ELECTRICAL CHARGE DISTRIBUTION ON A DIELECTRIC SURFACE

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During breakdown in the strongly inhomogeneous field of a grazing spark one finds local zones with longer-lasting luminosity, which are formed both in the final and preliminary stages of the discharges [1]. In the final stage such zones are formed in a stable manner in bends of the discharge channel given the condition that the discharge channel length exceeds a critical value. In this case the lifespan of the local luminous zones may be an order of magnitude higher than that of direct discharge channel segments. In the preliminary stage of discharge, segments with longer-lasting luminosity are formed on an alternate leader trajectory or lateral branches. In this case the lifespan of their luminosity is much less, yet still sufficient for detection by an SFR-2M high speed photorecorder.

The goal of the present work is to study the mechanism by which local luminous zones are formed in the initial stage of a grazing spark. It is assumed that local zones with an elevated charge carrier concentration are formed during the breakdown process.

Visualization methods were developed to verify the assumptions regarding charge carrier concentration. This was done by photographic methods. The visualization of the electrical charge distribution over the photomaterial surface is based on the fact that in an electric field the latent image centers shift in a direction opposite to the applied field [2]. With simultaneous action on the emulsion of a brief (about 10^{-6} sec) subillumination, which increases light sensitivity by an order of magnitude, and an electric field, which depending upon its direction either increases or decreases the light sensitivity of the emulsion [3], it was possible to obtain an image of the electric charge distribution on the film surface.

The charge visualization method was developed with a weakly scintillating discharge — an impulse corona from a point. The visualization conditions were chosen such that there were no images of the pulsed corona without external subillumination, while the action of such illumination produced only a slight increase in dogging of the film. Consequently, neither the pulsed corona, nor the uniform subillumination individually could produce an image, which could be produced only by their combined action.

In the discharges studied the radiation from a developing spark was used for subillumination of the film. In this case an image of the light-emitting elements of the discharge is formed — Lichtenberg figures [4], together with an image of the electrical charge distribution in the streamer system on the breakdown front and in a radial direction from the spark channel. This distribution coincides with the moment that light emission from the developing spark ends, which is the time that ionization processes in the discharge gap are completed. It is difficult to produce uniform illumination of the film in light-emitting discharges, especially for a long grazing spark [5]. The images produced with automatic subillumination practically coincide with electrographic ones [6], but the method of charge visualization using photomaterial has significantly higher sensitivity and greater resolving power.

A study was made of electrical charge distribution over the length of a grazing spark developing directly on the surface of the photographic film in a long discharge gap under the conditions described in [5], which described the experimental technique and oscilloscope measurements, as well as grazing sparks in a capacitive discharge with the same power supply. In this case the film was located on the surface of an insulated grounded electrode.

The capacitive (barrier) discharge was a discharge in a gas gap with electrodes insulated by a dielectric [6, 7]. The area of the plane electrodes was 10 × 50 cm, with gas gap length of 1.5 cm. A cosine-shaped voltage with amplitude up to 70 kV was applied to the high voltage electrode. The oscillation period was 9.8 μsec, with decrement of 0.3. Maximum current

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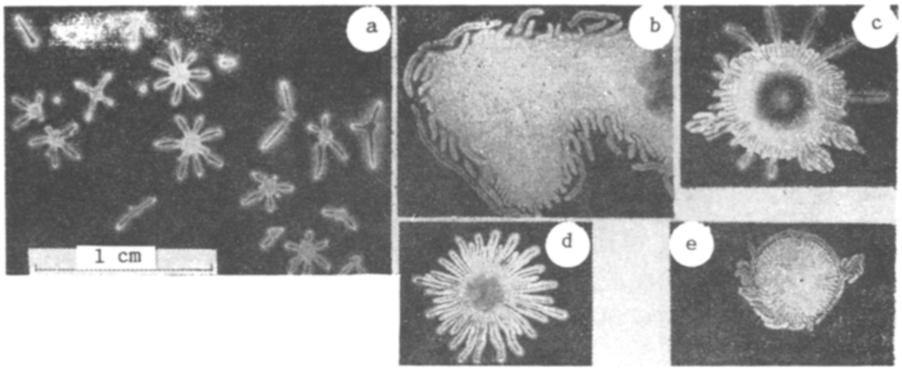

Fig. 1

amplitude at the electrodes was 200 A, with duration of about 1 μsec, after which the current fell to 10-2 A. It can be concluded from current oscillograms that the basic processes of discharge change on the dielectric surface in the capacitor gap under the conditions chosen are limited by the leading edge of the voltage pulse. This conclusion was confirmed by the character of the charge images obtained upon reversal of power supply polarity and comparison with the charge images of [6].

The development of grazing sparks in a long discharge gap at the inflection point of the breakdown characteristic [5] and along the dielectric surface in the capacitor gap can be considered qualitatively similar as a result of the following basic processes.

1. Initial ionization occurs in marked volumes of the gaseous medium. In the long gap high-speed breakdown waves [8, 9] produce the initial ionization, while in the capacitor gap the initial process is quite homogeneous ionization of the gaseous medium due to the dielectric on the electrodes.

2. A high rate of voltage increase creates a nonequilibrium recombination plasma in the gas, charge redistribution produces current surges, and induced turbulent fields [10] are formed, which in the authors' opinion play a significant role in the process of charge localization in the gap.

3. Through-current is absent from the discharge gap, this being true in only a portion of the long spark. Therefore the main process is not heating of the spark channel by through-current, but charge accumulation in the gap, which is necessary for further development of the breakdown. The absence of through-current also aids recording of charge localization processes.

The main difference between grazing sparks in a long gap and a capacitive discharge is the degree of electric field homogeneity. In the severely inhomogeneous fields of [5] the rate of breakdown development is rapid, the low duration of each stage hindering recording of electrical charge on film, since over the time of subillumination pulse action multiple redistributions of charge over the surface occur. In the capacitor gap the initial electric field distribution is relatively homogeneous, the inhomogeneous field developing due to inhomogeneous charge distribution on the dielectric surface upon significant excess of the applied voltage above the breakdown value for the gas gap. Therefore development of the grazing spark in the capacitor gap and the corresponding stages of charge distribution become accessible for recording. Moreover, the process of charge spreading over the dielectric surface is of independent interest.

In the capacitor gap for positive voltage on the high voltage electrode approximately equal to the breakdown value, individual streamers are formed in the gas gap, the trajectories of which continue onto the film surface (Fig. 1a). By the term streamer we mean an electron avalanche surrounded by a sheath of positive charge. In the literature [11] the term streamer has a somewhat different meaning. The charge image of the streamer is formed upon action of the external subillumination pulse, which creates latent image centers uniformly over the photographic film surface. Negative charge (an avalanche electron) reduces sensitivity of the emulsion, destroying latent image centers, so that zones of negative charge action have a density lower than that produced by the uniform subillumination. In the charge images presented here this effect can be observed for negative charge action on

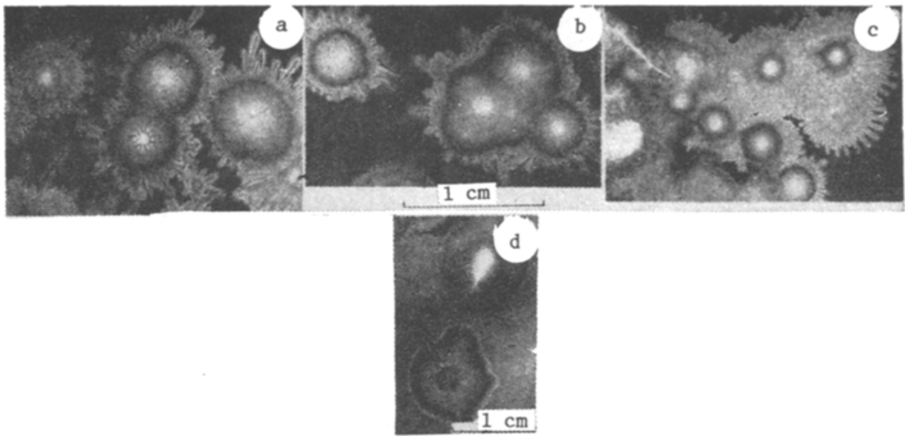

Fig. 2

positively charged portions of the film. Positive charge increases emulsion sensitivity due to sintering of latent image centers in the direction of positive charge. Therefore the charge image of the streamer is the image of both positive charge (light aureole) and negative charge (dark center). The interaction of the external subillumination and electric field with the emulsion are nonlinear in character and determination of the charge concentration photometrically is not possible. When the voltage exceeds the breakdown voltage on the film segments positively charged by streamers are formed (Fig. 1b).

With further increase in voltage on the high voltage electrode in the gas gap of the capacitor discharge, spark channels develop which transport a larger charge to the film surface, forming their own streamer system. The zone of contact of the spark channel with the film surface can be considered as a local discharge, from which the processes of streamer formation and ionization of the capacitor discharge gap develop. The qualitative picture of the growth of local discharge can be described as follows. In a direction radial to the local discharge a streamer system begins to develop (Fig. 1c), controlled by two processes in the local discharge center:

due to a drop in electric field intensity E in the spark channel accumulation of charge +q leads to a decrease in current through the channel;

neutralization of the center charge by a charge transported by streamers −q (Fig. 1d, dark spot in center) leads to an increase in E and current through the spark channel.

The time interval between these processes, calculated for an average electron avalanche velocity, comprises $(1\text{-}2)\cdot 10^{-8}$ sec, which corresponds to node development times in a pulsed corona column in air [12]. The development of nodes in individual directions in the local discharge streamer system (Fig. 1e) can be considered a process of growth of future local discharges, while the process of charge localization is apparently among the earliest stages of breakdown.

Nodes develop in the streamer system at the time of neutralization of local discharge centers, and at some time E in the peripheral zone of the local discharge proves to be higher than the E value created by the center. Streamers develop on the periphery of the local discharge in the region with highest E at the given time, i.e., along the equipotential relative to the initial discharge center (Fig. 1e). Since the charge images are the image of the final stage of charge distribution over the surface, it can be proposed that at the time of voltage increase streamer development takes place alternately in both the radial and equipotential directions. It is possible that streamer development along the equipotential relative to the local discharge center can be treated as a process of charge equalization over the length of radial streamers. The existence of such a process is indicated by the fact that a local discharge not interacting with others has the form of a true circle on the film surface. In the case of a homogeneously charged surface streamer development also occurs in directions normal and parallel to the streamer front (Fig. 1b).

Individual local discharges formed by both spark channels in the capacitor discharge and nodes of the streamer system combine into larger local discharges with a single streamer system and single charge shells (Fig. 2a, b). The local discharge shell can be considered an annular zone about a center having excess charge of one sign. In Fig. 2a, b these annular

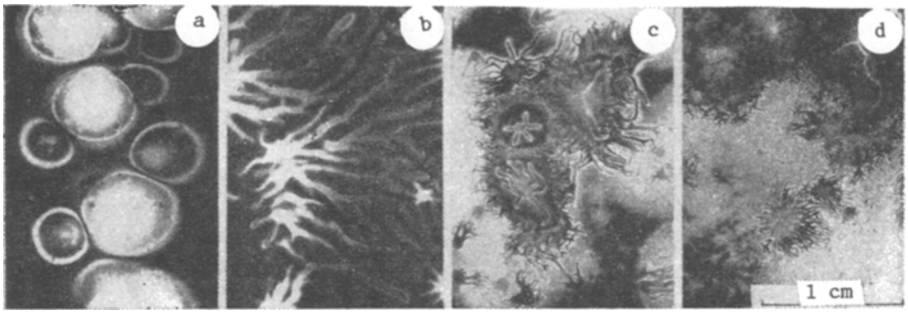

Fig. 3

zones have negative charge (dark rings around the centers). Local discharges formed on a surface charged homogeneously by streamers may have a positively charged external shell. In this case local discharge interaction has the character of interaction of their external shells with excess charge of opposite signs (Fig. 2c).

At the edges of the electrodes of the capacitor discharge the electric field is less homogeneous, which encourages formation of a grazing spark. The spark channel which forms causes field intensification on the development front, so that a chain of local discharges is formed on the future spark channel (Fig. 2d).

For negative polarity on the high voltage electrode local discharges are formed without formation of a streamer system (Fig. 3a). This is because the charge of the dielectric surface and the excess streamer charge are of the same sign, so that streamers develop in the gaseous medium above the dielectric surface. In the slightly inhomogeneous field at the electrode edges one can obtain a negative streamer image, but it will be diffuse (Fig. 3b). Absence of streamer system images in the negative local discharge image permits a clearer representation of local discharge structures and their interaction.

A negative local discharge (Fig. 3a) is a complex system involving a positively charged center, negative charge region around the center, positively charged shell, and external negative shell, the presence of which is indicated by the dark band between closely situated discharges. The excess negative charge is mainly concentrated around the positively charged center. This is indicated by the displacement of the center of the smaller discharge in the direction of the larger, their merger being retarded for some time by their external shells. As the shells are destroyed in the region of contact, the local discharges merge together, charges of both signs are redistributed over inner and outer shells, and they probably recombine. A possible analogy is the growth of a large crystal and solution of fine ones in a saturated solution. The structure of a positive local discharge is apparently the same, but there is more positive excess charge than negative.

With further increase in negative polarity voltage and intensified ionization, positive ions neutralize surface charge and sharp secondary streamers are formed. In the center of the larger local discharges formation of a grazing spark channel begins (Fig. 3c). At the electrode edges on the future spark channel (in analogy to Fig. 2d) chains of negative local discharges are created (Fig. 3d).

In recording negative local discharges by selecting the subillumination regime we can obtain an image of charge distribution, as well as a more detailed image of processes occurring in the radial and equipotential directions from the center (Fig. 4a). Within the charge image of the center of a large local discharge one can distinguish a simpler structure: a positive center and negative shell. The authors have termed such a structure a granulated discharge. This is a more stable form of existence for electrical discharge as compared to a plasma.

The development of the spark channel along the chain of local discharges occurs either along the trajectory of one of the radial streamers, in which case the local discharge is included within the spark channel trajectory, or along the equipotential around the local discharge (Fig. 4b). Individual sparks are formed in the local discharge chain on the future discharge trajectory (Fig. 4c). For high speed photorecording of this process a beaded discharge structure in the developing stage is obtained [1]. As a rule, the beaded structure is realized on an alternate discharge trajectory or on side branches, i.e., at a field value sufficient for formation of large local discharges but without development of a single spark

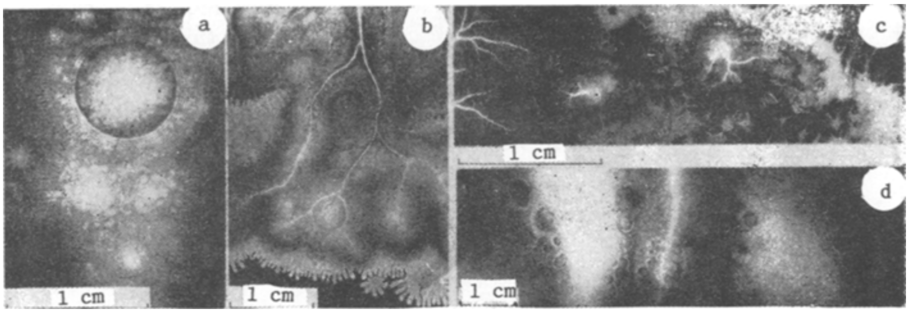

Fig. 4

channel along the chain of local discharges. It can be concluded from Fig. 4b, c that the local discharge is one cause of the twisted form of the spark channel and its branching.

Apparently the initial stage of charge localization is formation of clusters [13], consisting of a positive ion in the center and neutral atoms formed due to polarization in the electric field of the ion of the external charge shell. The clusters may consist of hundreds of atoms and molecules [14, 15]. As an initial hypothesis we assume that the process of local discharge merger (Fig. 3a) is similar to formation of a granular charge upon cluster merger.

To create a cluster plasma it is necessary that the discharge plasma be of the recombination of nonequilibrium type. The simplest way of obtaining such a plasma is driving the discharge by brief (less than 10^{-6} sec) voltage pulses. This regime is automatically realized in the spark channel of the capacitor discharge. In the grazing spark, for a channel length greater than the critical [5], voltage sources are produced by formation of a stepped leader. Under these conditions in the extremely inhomogeneous field of the breakdown front, where the rate of charge spreading over the surface is much greater, it is difficult to obtain charge images of usable quality because of parasitic subillumination from the spark channel. In the radial direction from the long spark channel, where the charge spreading rate is approximately the same as in the capacitor discharge, one can obtain charge images approximately the same as those of Figs. 1-3 in the developing grazing spark.

The length of the discharge gap decreases significantly if the discharge is supplied by brief voltage pulses in analogy to the stepped leader. In this case we have a charge image of the column of surface charge of the developed grazing spark, having limited the energy in the high current stage of the discharge (Fig. 4d). Here the processes of charge granulation and primary streamer and local discharge formation are even clearer than in the capacitor discharge. It is evident from Fig. 4d that a granular charge region is formed upon decay of the primary streamer system.

Thus the breakdown process is a chain of processes all of the same type: cluster creation in the stage of electron avalanche formation, followed by granular charge during formation and decay of the primary streamer system, local discharges during secondary streamer formation, merger and growth of local discharges in the column of the surface and volume charge of the spark channel. These processes occur with stepped increase in energy in all stages of the breakdown. It should be stressed that such an approach is applicable only to the breakdown of long discharge gaps.

For the grazing spark one can also regard as an attribute of a long discharge gap the fact that in the gaseous medium above the dielectric surface there occur the same processes of primary and secondary streamer formation as on the dielectric surface. In this case the density of the network of streamer channels is significantly less than on the surface, but increases rapidly with increase in applied voltage. It is the formation of a column of space charge above the dielectric surface which permits treating the grazing spark as a lightning model. Current surges in the breakdown process create induced turbulent fields with closed force lines in the space charge column [10], which is of special significance in formation and especially stabilization of local discharges. Streamer development along local discharge equipotentials on the surface and processes in the turbulent field within the space charge column are apparently qualitatively similar, since the basic condition for charge localization is satisfied — creation of a recombination-nonequilibrium plasma, where a significant fraction of the charged particles are clusters [13]. Therefore an understanding of the processes of charge spreading along the dielectric surface is a significant aid to understanding the processes that occur in the space charge column of a grazing spark and lightning.

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