DEVELOPMENT OF SURFACE DISCHARGE ALONG A DIELECTRIC WITH LARGE DIELECTRIC CONSTANT IN GAS IN THE NANOSECOND RANGE

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The discharge from a metallic edge along the surface of a dielectric with dielectric constant of the order of 100 or larger is investigated. The dependences of the rate of expansion of the discharge, the time lag, and the volt–ampere characteristics are obtained for exposure times of the order of 10^{-9} sec for plates made of barium titanate, titanium dioxide, and steatite ceramicwith thickness of the order of 1 mm or less at voltages up to 1.5 kV of different polarity. The average rate of expansion of the figure of luminosity after a time of ≤ 3 nsec is equal to 10^6 cm/sec in order of magnitude. It is shown that from a negative point the discharge is initiated by the self-electron emission current, while from a positive point it is initiated by the self-ionization current. The basic equations are given for a commutator utilizing surface discharge from a large number of points.

1. Formulation of the Problem

For triggering spark dischargers in a gas with an accuracy of 10^{-10}-10^{-9} sec, pulsed radiation sources with the same triggering accuracy are required. As shown in [1], the discharge in a gas with such accuracy is initiated for field intensities $E > 10^5$ V/cm. At small voltages large field intensities in the gap may be obtained at electrodes with small radii of curvature by introducing a dielectric with large dielectric constant ε_* in the gap, or by the joint effect of these factors [2, 3]. Below we present the results of investigation of discharge in a system with metallic edge touching a dielectric plate, and also in the case of two metallic edges separated from each other by a distance l, one of which touches the plane and the other of which is separated from it.

2. Experimental Procedure

The experiments for single edges (Fig. 1) were conducted on disks of barium titanate, titanium dioxide, and steatite ceramic with 10-mm diameter and thickness d = 0.5 mm. The planes of the disk were published by diamond buffing and one of these was metal plated by brazing silver. In the system of two points (Fig. 2) samples of ceramics were used in the form of slabs of dimensions $5 \times 6 \times 0.5$ mm. Points with a 50-μ diameter were made from molybdenum wire by the method of electrochemical etching; the shape of the point was controlled during the experiment with the use of an MIM-8M microscope. Voltage pulses with amplitude up to 2.5 kV having a front <1 nsec were applied to the systems of electrodes.

During the application of the pulsed voltage a displacement current flows across the point before the initiation of the surface discharge (Fig. 1); this current is determined by the static capacitance C_0 of the point relative to the metallized plane. This makes it difficult to record the instant of application of the voltage in reference to the instant of start of the discharge. In order to eliminate this current a compensating capacitance $C_+ = C_0$ was connected to the investigated electrode system, and identical voltage pulses U(t) of different polarity were simultaneously applied; these pulses passed through the cables L_1 and L_2 with equal wave impedance R (Fig. 1) from the generator 2 connected to the constant voltage source 1. In this case the current recorded in line L_4 by the I2-7 oscillograph 3 before the start of the discharge in the

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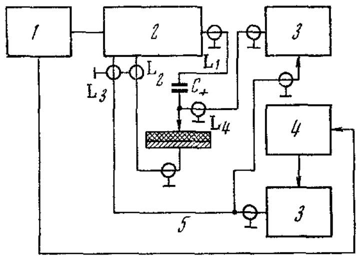

Fig. 1

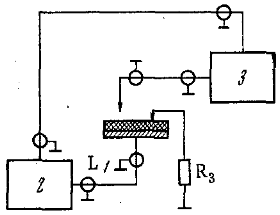

Fig. 2

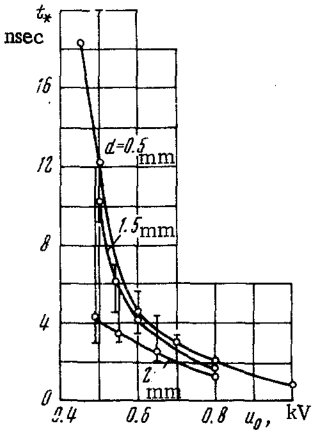

Fig. 3

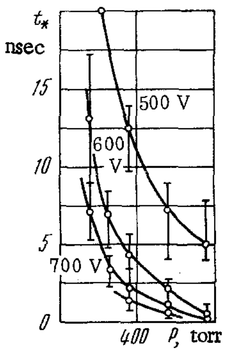

Fig. 4

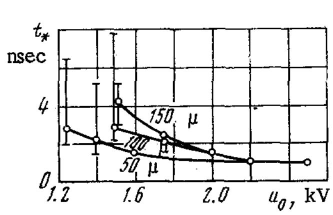

Fig. 5

system was equal to zero. The instant of application of the voltage is determined by the wisp on the oscillogram of the discharge current for L and C disconnected or for $C_+ = C_0$.

The criterion of appearance of the discharge in the investigated system was the appearance of a signal across L_4 on I2-7 oscillograph 3 triggered through the line 5, and at the output of the PM-36 photomultiplier 4 having a passband of about 100 MHz recording the light from the discharge. The signal from the photomultiplier was fed to the input of I2-7 either through the amplifier U-3-5A or directly. The matching of the compensating capacitance was done at voltages lower than the voltages of the development of the discharge. The absence of the discharge was monitored through the record of the signal with PM. The scheme shown in Fig. 2 was used for the determination of the time lag in the system with the point separated from ceramic. A voltage pulse with a duration of 20 or 200 nsec was formed in generator 2 during the discharge of a homogeneous line through a fast commutator and was fed to the metallized plane of the dielectric through line L_1. The current from the point separated from ceramic was oscillographed; the other point either touched the ceramic and was grounded through the resistance R_3, or was removed. The value of C_0 for the point separated from the dielectric was small, and therefore the compensating capacitance was not required.

The scheme for the investigation of the space–time characteristics of the discharge was a combination of the schemes of Figs. 1 and 2. From a pulse-forming device, which is not critical to the load resistance and is located in block 2, voltage pulses with 1, 2, 4, and 8 nsec length and amplitude from 0.1 to 2.5 kV were fed to the system with the investigated point along one line, and along the other line the same pulses were fed to an inverter, where their polarity was changed to the opposite and a compensating voltage drop in capacitance C_+ was ensured. Block 2 also contained the forming circuits for triggering the light amplifier US-01 and oscillograph I2-7. All the circuits in block 2 were triggered simultaneously with the use of a special electromechanical commutator. This scheme† made it possible to take the oscillograms of the current and to obtain the integral pattern of the surface discharge. The image of the investigated pattern of the discharge was projected on the photocathode of an image converter with "Helios-40" objective with an amplification of about 10. The exact size of the image on the screen of the image converter was determined by photographing a scale grid placed at the location of the investigated object.

3. Experimental Results

Voltage for the Initiation of the Discharge. The resolution of the recording system in respect to current was $\sim 6 \cdot 10^{-2}$ A per 1 mm deflection of the beam on the screen of the oscillograph. A reliable recording of discharge currents of the order of 0.1 A was ensured at a line thickness of ~0.3 mm. The voltage pulse of positive and negative polarity applied to the point had a duration of 0.2 μsec, and the air pressure was varied in the range 760-100 torr. In these conditions for plates of barium titanate ($\varepsilon_* = 1400$) with thickness d = 0.5, 1, 1.5, and 2 mm a current of the order of 0.1 A developed at a voltage U_0 = 350-450 V. Similarly for plates of tikond ($\varepsilon_* = 80$, d = 0.5, 1, and 2 mm), U_0 = 750-900 V, and for steatite plates ($\varepsilon_* = 10$, d = 0.5 mm), U_0 =

†B. M. Koval'chuk, "Development and investigation of generators of nanosecond pulses of large current," Candidate's Dissertation, Tomsk, 1969.

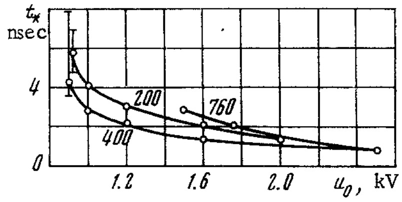

Fig. 6

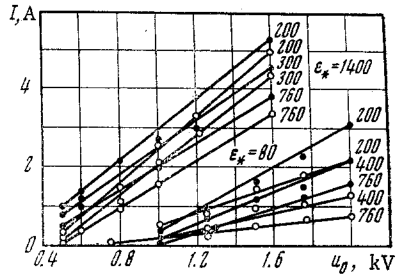

Fig. 7

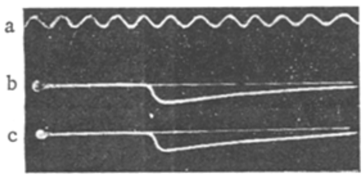

Fig. 8

1200-1500 V. From the investigation of the emission with the PM it was established that light in the system is detected at voltages of approximately 250-300 V for barium titanate, 600-700 V for tikond, and 1000-1100 V for steatite.

The voltage at which the light pulse appears is largely determined by the microgeometry of the electrode system; for example, when one and the same metallic electrode made in the form of an edge touches different points of the ceramic the discharge starts at voltages differing by 100-150 V. When a wide metallic plate is used as the electrode, the voltage at which the discharge appears is equal to the minimum value for the given ceramic, since in this case there are several points of contact and the discharge appears at the point with minimum discharge voltage. When voltage pulses of single polarity are applied, the potential at which the discharge appears increases with the number of pulses. This is explained by the presence of charges remaining on the ceramic from the preceding discharges. In order to eliminate this phenomenon, the output of generator 2 (Figs. 1 and 2) was shunted by a large inductance L (not shown in the figure); thus, due to the transient process in the circuit, voltage pulses of alternating polarity were applied to the edge for a time of the order of 10^{-6} sec or more. The presence of L did not cause distortion of the voltage pulses with duration $\leq 2 \cdot 10^{-7}$ sec.

Retardation of the Discharge. The current from the edge (Fig. 1) in pulses of negative polarity was recorded almost without any lag with respect to the instant of application of the voltage.

For steatite ceramic, the lag of the discharge was observed for pulse amplitudes close to the voltage for the development of the discharge. For amplitudes exceeding the initial amplitudes by 5-10% the lag decreased sharply and became <1 nsec. The absence of lag of the discharge along the surface of barium titanate and titanium dioxide was observed in air at 760-100 torr.

For voltage pulses of positive polarity, the discharge current lags behind the instant of application of the voltage pulse. The amount of the lag fluctuates from pulse to pulse. The scatter and the absolute value of the lag t_* decrease with the increase of the voltage. The dependence of t_* on the voltage U_0 is shown in Fig. 3 for barium titanate of thickness 0.5, 1.5, and 2 mm at a pressure p = 400 torr. The points on the figure represent average values of 10 pulses.

The dependence of t_* on U_0 for different p and d = 0.5 mm is shown in Fig. 4. The decrease of the time lag with the increase of the pressure is typical.

Lag of the Discharge in the Presence of an Auxiliary Edge. The dependence of the time lag of the breakdown from a separated edge on the applied voltage U_0 is shown in Figs. 5 and 6 for a pressure p = 400 torr and gaps δ = 50, 100, and 150 μ, and also for δ = 100 μ and p = 200, 400, 760 torr. It was found that t_* does not depend on the polarity of the edge. This indicates that the discharge between the edge and the ceramic is initiated by photoabsorption of the gas in the region of the edge.

Growth of Current and Development of the Discharge along the Surface of the Ceramic. The oscillograms of the discharge current for a negative edge U_0 = 2 kV are shown in Fig. 8b, c for the edge touching the dielectric (barium titanate) or separated from it by a certain distance (100 μ) at a pressure p = 760 torr; they are practically identical. The frequency of the calibration oscillations (Fig. 8a) is 500 MHz. This corroborates the assumption that the decisive process in both cases is the surface discharge along the ceramic. The dependence of the current amplitude on voltage is shown in Fig. 7 for different polarities of the edge and at air pressures p = 200, 300, 400, and 760 torr for barium titanate and titanium dioxide with thickness d = 0.5 mm. A small difference in the amplitudes of the current pulses of different polarity for large U_0 and ε_* is typical.

Figures 9 and 10 show the image converter photographs of the discharge along the surface of barium titanate of thickness d = 0.5 mm for voltage pulses of positive and negative polarities, respectively, with pulse length t_0 = 1, 2, 4, 8 nsec in air at atmospheric pressure. For t_0 > 1 nsec and $U_0 \geq 1.6$ kV these pictures are practically independent of the polarity of the pulses and represent a homogeneous diffuse glow.

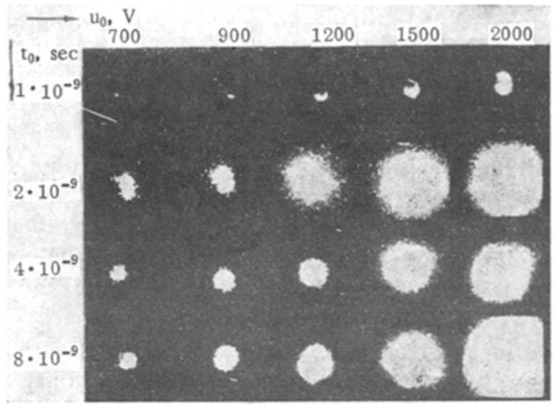

Fig. 9

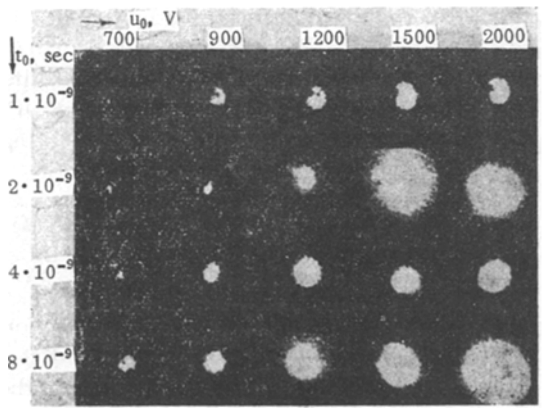

Fig. 10

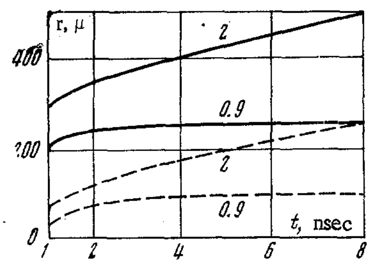

Fig. 11

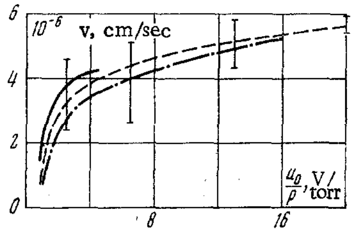

Fig. 12

The radii of the figures of discharge along the surface of barium titanate of 0.5 mm thickness at atmospheric pressure, averaged over five pictures, are shown in Fig. 11, by continuous curves. The graph of the average velocity of expansion of the figure of discharge for a negative edge is given in Fig. 12 and is shown by continuous lines.

4. Discussion of Experimental Results

The absence of time lag of the discharge from the metallic edge in the case of pulses of negative polarity indicates that there are free electrons at the cathode capable of initiating the avalanche process at the instant when the voltage at the surface of the dielectric is sufficient for the development of ionization phenomena. The free electrons can appear as a result of amplification of the field in the microgaps between the metallic electrode and the ceramic. In the electrode system with the edge against the disk (Fig. 1), if its capacitance is approximated by the capacitance of a hemispherical condenser with two-layer dielectric (gas and ceramic), for the field at the edge we obtain

$$E \approx \frac{U_0}{\delta}\left(1+\frac{\delta}{r_0}\right)\left(1+\frac{r_0}{\varepsilon_* \delta}\right)^{-1} \tag{4.1}$$

where r_0 is the radius of the edge, ε_* is the relative dielectric constant of the ceramic, and δ is the length of the gap between the edge and the ceramic. Equation (4.1) is valid for $\delta/d \ll 1$, $r_0/d \ll 1$ (d is the thickness of the ceramic). It follows from (4.1) that for $\varepsilon_* \gg 1$ almost all the voltage is applied between the edge and the ceramic. For example, for $U_0 = 0.5$ kV, d = 0.5 mm, $\varepsilon_* = 1400$, and $\delta = 5 \cdot 10^{-4}$ cm, we have $E > 10^6$ V/cm. If $r_0 \ll \delta$, according to (4.1) we have an additional amplification of the field. Considering the local amplification of the field, we can assume that an intensity up to 10^7 V/cm and more exists in the gap. The appearance of free electrons in the gap at intensities of the order of 10^7 V/cm for a period of $<10^{-9}$ sec can be explained by the self-emission from the cathode and impact ionization at the surface of the electrodes [4]. According to [5] on a cathode in fields of the order of 10^7 V/cm an eruption of microprojections occurs due to thermionic heating of the sharp tips.

The presence of lag of discharge in experiments with steatite ceramic ($\varepsilon_* = 10$, $E < 10^6$ V/cm) supports the assumption about the appearance of free electrons as a result of amplification of the field in metal-ceramic microgap.

Let us now investigate in greater detail the process of lag of discharge along the surface of the ceramic for a positive edge. The time lag t_* depends on the rate of arrival of the initiating charges (ion current) and the rate of development of the discharge. The first process is determined by the normal component of the field at the electrode and in the gaseous gap between the electrode and ceramic (about 10^7 V/cm and larger), while the second is determined by the tangential component at the surface of the dielectric. The discharge along the dielectric is mainly a gas discharge close to the surface of the dielectric. The characteristic time for its development is proportional to $(\alpha v_-)^{-1}$ (where α is the coefficient of impact ionization and v_- is the drift velocity of the electrons). It can be shown that this time will increase with pressure. Hence, a decrease of t_* with the increase of pressure (Fig. 4) cannot be explained as due to the development of the discharge.

Let us see how the ion current depends on pressure. At field intensities of about 10^8 V/cm positive ions appear at the surface of the edge due to self-ionization or desorption of atoms and molecules at the surface of the edge by the field. At large gas pressures the most efficient source of ions is self-ionization [6]. The time required for self-ionization of hydrogen, for instance, in an electric field of 10^8 V/cm is 10^{-10} sec [6]. The current density produced by the self-ionization of the gas atoms is given by the relation [6]

$$i_+ \sim pE^2 / T^{3/2} \tag{4.2}$$

where p is the pressure, E is the field intensity at the edge, and T is the gas temperature. This relation shows that the ion current increases with the pressure. Apparently, it is just this effect that is responsible for the decrease of t_* with the increase of pressure for a positive edge.

The values of the radii of the discharge figures shown in Fig. 11 may be compared with those computed from the oscillograms of the current i(t) assuming that the plasma is ideally conducting.

First the capacitances C(t) of the discharge figures were obtained from the measurements of i(t) making use of the equation

$$C(t) = \int_0^t idt / (2U(t) - Ri) \tag{4.3}$$

where U(t) is the voltage pulse and R is the active resistance in the discharge circuit. The capacitance C(t) in (4.3) was equated to the capacitance of a disk of radius r for a thickness of the dielectric $d \gg r$ [7]

$$C(t) = 4\varepsilon_0\varepsilon_* r \tag{4.4}$$

where ε_* is the relative dielectric constant of the ceramic ($\varepsilon_* \gg 1$), $\varepsilon_0 = (4\pi\, 9 \cdot 10^9)^{-1}$ F/m. For the thickness of the dielectric d of the same order of magnitude as r the value in (4.4) was multiplied by a

$$a = 1 + r / d \tag{4.5}$$

for approximate calculations of C(t).

The error of the computation in the last case did not exceed 30%. This is easily verified by comparing (4.4) and (4.5) with the equation for a plane condenser with $r \gg d$ or with (4.4) for $r \ll d$. Graphs of r(t) obtained with the use of (4.3)-(4.5) are shown in Fig. 11 together with the results of analysis of the image converter pictures by the dashed lines. It can be seen that the radius of the figure of the glow appreciably exceeds the computed radius; however, the average rates of expansion for $t \approx 2$ nsec are approximately the same in both cases. Apparently, the figure of the discharge glow consists of a region of high-conductivity plasma and a weakly ionized region of low conductivity in which an intense development of the processes of attachment and recombination may occur with the decrease of the voltage. In this case, the computed values from (4.3)-(4.5) define approximately the boundary of the plasma with high conductivity. The presence of the weakly ionized region may explain the decrease of the amplitude of the current pulse on feeding a series of single-polarity voltage pulses (see Sec. 3).

Figure 12 shows the curves plotted (dashed and dash-dot) from (4.3)-(4.5) and experimental graphs of the average rate of expansion of the figure v for barium titanate of 0.5 mm thickness for voltages $0.7 < U_0 < 2$ kV, air pressure $100 < p < 760$ torr and $t \leq 3$ nsec. It can be seen that for $U_0/p \geq 4$ V/torr v is almost independent of U_0/p.

It follows from (4.4) that for $r/d \ll 1$ (for $1 < t < 3$ nsec, $r/d \leq 0.2$) the capacitance C(t) is determined by ε_* and r and is independent of d. In this case in the discharge of the line with wave impedance R through the edge with zero initial capacitance the amplitude of the current pulse is

$$I \approx \frac{4\varepsilon_0\varepsilon_* vU_0}{1 + 4\varepsilon_0\varepsilon_* Rv} \approx 4\varepsilon_0\varepsilon_* vU_0 \tag{4.6}$$

since in the experiment $4\varepsilon_0\varepsilon_* Rv \ll 1$. Here U_0 is the amplitude of the voltage pulse. For $v \approx$ const the dependence given by (4.6) is in qualitative agreement with Fig. 7.

5. High-Speed Discharger with a Large Number of Channels

According to (4.6) the current I does not depend on the wave impedance R. This makes it possible to make use of parallel operation of many edges (in the general case n) separated from the dielectric for the commutation of currents of the order of kiloampere, if their distances from the dielectric are such that the time lag is smaller than 1 nsec (see Figs. 5 and 6). One or several edges touching the dielectric may be used to trigger such a commutator. In order that the edges do not affect each other during the discharge, they should be arranged at a distance $l \gg 2vt_0$, where t_0 is the duration of the current pulse. The amplitude of the current in such a system will be n times larger than in (4.6), and the duration of the pulse at half-height will be

$$t_0 \approx 0.25C^\circ / \varepsilon_0\varepsilon_* nv \,. \tag{5.1}$$

For example, in order to obtain a current with 5 kA amplitude for $t_0 = 2$ nsec on a barium titanate disk ($\varepsilon_* = 1400$), it is necessary to have about 1600 edges for $U_0 = 2$ kV, $p = 760$ torr, $v = 3 \cdot 10^4$ m/sec, $C^\circ \approx 5$ nF. For the proposed commutator it is important that the storage capacitance be charged up to the point of its triggering. Therefore, the discharge from the edges touching the surface of the dielectric must be initiated by an extraneous voltage source.

LITERATURE CITED

1. G. A. Mesyats, Yu. I. Bychkov, and A. M. Iskol'dskii, "Time of formation of discharge in short air gaps in the nanosecond range," Zh. Tekhn. Fiz., 38, No. 8, 1281-1287 (1968).
2. L. Lavoic, S. Parker, C. Rey, and D. M. Schwarts, "Spark chamber pulsing system," Rev. Sci. Instrum., 35, No. 11, 567 (1964).
3. B. M. Koval'chuk, V. V. Kremnev, and G. A. Mesyats, "Avalanche discharge in a gas and generation of nano- and subnanosecond pulses of large current," Dokl. Akad. Nauk SSSR, 191, No. 1, 76-78 (1970).
4. L. Leb, Basic Processes of Electrical Discharge in Gases [in Russian], Gostekhizdat, Moscow (1950).
5. S. P. Bugaev and G. A. Mesyats, "Emission of electrons from plasma of incomplete discharge along a dielectric in vacuum," Dokl. Akad. Nauk SSSR, 196, No. 2, 324 (1971).
6. É. W. Muller, "Self-ionization and self-ion microscopy," Uspekhi Fiz. Nauk, 77, No. 3, 481 (1962).
7. V. A. Govorkov, Electric and Magnetic Fields [in Russian], Énergiya, Moscow (1968).