$x = \sqrt{2{,}3\cdot10^{-7}T^{1,5}\exp(-4.5\cdot10^4/T)}. \tag{4}$$

Results of x calculations with Eq. (4) are shown in Table 1.

The difference between the temperature of the channel and the surrounding crystal generates an intense heat flux (energy transfer by collisions). It follows from Eq. (1) that to determine the quantity of energy W_c transferred through the channel wall by thermal conductivity it is necessary to determine the quantity Δ. The values of Δ can be found with the aid of the Fourier similarity criterion. If we assume that the temperature in the heated crystal layer changes linearly along the radius, then m = 1 and the Fourier similarity criterion

$$\frac{at_f}{r^2} = \frac{1}{4}\left(1 + \frac{4}{9}\Delta\right)\Delta^2. \tag{5}$$

Equation (5) defines the dependence $\Delta = f[t_f, r(t_f)]$. Values of $r(t_f)$ are presented in Table 1.

The thermal diffusivity coefficient a can be determined from the physical constants λ and c of the crystal. The heat flux radiated by the channel into the surrounding medium changes the thermophysical properties of the crystalline lattice. In the region directly adjacent to the channel the material is in a fused state. With removal from the channel the temperature decreases to the original value.

The linear expansion coefficient δ is related to the specific heat and thermal conductivity coefficient λ by the expressions

$$\lambda = \beta_1\delta^{-2}, \tag{6}$$

$$c = \beta_2\delta, \tag{7}$$

where β_1 and β_2 are constants.

The function $\delta = f(T)$ over the temperature interval $0.05 \leqslant T/T_f \leqslant 1$ for NaCl single crystals was presented in [4]. It can be represented in the form

$$\delta = 2\cdot10^{-6} + 5\frac{T}{T_f}10^{-6}. \tag{8}$$

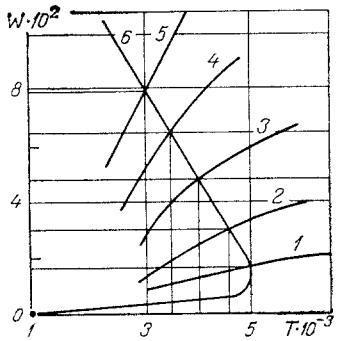

Fig. 2. Graphical determination of breakdown channel temperature (curve 6); curves 1-5 correspond to rows 1-5 of Table 1.

For NaCl single crystals $\beta_1 = 25.2 \cdot 10^{-14}$ J/°K³·cm·sec and $\beta_2 = 0.35 \cdot 10^6$ J/g·°K². Using Eq. (8) in Eqs. (6) and (7), we obtain the mean thermal conductivity value c = 1.62 J/g·°K and thermal conductivity coefficient $\lambda = 1.4 \cdot 10^{-3}$ J/°K·cm·sec. Then the thermal diffusivity coefficient $a = \lambda/\gamma c = 3.9$ cm²/sec.

The mean heating time t_f in Eq. (5) for the discharge formation stage was taken equal to $t_f = t_{fo}/2 = 2 \cdot 10^{-7}$ sec, and set equal to the measured time interval in the completion stage. Results of Δ calculations by Eq. (5) are presented in Table 1.

Substituting numerical values for the quantities appearing in Eq. (1) we obtain an expression for the energy balance in the breakdown channel:

$$W = r^2\left[1{,}26 \cdot 10^4 + 0{,}48 \cdot 10^4 + \alpha \cdot 25 \cdot 10^3 + x \cdot 27{,}4 \cdot 10^3 + 0{,}93\,T\,(x+2) + 16\Delta T\left(1 + \frac{1}{3}\Delta\right)\right] \text{ J.}$$

With the aid of experimental channel radius and discharge time values, curves (1-5) were obtained, depicting the dependence of total energy W on channel temperature (Fig. 2). The points where these curves intersect the horizontal lines corresponding to the experimentally determined energy liberation in the channel define the channel temperature. In defining temperature in the discharge formation stage the degree of ionization x was determined from Eq. (2).

The channel temperature in the discharge formation stage is equal to 1000°K. It is shown by a point in Fig. 2. In the first ten nsec of the completion stage the temperature increases from 1000 to 5000°K, and then decreases.

Table 1 presents results of calculating the corresponding energy balance. The first five lines refer to the completion stage and the sixth, to the discharge formation stage. The major fraction of the energy liberated in the channel is expended in heating and fusion of the crystal region occupied by the channel, in radiation of heat due to thermal conductivity and dissociation of molecules. With increase in temperature the fraction of energy $W_I + W_t$ increases. In the formation stage 50% of the energy liberated in the channel is radiated into the surrounding medium due to heat transfer.

NOTATION

d, interelectrode distance; l, breakdown channel length; n_o, number of NaCl molecules per cm³; γ, crystal density; L_f, specific heat of fusion; T_f, fusion temperature; c, specific heat; α, degree of dissociation of NaCl molecules; x, degree of ionization of Cl^- ions; W_i, ionization energy of Cl^- ion; T, breakdown channel temperature; m, temperature change index in heated layer; Δ, relative heated layer; b, heated layer thickness; E, breakdown strength; v, velocity of electron motion in breakdown channel along discharge path; t, discharge time; p, pressure; a, thermal diffusivity coefficient; t_h, mean heating time; r, breakdown channel radius; V, breakdown channel volume; W_h, W_f, energies expended in heating

and fusing crystal region directly adjacent to channel; W_D, W_I, energies expended in dissociation and ionization of NaCl molecules located in channel; W_t, energy expended in increasing particle temperature in channel; W_c, energy radiated from channel surface into crystal due to thermal conductivity of crystalline lattice; W, energy liberated in breakdown channel; k, Boltzmann's constant.

LITERATURE CITED

1. V. I. Obukhov and A. I. Lisitsyn, "Spark temperature in breakdown of solid dielectrics," Inzh.-Fiz. Zh., 6, No. 1, 66-72 (1963).
2. V. I. Obukhov, "Optical phenomena in breakdown of solid dielectrics," Izv. Sev.-Kavkaz. Nauchn. Tsentra. Vyssh. Shkol., Estestven. Nauka, No. 3, 51 (1980).
3. Chemistry Handbook [in Russian], Vol. 1, Khimiya, Moscow (1966).
4. A. A. Vorob'ev, Physical Properties of Ionic Crystalline Dielectrics [in Russian], Tomsk State Univ. (1960).
5. N. M. Torbin, "Discharge formation processes in solid dielectrics," Fiz. Tverd. Tela, 3, No. 11, 3273-3277 (1961).

INTENSIFIED PLASMA DEPOSITION WITH ACOUSTIC AND ELECTRICAL OSCILLATIONS APPLIED TO THE HETEROGENEOUS JET

G. P. Lizunkov, V. D. Shimanovich, I. S. Burov, and A. F. Il'yushchenko

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An experimental study has been made on the scope for improving the integral characteristics of plasma deposition when strong acoustic and electrical fluctuations are superimposed on a heterogeneous plasma jet.

Optimizing particle heating in a hot jet is important in depositing protective coatings. In the case of a homogeneous stationary plasma, the heat flux to the powder particles is [1]

$$Q_p/F \sim \alpha T_g l/v_p. \quad (1)$$

It follows from (1) that the heat-transfer rate will increase if the increase in one of the parameters α, T_g, and l/v_p appreciably exceeds the possible reduction in the others. The rate of heat transfer between particles and the plasma flow in coating deposition may be estimated from integral characteristics: the coefficient η for the plasma jet power use and the coefficient β for powder use, since there is a correlation between η and β, on the one hand, and the amount of the particles melted, on the other.

It has been found [1, 2] that high-frequency fluctuations in the electrical parameters of the arc increase η and β, while low-frequency ones reduce them.

The experiments were performed with a plasma deposition apparatus whose acoustic and electrical characteristics were studied in [3]. The acoustic oscillations were generated either by the plasmotron at its outlet or by means of gas-jet rod radiators [4] set up in various parts of the jet and around the substrate (Fig. 1a).

To increase the acoustic pressure amplitude and to focus the acoustic field, the plasmotron and the sources were set up within a concentrator or horn. When gas-jet radiators were used, the air flow was deflected from the direction of the beam of acoustic oscillations to prevent it from influencing the plasma jet. The acoustic characteristics were as follows: frequency 5-10 kHz, acoustic pressure level 150 dB, and acoustic power from 0.1 to 1 kW. The working conditions in the plasmotron were monitored from the average and fluctuation characteristics as recorded by probe instruments, oscillograms, and spectrograms. The Ni—Al powder was deposited on steel substrates of area 80 × 80 mm at 120-170 mm from the end of

Belorussian Regional Powder Metallurgy Cooperative and Institute of Physics, Academy of Sciences of the Belorussian SSR, Minsk.

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