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METHOD OF CONTROLLING THE GROWTH AND FORMATION OF A SYSTEM OF PARALLEL SLIDING SPARK CHANNELS IN AIR AT ATMOSPHERIC PRESSURE

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A method of controlling the growth process of a sliding spark along the surface of a film dielectric by introducing emission centers from chemical compounds with a low electron work function into the surface is presented. It is shown that it is possible, by using this method, to produce a spark channel with sharp corners, such as a Z-shaped channel, and an ordered system of parallel channels, as well as a strictly rectilinear channel up to 2 m long. It is established that the rate of growth of the sliding spark is nonuniform. The mean rate is heavily dependent on the overvoltage, which is related to a reduction in the pauses in its growth.

A sliding spark is generated on the surface of a dielectric when a pulsed or high-frequency voltage is applied to electrodes located on the surface if there is a conductor under the dielectric layer. These sparks are generated in high-voltage techniques and are undesirable from the point of view of electrical insulation [1-3]. It is, however, extremely interesting to use the sliding spark as a means of initiating frequently repeated discharges over long discharge lengths and as linear or specially shaped high-luminosity emission sources. In addition, plasma surfaces can be formed by using the capacity to produce a parallel system of spark channels, which is important in, for example, the study of the interaction between a plasma and a dielectric surface in contact with it. In this case, in particular, the action of the plasma on the structural members of the piece of apparatus which enter the atmosphere can be simulated [4]. The aim of this paper is to devise a procedure for controlling the growth of sliding sparks and to form a system of parallel channels in the complete (high-current) discharge phase.

Sliding discharges are formed on the plane surface of a film dielectric covering a metallic sheet (the initiator). Two linear electrodes 32 cm long are placed parallel on the surface of the dielectric with the distance between them being variable from 12 to 100 cm. One of the electrodes is connected to the initiator. In separate experiments the distance between the electrodes reaches 800 cm. In these experiments the initiator is a metal cylinder enveloped in a dielectric film and the electrodes are annular in shape.

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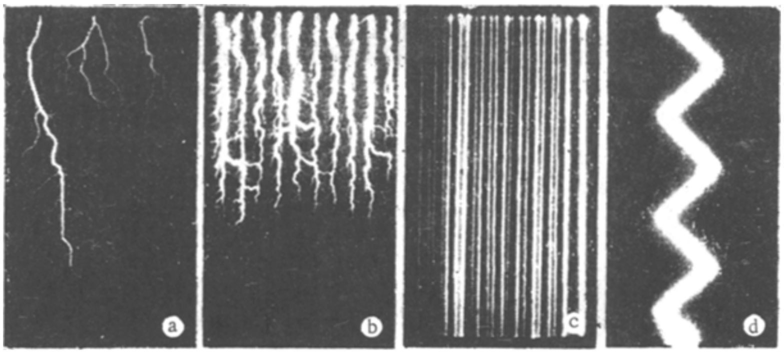

Fig. 1

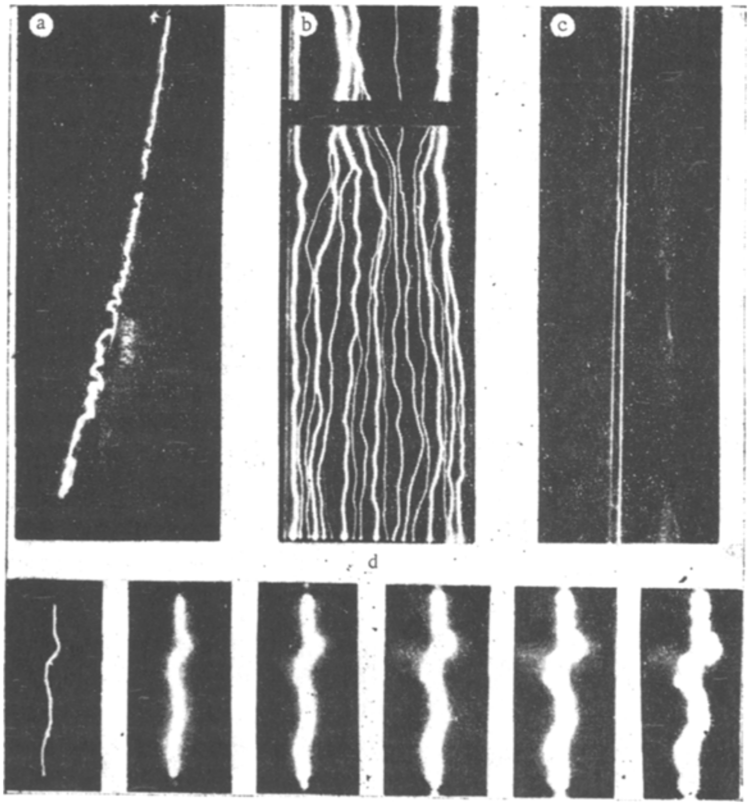

Fig. 2

A voltage pulse is fed when the capacitor discharges ($C = 12\ \mu F$, $u_0 = 3$-20 kV) to the first winding of the cable transformer which has one turn. The secondary winding has 10 turns so that a maximum voltage amplitude of up to 210 kV is possible. The voltage takes the form of a damped cosine curve with a period of 12-18 μsec. Polyethylene, polyethylene terephthalate, cellulose acetate, etc., films are used as the dielectric over the surface of which the discharge is generated. The thickness of the film is varied from 0.16 to 3 mm.

Space–time base scans of the luminescence of spark channels are mapped and photographed in this paper and oscillograph traces are taken of the voltage between the electrodes.

It is a well-known fact [5, 6] that the presence of small inhomogeneities in the discharge gap has a significant influence on its breakdown. This is an initial premise for the development of a method of controlling sliding spark growth. During the course of the investigations it is found that the determining factor is not so much the local distortion of the electrical field at the point where the inhomogeneity is located (a metallic powder, for example, is used) as the work function of electrons from the material of this inhomogeneity. (Control is stable when the polarity of the first half-period of the voltage in the gap is positive.) Finely disperse powders of graphite, aluminum powder, $BaSO_4$, BaO_2, ZnO, Cu_2O, TiO_2, etc., are used as the material for generating this kind of inhomogeneity. The best results are obtained with barium compounds which have a very low

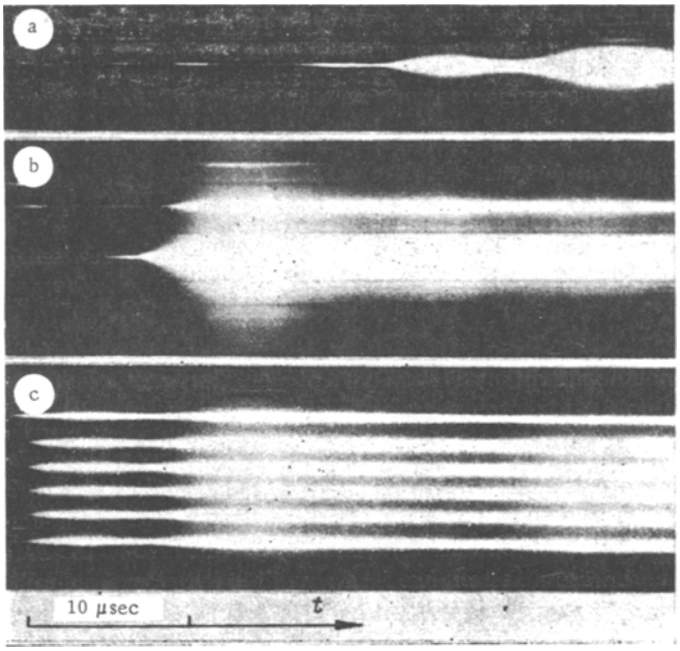

Fig. 3

work function (1-2 eV) [7]. (The work function of the metals W, Mo, Fe, Co, Cu, etc., is approximately 4.5 eV.) The stability and frequent repetition of the effect is ensured by the technique of depositing the powders onto the dielectric films. It is, as a result, possible to achieve multiple repetitions, governed primarily by the electric strength of the film itself. (Aspects of the techniques used to prepare and deposit the control coatings will be examined in a separate paper). The coating can be made in the form of strips of the required shape. The width of the strips is varied from 1 to 20 mm.

Some experimental results will be examined now. The action of the proposed method of sliding spark growth control is shown in Fig. 1; Fig. 1a is a spark without any control, 1b is with control (incomplete phase), and 1c and d are with control (complete phase).

The discharge conditions are as follows: length of spark gap, 50 cm; width, 32 cm; thickness of dielectric for Fig. 1a-c, $\Delta = 0.45$ mm (0.36-mm-thick polyethylene terephthalate covered with a 0.07 mm triacetate film) and for Fig. 1d, $\Delta = 0.65$ mm (polyethylene terephthalate 0.45 mm thick covered with electrical insulation cardboard 0.2 mm thick). The voltage amplitude is 44 kV (Fig. 1a and b), 126 kV (Fig. 1c), and 75 kV (Fig. 1d). The control strips are made of polystyrene lacquer with a filler of 95% finely disperse BaO_2 powders and 5% graphite. Figure 1c shows stabilizing strips with a CuO_2 powder filler deposited between the control strips. A comparison of the data in Fig. 1a and b shows that the sliding spark growth is stabilized, when control is applied, in space as well as in time (parallel sparks have a more even front). Figure 1c illustrates the possibility of producing a proper system of channels of already complete discharges. A fine network of these channels can be obtained by alternating strips on the dielectric surface using compounds with low (BaO_2) and high (Cu_2O) work functions, which prevents neighboring channels from "skipping."

Figure 1d illustrates the possibility of producing a complete discharge channel of a given shape. Attempts have been made previously to produce a predetermined channel shape giving the same shape to the initiator [8], but obviously a channel with sharp clear corners is produced first. Figure 2 shows photographs of a long sliding spark; Fig. 2a is a sliding spark channel 8 m long without any control in a 40-mm tube enveloped in a polyethylene film $\Delta = 2$ mm thick, voltage 180 kV; 2b is a sliding spark system without any control with a gap length of 100 cm on a surface covered by a dielectric having $\varepsilon = 3.4$ and $\Delta = 0.44$ mm (the lateral band visible is a shadow from a structural member); 2c is two parallel channels 2.2 m long made of 40-mm-diameter pipe enveloped in a dielectric, $\Delta = 0.9$ mm, voltage 85 kV, with control; and 2d is the development in time of the instability generated when the discharge is initiated. The conditions are as follows: $l = 50$ cm, $\Delta = 0.35$ mm, and $\varepsilon = 3.4$. After initiation through the spark channel the capacitor battery discharges $U_0 = 30$ kV, $W_0 = 40$ kJ. The time between frames is 8 μsec. It is clear that in the absence of a control strip the sliding spark (Fig. 2a and b) is uneven along the length of the gap. An even uniform channel (or, as shown in Fig. 2c, two such channels) can be produced by using the proposed method. If a capacitor battery with a large re-

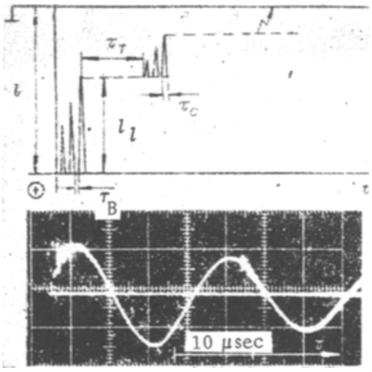

Fig. 4

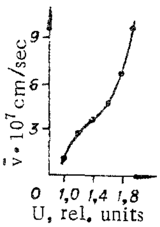

Fig. 5

serve of energy is connected to the electrodes, the unevennesses in the channel do not disappear but have a tendency to grow, giving rise to instabilities (Fig. 2d). The probability of instabilities emerging is reduced considerably by the possibility of initiating a channel which is uniform along its length [9].

A study of the results of investigations into the rate of sliding spark growth is interesting both from the point of view of the simultaneous "intergrowth" of a system of parallel channels and from the point of view of the breakdown formation time. In fact, for lengths of a few meters the discharge may be incomplete over the time of the first half-period, which takes the form of a damped cosine curve of the voltage. A pause in its growth is then generated [Fig. 3: a) $U = 60$ kV; b) $U = 72$ kV; c) $U = 90$ kV; $l = 50$ cm, $\Delta = 0.42$ mm, and $\varepsilon = 3.4$]. Thereafter, the spark can continue growing and the gap may break down, but is also possible that there will be no breakdown, depending on the duration of the period and the rate of voltage oscillation damping.

Time bases plotted when the slit of the high-speed photographic recording device (SFR) lies along the direction of spark growth are analyzed (the direction is stabilized by the control method described above) and it is found that the time from the moment at which the spark channel is generated to the moment at which the gap breaks down does not correspond to the instantaneous velocity of the sliding spark. It is generally made up of four components.

The τ_T pause characterizes the time lag in the progressive growth of the sliding spark between the half-periods of the voltage (Figs. 3 and 4; in Fig. 4 the arrow shows the moment of breakdown). The τ_B time characterizes the duration of the pauses between jerks in the leader process of sliding spark growth. Obviously, this pause is related to the time required for heating up the leader channel and the potential along it caused by this redistribution. As indicated by the space–time base scans of the process of progressive channel growth, this pause is not due to the inflow of side branches into the leader channel, which is the distinguishing feature of the sliding spark. The magnitude of v_l (the velocity of the leader between τ_B pauses) lies within the limits of $3 \cdot 10^8$ and $8 \cdot 10^8$ cm/sec under the conditions prevailing. It is shown by the measurements that the rate of heating v_h of the sliding spark channel after the discharge gap* has been closed by the leader is one order of magnitude greater: $v_h = (1\text{–}5) \cdot 10^9$ cm/sec.

The τ_T pauses have the greatest duration. It is established that breakdown can occur over several half-periods during which subsequent amplitudes are reduced by a factor of not more than two compared with the first amplitude, which then corresponds to the breakdown voltage. As the voltage U increases, the duration of the τ_T pauses is reduced sharply. These pauses exert a maximum influence on the synchronism of the growth of parallel sparks and on the formation of a system of parallel channels, which is illustrated in Fig. 3. With a minimal breakdown voltage there are several pauses and only one complete discharge channel is formed (Fig. 3a). If the voltage is increased, the number of these pauses is cut down and the number of simultaneously complete channels is increased as well. A dense system of parallel channels with control (Fig. 3c) can be achieved only when breakdown takes place in the first half-period of voltage.

The τ_B pauses have a duration of fractions of a microsecond and the number of them K, in a direction close to the breakdown direction, is 5–8, independent of the length of the gap when $l \geq 20$ cm.

As the voltage beyond breakdown increases, the number of pauses K falls sharply to zero. The breakdown of the discharge gap is then effected by the leader moving virtually ceaselessly from one electrode to another.

*The heating is uneven along the length of the gap as a result of which the photo-scanning records the movement of the region of increased luminosity at a rate of v_h.

In Fig. 5 the dependence of the mean rate $\bar{v}$ of sliding spark growth on the overvoltage is plotted [discharge length, 2.5 m; breakdown voltage, $U_{bd}=80$ kV (taken as unit of measurement), $\Delta=0.9$ mm, and $\varepsilon=3.4$]. This rate is determined from the ratio l/τ_f, where l is the length of the discharge gap; τ_f is the breakdown formation time; $\tau_f=(\tau_T+\tau_B K)n+\tau_c+\tau_h$, where n is the number of half-periods of voltage oscillations up to the moment of breakdown; τ_c is the time determined from the ratio l/v_l; τ_h is the time required to heat up the spark channel after the gap has been closed by the leader $\tau_h=l/v_h$ As the voltage is increased, n and K tend toward unity. The values of τ_T and τ_B tend to zero, τ_f in this case being equal to the sum of $\tau_c+\tau_h$ and the mean rate tends towards rates of the order of $(3-5)\cdot 10^8$ cm/sec, i.e., it approaches the magnitude of the velocity of the leader v_l. The sum of $\tau_h+\tau_c$ governs the magnitude of the statistical spread of the time required to close the discharge gap; by separate channels growing in parallel. It is weakly dependent on the overvoltage.

It follows from an analysis of the set of experimental data that a certain value of the overvoltage U_m/U_{bd} must be used to obtain a spark channel system of maximum density on a dielectric surface. This value is influenced basically by two factors: the length of the discharge gap l and the permittivity of the dielectric onto the initiator $c=0.88\varepsilon/d$, pF/cm^2; d, mm (ε in relative units). The minimum value of $U_m/U_{bd}\approx 1.2-1.3$ occurs when $l \gtrsim l_k=1.8$ sec$^{-0.5}$, m. It is then possible to produce a system of spark channels with a spacing of 1.5-2 cm.

If $l \leq l_k$, the magnitude of U_m/U_{bd} increases so that

$$U_m = 1.3U_k;\ U_k = 130 \text{ sec}^{-0.5}, \text{eV}. \tag{1}$$

When $l \leq l_k$ the breakdown voltage $U_{bd} \leq U_k$. As l is reduced, the magnitudes of U_k and U_m remain constant, while the magnitude of U_m/U_{bd} rises corresponding to the reduction in U_{bd} as l falls. Relation (1) is confirmed at least in the region under investigation $c \geq 0.5$.

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