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DYNAMICS OF THE DEVELOPMENT AND STRUCTURE OF A BARRIER DISCHARGE IN A LARGE GAP

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UDC 533.09

The barrier discharge (BD) has been used in the past mainly in ozonizers and has been investigated under the optimum conditions for these devices: $U = 3$–10 kV, $f \simeq 10$ kHz, a gas gap of 0.1–0.4 cm, and with barriers of glass [1]. Spectroscopic investigations of BD have been made in recent years under similar conditions [2, 3]. In all the reports the multichannel nature of its structure was noted as a specific feature, which permitted its use in [4] for the synchronous initiation of 20 high-current autonomous discharges and in [5-7] for the formation of multichannel high-current discharges.

However, the nature of the multichannel structure and the mechanism of its development have been studied inadequately up to now. This circumstance, as well as the fact that in [4, 5] the BD was generated in a larger gas gap and at a higher magnitude and frequency of the supply voltage, served as a basis for the formulation of the present work. In it we investigated the dynamics of the development of a BD, its structure, the influence of the parameters of the discharge and supply circuits and of the gas composition on its properties, and the dependence of the delay time of the discharge initiated by it on the voltage on the barrier electrode.

Description of Experimental Installation

A diagram of the experimental installation is presented in Fig. 1. Inside the chamber, through which argon could be blown, the two plane primary electrodes 1 and 2 having a cross section of 4.5 × 0.8 cm were placed with a gap of 0.8-3 cm. The ends of the electrodes had a wedge shape ($\measuredangle = 90°$). Between them there was a trigger electrode 3 in the form of a wire 0.15 cm in diameter or an aluminum cylinder 1 cm in diameter and 4.5 cm long, enclosed in a quartz tube sealed at one end and having an inner diameter of 0.15 and 1 cm, respectively, and a wall thickness of 0.15-0.2 cm. The voltage was supplied to it from a step-up transformer constructed on three F 1000 ferrite rings with dimensions of 110 × 60 × 15 mm. A capacitor $C_1 = 0.01$ or $0.1\ \mu F$ was discharged through the first winding ($w = 2$). A high-voltage pulse with a frequency of 1.3 and 0.45 mHz, respectively, was transformed in the second winding ($w = 20$); its amplitude depended on the initial voltage on C_1 and was varied from 20 to 60 kV. The BD grew from the surface of the quartz tube 3 to each of the primary electrodes 1 and 2 (Figs. 1-3). Their wedge shape predetermined the formation of all the channels in the same plane, which made it possible, by placing the photographic apparatus 4 normal to it, to focus the images of all the channels on the film. The voltage U on the BD was measured with a capacitive divider, $C_3 = 16$ pF and $C_4 = 0.015$ pF (1 : 1000). To measure the current I of the BD and the delay time of the initiated discharge of the capacitor $C_2 = 2200$ pF we used $R_s = 5.1\ \Omega$, common to the two discharge circuits. The voltage from R_s was applied to the plates of the tube of an S1-42 oscillograph while the voltage from C_4 was applied to its amplifier through a delay line ($t = 0.3\ \mu$sec).

Description of Experiments

The low brightness and small transverse size of the BD channels hinder the use of streak-camera photography in its investigation, and therefore the dynamics of its development was obtained from the compari-

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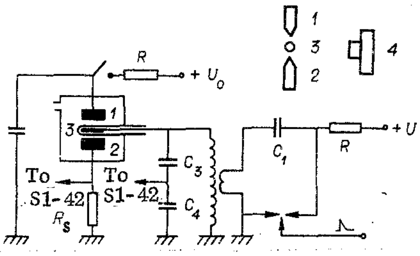

Fig. 1

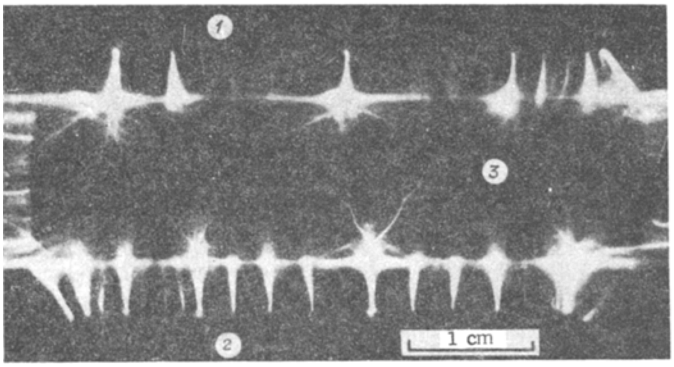

Fig. 2

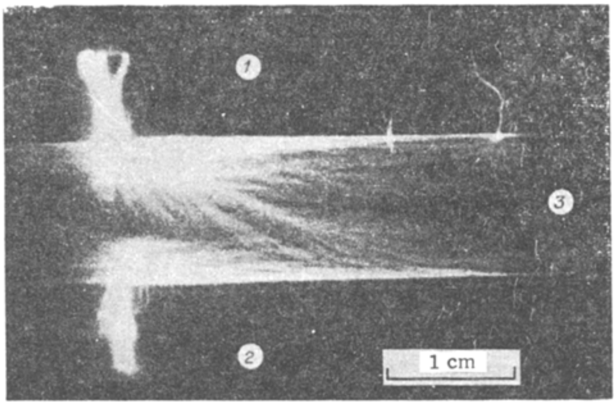

Fig. 3

son of photographs and oscillograms of I and U for different experimental conditions. The capacitor C_2 was not charged in these experiments.

The BD emission was photographed in single exposure with a Zenit camera on isopanchrome film of type 24 with a sensitivity of 5000 All-Union State standard (GOST) units (4 in Fig. 1).

On the basis of Fig. 2 ($C_1 = 0.01$ μF, U = 50 kV) we can say that a large number of channels (up to 20 cm^{-1} in some photographs) start to develop in air. However, the number of channels bridging the gap is considerably less, and they can be divided into three types: diffuse over the entire length, conical with a diffuse spot at the dielectric, and, against the background of some of them, bright uniform channels ending at the dielectric in a Lichtenberg figure of creepage discharge (CD). The diffuse channels developed, as a rule, at a voltage of up to 30 kV and sometimes almost merged over a considerable length of the electrodes. The conical channels occurred at all voltages up to 60 kV. Channels of type III developed at $U \geq 30$ kV for a capacitance C = 0.1 μF and $U \geq 40$ kV for C = 0.01 μF.

The number of channels depended more on the voltage on the barrier electrode, while their apparent diameter depended on the capacitance C_1. The average interval between conical channels was 0.4 cm and that between channels of type III was 1 cm. In argon under similar conditions one or two channels finally developed along the edges of the electrode (Fig. 3, $C_1 = 0.01$ μF, U = 50 kV).

Oscillograms of the current and voltage of BD in air (Fig. 4, U with a delay of 0.3 μsec) and argon were obtained for C = 0.01 and 0.1 μF. The form of I and U indicates the presence of two periodic processes in the discharge circuit. One of them has a period dependent on the parameters of the primary circuit: T = 0.75 μsec for C = 0.01 μF and T = 2.2 μsec for C = 0.1 μF. Damped sinusoidal oscillations with such periods could be observed when the secondary winding was short-circuited to R_s. The second process is connected with the development of the BD and with subsequent damped oscillations with T = 0.3 μsec which depend on the capacitance of the barrier. In the case of C = 0.01 μF the BD developed only during the first half-period of the oscillations in the primary circuit, while in the case of C = 0.1 μF it developed during two half-periods. In this case with the smaller capacitance at a voltage of up to 40 kV there was only a positive pulse on the oscillograms (~ UdC/dt), while with the larger capacitance there was a positive pulse and, with an interval of 1.1 μsec, a negative pulse at a voltage of up to 30 kV. The amplitudes of these pulses (8 and 6 A in Fig. 4) varied in proportion to the voltage on the barrier electrode. With a further increase in the voltage a negative current pulse (~ CdU/dt) appeared on the oscillogram for C = 0.01 μF and a negative and positive pulse appeared in the case of C = 0.1 μF. Channels of type III appeared on the corresponding photographs. The amplitudes of these pulses

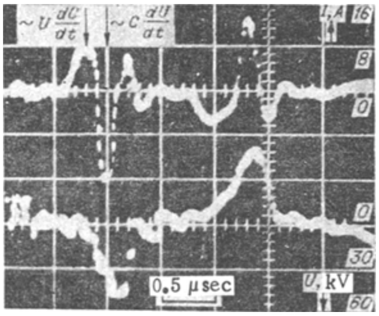

Fig. 4

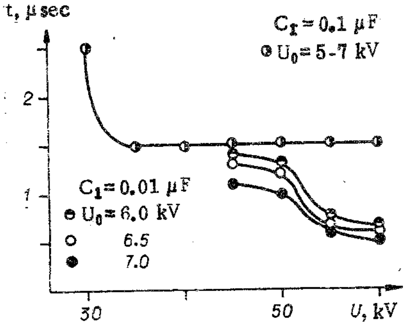

Fig. 5

varied faster than the voltage, and at U = 50 kV they comprised 16 and 12 A. The current density in four to five such channels with a total cross-sectional area of $5 \cdot 10^{-3}$ cm^2 was $3 \cdot 10^3$ A/cm^2, while the rate of current rise was $> 10^8$ A/sec.

The oscillograms of I and U in air and argon were similar in form and the current amplitudes varied as $\sim \sqrt{C_1}$, but they were twice as large in argon as in air.

The absence of materials of suitable electric strength with ε considerably exceeding the ε of quartz prevented an investigation of the influence of the specific capacitance of the barrier on the properties of the discharge. And the influence of a change in the capacitance of the barrier on account of the diameter and length of the trigger electrode is hard to determine, since the field in the discharge gap is essentially nonuniform. Therefore, we can only say that the amplitude of the BD current varies as $\sim \sqrt{C_b}$, while the shape hardly depends on it.

The experiments on determining the delay time t of the initiated discharge of C_2 followed two goals: to measure the delay time of the discharge of C_2 in air after the application of the trigger pulse to the air discharger in the primary circuit of the transformer (it also triggered the oscillograph) and to establish what phase of the BD is responsible for its initiation.

Since the current pulse of the discharge of C_2 also flowed through R_s, on the oscillogram it was superimposed on the BD current at a certain moment. With an increase in the amplitude of the voltage on the trigger electrode the current pulse of the discharge of C_2 was shifted on the oscillogram, tending toward the leading front of the negative pulse of the BD current.

The results of measuring the delay time in the initiated discharge as a function of the amplitude of the voltage on the trigger electrode with different voltages on the gap for the two capacitances $C_1 = 0.01$ and 0.1 μF are presented in Fig. 5, from which it follows that with an increase in the amplitude of the voltage on the trigger electrode the delay time approaches some minimum limit, equal to 0.5 μsec for C = 0.01 and 1.5 μsec for C = 0.1 μF, and then remains constant after reaching it.

Discussion of Results

Before considering the results obtained, let us analyze the specifics of the spatial formation of a BD in comparison with an ordinary spark discharge.

It is known that one discharge channel develops, as a rule, in a discharge gap formed by metal electrodes. This is connected with the fact that the surfaces of conducting electrodes are equipotential, so that the channel which develops first reduces the potential difference between them, preventing the development of subsequent channels at other points. In the case of a BD the equipotential nature of the surface of the dielectric is established through the development of a CD along it, but since its velocity in air is low, $\approx 10^7$ cm/sec, it will occur only near the first channels, while at some distance from them the initial potential will be retained, and channels developing with a delay can form there. Therefore, the higher the velocity of the CD, the less frequent the channels, but the amount of current in each of them grows.

Another feature of a BD is connected with the fact that, in series with the active resistance which is nonlinear in time, there is a nonlinear capacitive resistance of the gap. In fact, the total capacitance of the gap consists of the series-connected capacitances of the dielectric barrier and the gas gap. The permittivity of quartz is four times higher than that of the gases, while the lengths of the gas gaps used are three to six times greater than the thickness of the tube wall, so that the total capacitance was initially determined by the capacitance of the gas gap and comprised a small fraction of the capacitance of the barrier. Accordingly, the voltage applied to the electrodes was divided in inverse proportion to the capacitances, and at the initial moment it fell almost entirely on the gas gap. After its breakdown the total capacitance was increased to the capacitance of the barrier and all the voltage was applied to the dielectric.

Since a systematic description of an electrical circuit containing nonlinear elements is complicated, we present an equivalent circuit for the discharge circuit in the form of an oscillator loaded onto a capacitance which varies periodically, synchronously with the discharge. The charge carried in such a circuit is $q(t) = C(t)U(t)$ while the current is $i(t) = dq/dt = U(t)dC/dt + C(t)dU/dt$. The clear correlation between the types of channels in the photographs and the current pulses on the oscillograms and the character of the dependence of their amplitudes on the voltage allow us to say that the first phase of the BD corresponds to diffuse and conical channels with a current amplitude of $\sim U(t)dC/dt$ in them, while the second phase corresponds to channels having a CD with a Lichtenberg figure and a current amplitude of $\sim C(t)dU/dt$.

With allowance for the foregoing, the dynamics of the development of a BD in air can be represented as follows. Upon the application of voltage to the electrodes, polarization charges developed on the surface of the dielectric and discharge channels began to develop in the gas from certain points. Because of the natural time scatter in their development, the equipotential nature of the surface of the dielectric was disrupted and a CD developed. Its velocity was initially small with the low field strength in the gap and consequently along the dielectric, so that many channels of types I and II developed with a low current density. As the conductivity of the gas gap increased, the capacitance between the electrodes increased to the capacitance of the barrier, and it was charged during this first phase of the BD. With the end of its charging the discharge died out, and the capacitance of the entire gap decreased to the capacitance of the gas gap. And since the stored charge, now excessive, could not decrease instantaneously, the voltage on the barrier grew sharply, but now it was of the other polarity relative to the gas gap and in antiphase with the voltage on the transformer winding. Therefore, although the total voltage in the circuit fell to zero (see Fig. 4), the voltage jump on the gas gap led to its breakdown and the generation of a negative current pulse in the circuit, corresponding to the second phase of the BD.

As seen from the oscillogram, the duration of the second phase is half as long while the current amplitude is twice as great as that of the first, which indicates equality of the charges carried in the circuit during each phase.

Because of the sharp voltage increase, the velocity of the CD grew, the number of channels was reduced, and the entire charge in the second phase was carried through several channels of type III. The decrease in the duration of the current pulse and in the number of channels led to a considerable increase in the current density to $3 \cdot 10^3$ A/cm^2 and to strong heating of the plasma. Therefore, the high conductivity of the channels was subsequently retained for a long time, the capacitance of the gap remained constant and equal to the capacitance of the barrier, and damped C, L, R oscillations occurred in the circuit.

The dynamics of a BD in argon is similar, judging from the qualitative similarity of the oscillograms of I and U. The increase in the current amplitude and the smaller damping of the C, L, R oscillations are connected with the increased conductivity of the discharge channels, whereas the reduction in their number is explained by the velocity of the CD being two to three times higher in argon [8].

The above concepts of two phases in the development of a BD permit an understanding of the results of the experiments on measuring the delay time of the discharge of C_2 in air (Fig. 5).

Actually, since the number of channels in the second phase is three to four times less while the current amplitude is twice as great, the current density in them is six to eight times greater than in the channels of the first phase. Therefore, the discharge of C_2 is initiated by the negative current pulse of the second phase, while its leading front is also the minimum limit to which the delay time approaches with an increase in the voltage on the barrier electrode. And the threshold nature of this dependence is determined by the character of the voltage dependence of the amplitude of the current pulse, $\sim C(t)dU/dt$. It must be considered that the delay includes not only the time of the first phase of the BD but also the time of development of the breakdown of the air discharger following the application of the trigger pulse to it.

The experimental results obtained in the work allowed us to establish that the multichannel nature of the BD structure is connected with the natural time scatter of the formation of discharge channels at different points of the surfaces of the electrodes and with the conditions of the development of the CD along the dielectric barrier. The smaller the scatter and the velocity of the CD, the weaker the concurrence between the channels and the more uniform the discharge will be, changing into a volumetric discharge in the limit.

The dynamics of the BD is determined by the variation of the capacitance between the electrodes, consisting of the capacitance of the barrier and the capacitance of the gas gap, in the process of the discharge. The amplitude of the BD current pulses depends on the voltage on the electrodes and the capacitance of the barrier.

The considerable current density in the channels and the steepness of the leading fronts of the pulses make it possible to synchronously initiate a large number of autonomous discharges with its help and to form high-current, multichannel discharges.

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INVESTIGATION OF THE PLASMA STRUCTURE FORMED ON THE SURFACE OF A BODY IN FLOW OF A PARTIALLY IONIZED GAS

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In [1] a technique was suggested for creating artificial plasma structures around bodies in flow of a rarefied plasma by blowing a neutral gas from the surface and subsequently ionizing it by electron collision. It is of interest to understand the relationship between the structure of the plasma formations on the body surface and the function of the different systems. The present paper gives results of an investigation of the influence of the body surface potential on the shape and structure of the plasma formations generated about a metal body in flow of partially ionized nitrogen.

The experimental investigations were conducted on a gasdynamic plasma facility in flow of a rarefied plasma generated by a gas-discharge accelerator. The plasma flow reaches the working chamber in which the residual gas pressure is $7 \cdot 10^{-7}$–$1 \cdot 10^{-6}$ torr. The plasma flow parameters at a working chamber pressure of $\sim 1.6 \cdot 10^{-5}$ torr were determined by means of movable electric probes mounted on a traverse mechanism; a single cylindrical probe, made of molybdenum wire of diameter 0.09 and length 4.0 mm; and a cylindrical probe in the form of a hot-wire anemometer [2], with a working element made of tungsten wire of diameter 0.06 and length 6.5 mm. Special attention was paid to probe cleanliness during the measurements. Immediately prior to the measurements the probes were heated up to temperatures ~1500°K, which allowed the influence of impurities on the measured results to be excluded.

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