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PREBREAKDOWN STAGE OF A SURFACE DISCHARGE FIRED BY A PULSE IN THE AIR AT ATMOSPHERIC PRESSURE

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Results of investigation of a high-current plane pulsed surface discharge with separated torches fired in the air at atmospheric pressure are presented. The dynamics of ignition and development of the discharge in the prebreakdown stage has been considered. The main parameters of the plasma in the prebreakdown stage (the stage of intense prebreakdown glow) have been determined by spectroscopic methods and the influence of the dielectric material of a substrate on the plasma parameters has been analyzed. It has been established that the duration of an intense prebreakdown glow depends on the experimental conditions. A physical pattern of formation of an intense prebreakdown glow is proposed.

The operation of many electric-discharge systems is based on a high-current pulsed discharge on a dielectric surface. A plane pulsed surface discharge is widely used in intense radiation sources for photography and spectroscopy [1–5] and in various lasers [6, 7]. A cylindrical pulsed surface discharge finds wide application in generators of pulsed erosion plasma jets (pulsed-erosion-plasma accelerators, plasmatrons, diaphragm electric-discharge shock tubes, etc.). Considerable recent attention has been focused on the use of a plane pulsed surface discharge for investigating the bactericidal action of a spark discharge on a water surface (in a similar way to a discharge in a water volume) [8] and the plasma-chemical destruction of freons (a creeping surface discharge [9]). However, as judged from the available literature, a high-current pulsed surface discharge has not been adequately explored. Therefore, we attempted to make up for this deficiency.

In the present work, prominence was given to the study of the formation of the surface plasma at the initial stage of a plane pulsed surface discharge and the influence of this stage on the further development of the discharge. We also investigated the dependence of the plasma formation on the material of the electrodes and the substrate and the ambient pressure. For more complete understanding of the physical processes occurring in a plane pulsed surface discharge with separated torches, the gasdynamic structure of the electrode plasma torches and its influence on the dynamics of the discharge and the plasma formation were considered. The experimental investigation of surface plasma formations was supplemented with the theoretical study of the discharge dynamics, which made the analysis of the results obtained easier.

Apparatus, Experimental Conditions, and Investigation Methods. A pulsed surface discharge was experimentally investigated using a discharge device of plane configuration with a parallel placement of electrodes (Fig. 1). This device allows one to simultaneously investigate the near-electrode and near-wall regions of the discharge under the conditions where the electrode plasma torches are separated and free to flow, which eliminates the contribution of the torch component to the electrode erosion and the collision of supersonic electrode torches [10, 11].

A discharge was fired by a high-voltage pulse fed from the control pulpit of a superhigh-speed photography apparatus (SPA) to the starting electrode positioned in the discharge gap on the surface of a substrate near the center of the spacing between the anode and cathode. All investigations were carried out in the regime of single pulses and, after each discharge, the initial conditions were reproduced. The horizontal position of the substrate surface was controlled using a light ray.

The energy storage was a capacitor bank comprising 48 condensers (K-74-I2 type) of total capacitance 24 μF. An IM-5-150 condenser was used in some cases. The capacitor bank made it possible to fire surface discharges in the

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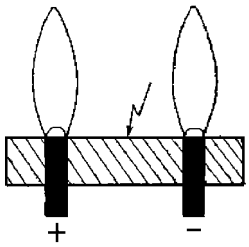

Fig. 1. Scheme of a plane surface discharge in the case of parallel placement of electrodes.

case were the electrode spacing was as large as 3 cm or more at an operating voltage of up to 10 kV. An oscillating discharge was fired under the following conditions: half-amplitude duration, 14 μsec; maximum discharge current in the first half-period, 14 kA; atmospheric pressure; voltage, 6 kV; electrode spacing, 2 cm; electrode diameter, 0.2–0.3 cm.

Substrates of fluoroplastic, the crystalline salt NaCl, and textolite were used in the investigations. The substrates were made in the form of a parallelepiped 4 × 2 × 1 cm in size. The materials indicated were selected from the following considerations. Fluoroplastic is a good insulator that is widely used as a plasma-forming material in pulsed erosion-plasma accelerators. The elements entering into the composition of fluoroplastic $(CF_2)_n$ have a high ionization potential (E_∞^C = 11.26 eV and E_∞^F = 17.24 eV). The crystalline salt is transparent for radiation in a wide spectral range and contains the alkali metal sodium, having a low ionization potential (E_∞^{Na} = 5.14 eV). Textolite, which is quite opaque for visible light, contains carbon and alkali elements. The electrodes were made from aluminum and copper wires.

The dynamics of a discharge was investigated by photoographic scans made with the use of an SPA and a triggered photorecorder in the frame-by-frame and continuous photography regimes. Longitudinal and transverse images of surface plasma formations projected onto the slit of the apparatus were photographed. To improve the spatial resolution, in investigating the kinetics of the plasma-bunch radiation, we used an achromatic condenser as the input objective of the SPA, which made it possible to enlarge the image on photographic scans 3.5-fold.

The space-time spectroscopic characteristics of the plasma in the near-electrode and near-wall regions were investigated using an ISP-51 spectrograph connected to the SPA through a Jupiter-3 objective [12]. The plasma radiation spectra were photographed with a speed of up to $5 \cdot 10^5$ frames/sec. For the purpose of obtaining a better spatial resolution of the near-surface regions, the images of plasma formations on the spectrograph slit were enlarged fivefold with the use of a condenser with F = 9.4 cm. The concentration of electrons was determined by the method of Stark broadening of spectral lines. The theoretical error in determining the width of individual lines reached 20% [13]. The error in determining the halfwidth of lines in the spectra on photographic scans was ~15% [14]. The total error could reach 35–40%. To decrease the error in determining the spectral line width, we averaged it over the widths of several lines equal for analysis [12–15]. The Stark broadening method and the method of holographic interferometry give the same values of the electron concentration if they are used under similar conditions [12, 16].

The electron temperature was determined by the relative intensities of the spectral lines of the atoms of chemical elements characterized by one and the same degree of ionization. The absorption was estimated by the intensity and width of faint and strong lines of a multiplier. The error in determining the temperature by the method of relative intensities of spectral lines was (at $kT \approx E_{up} - E_{low}$) 25–30% [13, 14].

Experimental Results and Their Analysis. An analysis of the data obtained by the method of high-speed photography has shown that, in the case where a plane pulsed surface discharge is fired in a large electrode spacing (~2 cm) at atmospheric pressure, a fairly dense plasma is formed in the anode–starting electrode region immediately before the electrical breakdown of the electrode spacing [11, 17]. This plasma manifests itself as an intense glow that is preceded by a low-intensity glow appearing in the gap between the electrodes once a high-voltage pulse is supplied to the starting electrode. To fire a discharge, the voltage applied should be fairly high.

Once an intense prebreakdown glow appears, it begins to propagate toward the cathode with a velocity of $\sim 10^3$ m/sec. It is seen from the photographic scans and cinema frames (Figs. 2 and 3) that the intense prebreakdown glow is volumetric at this stage.

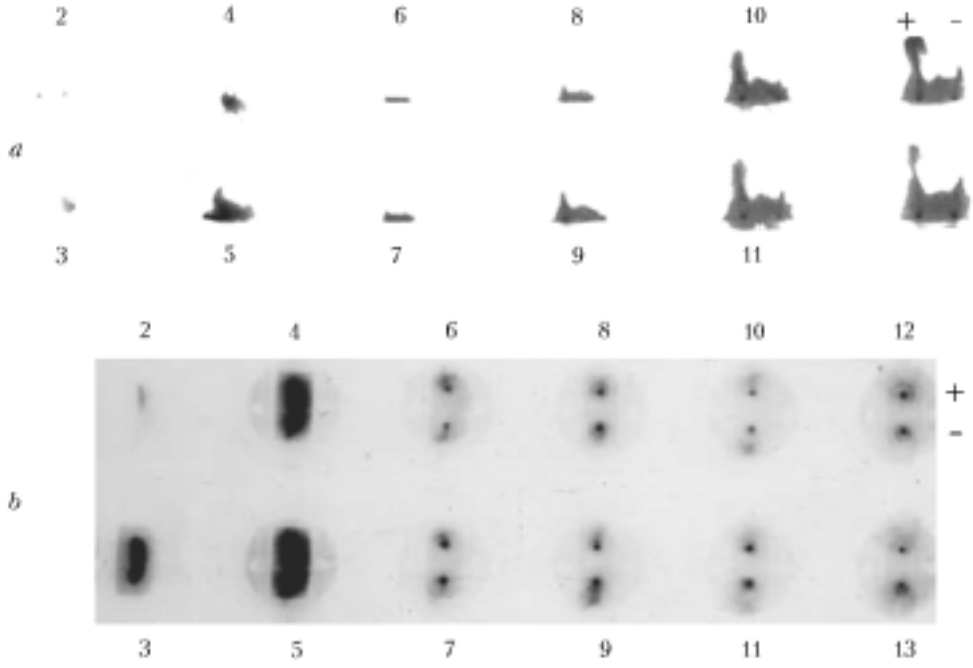

Fig. 2. Cinema frames of the glow of a discharge fired on a fluoroplastic substrate with the use of copper electrodes at an electrode spacing of l = 2 cm (the photographic speed is $2.5 \cdot 10^5$ frames/sec; 2, 3, ... is the sequence order of frames): a) frames transverse relative to the electrode spacing, U = 5 kV; b) frames frontal relative to the substrate surface, U = 6 kV.

The intensity of the glow at the prebreakdown stage (in the subsequent discussion the stage of an intense prebreakdown glow, i.e., the glow of a fairly dense plasma, will be called the "prebreakdown stage") decreases somewhat after a light strip appears and then increases once again (Fig. 3). Coincidentally with the widening of the prebreakdown glow region, an anode torch begins to form (Figs. 2 and 3). When the distance between the plasma formation and the cathode decreases to ~4 mm (at an electrode spacing of 2 cm and U = 6 kV), the gap between the electrodes is broken down. At the instant of breakdown, the intensity of the glow (especially in the near-electrode regions) increases sharply (Fig. 3).

In the case where the electrode spacing remains unchanged, the duration of the prebreakdown stage is determined by the voltage applied; it increases with decrease in the voltage. Figure 4 shows the dependence of the duration of the prebreakdown glow at the center of the electrode spacing on the voltage applied. As is seen, a further increase in the voltage can lead to the complete disappearance of the prebreakdown stage, i.e., to the "merging" of it with the breakdown stage.

At a constant voltage across the electrodes, the duration of the prebreakdown stage is determined by the electrode spacing. For example, when this spacing increases from 0 to 1.4 cm (C = 150 μF and U = 4 kV), the duration of the prebreakdown glow increases from 0 to ~1.5 μsec.

When aluminum electrodes are replaced by copper ones, the duration of the prebreakdown stage increases from 7–8 μsec to 10–12 μsec under typical conditions (the electrode spacing is 2 cm, C = 24 μF, and U = 6 kV). We did not detect a dependence of the duration of the prebreakdown stage on the substrate material.

A qualitative analysis of the emission spectra on cinema frames obtained by high-speed photography has shown that, in the prebreakdown stage of a discharge, there appear a low-intensity continuous background, lines of the electrode material and air elements, and, several microseconds later, lines of the substrate material.

An investigation of the space-time characteristics of the discharge considered has shown that, in the prebreakdown stage, the substrate material influences the near-surface processes. We investigated the intensity distribution of the lines and the continuous spectrum near the anode with the use of substrates made from different dielectrics. It has been established that, at the beginning of the prebreakdown stage, the intensity decreases with distance from the anode

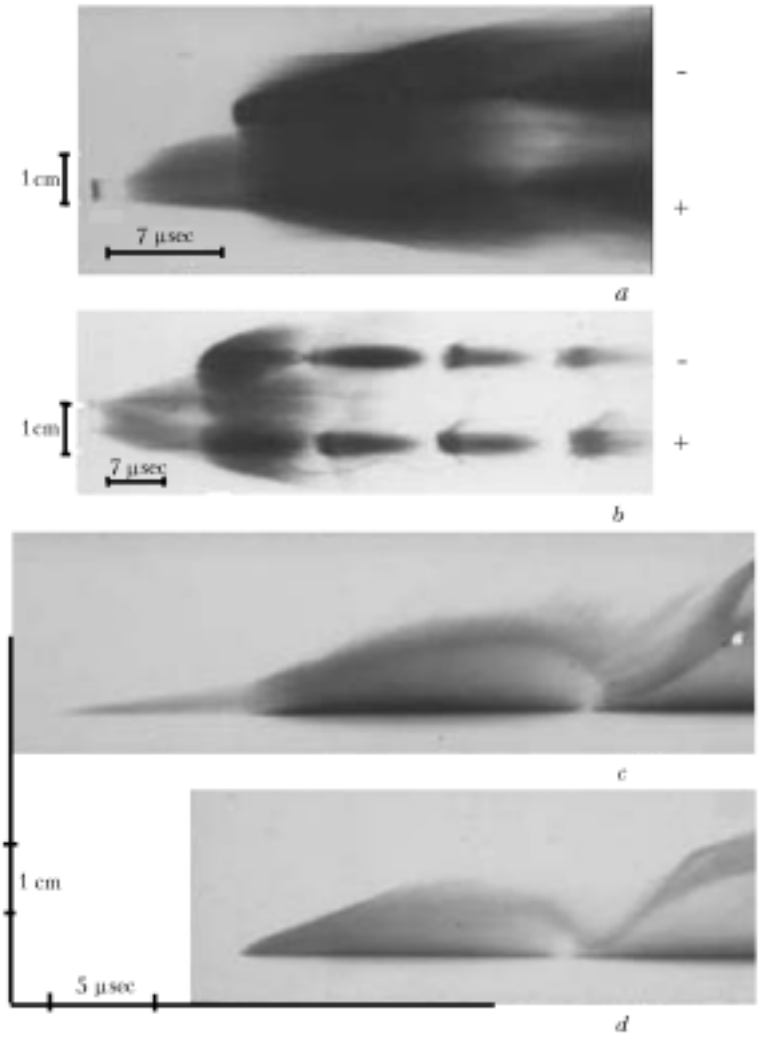

Fig. 3. Photographic slit scans of a discharge fired with the use of copper electrodes at l = 2 cm and U = 6 kV: a) frontal scans obtained with the use of an SPA (the slit is positioned along the discharge gap, a textolite substrate is used); b) scans of surface plasma formations obtained with the use of a triggered photorecorder (the slit is perpendicular to the electrodes, a fluoroplastic substrate is used); c) and d) scans of anode and cathode torches, respectively (the SPA slit is positioned along the torch, a fluoroplastic substrate and copper electrodes are used, l = 2 cm, U = 6 kV).

in the case of fluoroplastic and increases in the case of the crystalline salt (Fig. 5). When the radiation from the near-surface region of the substrates was detected, the intensities of the lines and the continuous background were maximum at a distance of 0.05–0.09 cm from the surface of the fluoroplastic and textolite substrates and near the surface of the crystalline-salt substrate (Fig. 5).

The space and time parameters of the discharge plasma were determined by the spectral lines of the atoms and ions of the substrate material, the nitrogen ions, and the double aluminum ions (near the substrate surface) as well as by the spectral lines of the double aluminum ions and the nitrogen atoms (near the anode surface). The temperature determined by the method of relative intensities represents the excitation temperature in the general case. However, in the case of a fairly dense plasma (with a density of 10^{17}–10^{18}cm^{-3}), where if only a partial local thermodynamic equilibrium exists and the lower level of analytical lines is considered, the temperature determined by the relative intensities of the lines represents the electron temperature.

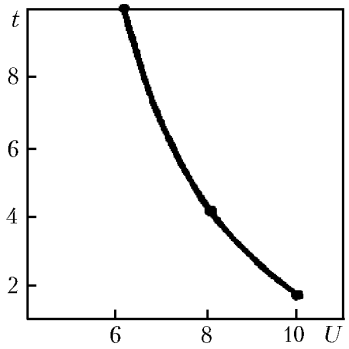

Fig. 4. Dependence of the duration of an intense prebreakdown glow on the initial voltage across the electrodes in the case where a discharge is fired on a fluoroplastic substrate with the use of copper electrodes at an electrode spacing of l = 2 cm. t, μsec; U, kV.

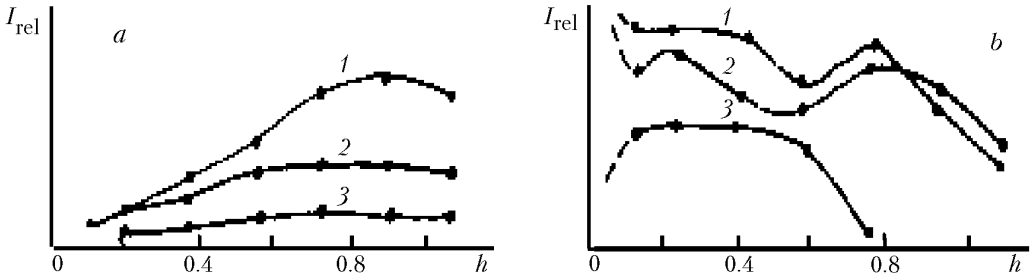

Fig. 5. Intensity distribution of the spectral lines and the continuous radiation spectrum detected at different distances from the anode at the prebreakdown stage of a discharge fired on different substrates: a) NaCl substrate [1) NII 444.7 nm, 2) AlIII 452.9 nm, 3) AlIII 451.2 nm]; b) fluoroplastic substrate [1) AlIII 569.6 nm, 2) AlIII 572.3 nm, 3) continuous radiation].

The electron temperature near the anode surface was determined by the lines of AlIII at 451.25 (E_{up} = 20.55 eV) and 447.99 nm (E_{up} = 23.54 eV) and the lines of AlIII at 451.25 and 572.26 nm (E_{up} = 17.80 eV). The electron temperature near the dielectric surface was determined by the lines of NII at 566.66 (E_{up} = 20.55 eV) and 549.56 nm (E_{up} = 23.41 eV). The probabilities of the transitions were taken from [18]. The electron temperature averaged over the temperatures along the observation ray was $(14–25)\cdot10^3$ K near the anode surface and $(18–30)\cdot10^3$ K near the substrate surface [11].

The electron concentrations at the prebreakdown stage were determined by the Stark broadening of the corresponding lines, namely, by the lines of AlIII at 451.25 nm and NII at 444.7 nm near the anode surface and the lines of FI at 623.9 nm, CIII at 481.9 nm, SiII at 634.7 nm, and NII at 567.9, 566.6, and 444.7 nm near the substrate surface. These concentrations are presented in Table 1. The broadening constants of the line of AlIII at 451.25 nm were taken from [19] and the broadening constants of the other lines were taken from [13]. It should be noted that the electron concentrations were determined using the most intense lines of plasma formations.

As is seen from the table, in the case of a plane pulsed surface discharge, the concentration of charged particles in the near-wall regions depends on the material of the substrate and the electrodes. For example, in the case where copper electrodes were used, the electron concentration at a distance of ~0.7 mm from the surface, determined by the lines of NII at 567.9 and 566.6 nm detected ~3 μsec before the breakdown, was $6\cdot10^{18}$ cm^{-3} for the fluoroplastic substrate, $(1.4–1.8)\cdot10^{18}$ cm^{-3} for the textolite substrate, and $1.4\cdot10^{18}$ cm for the NaCl substrate. The electron concentration at a distance of 0.4–0.55 mm from the fluoroplastic substrate surface, determined by the line of FI at 623.9 nm detected ~3 μsec before the breakdown, was $(1.2–1.3)\cdot10^{18}$ cm^{-3} in the case where copper electrodes were used and $6.6\cdot10^{17}$ cm^{-3} for the aluminum electrodes.

TABLE 1. Electron Concentration in Plasma Formations at the Prebreakdown Stage (N_e, 10^{18} cm^{-3})

Discharge conditions			Discharge region studied	λ, nm	*t*, μsec	*h*, mm								
Electrodes	Substrate	Location of the starting electrode				0.05	0.09	0.2	0.4	0.55	0.7	0.9	1.1	1.3
Copper	Fluoroplast	Center of the substrate	FI	623.9	9(3)	—	—	—	1.3	1.2	—	—	—	—
			NII	566.6	9(3)	7.8	6.6	5.6	5.6	6.8	6.0	—	—	—
Copper	Textolite	Center of the substrate	SiII	634.7	3(3)	—	—	—	—	—	0.7	0.8	—	—
			NII	566.6	3(3)	—	—	—	—	—	1.8	0.81	0.74	1.5
Copper	NaCl	Center of the substrate	NII	567.9	5(7)	—	—	—	—	3.0	1.4	0.89	0.81	—
			NII	566.6	5(7)	—	—	—	—	3.6	1.4	1.3	0.89	0.3
Aluminum	Fluoroplast	Center of the substrate	FI	623.9	9(3)	—	—	—	0.66	0.66	1.3	0.72	1.1	1.6
			ClII	481.9	9(3)	—	—	1.7	2.0	1.4	1.0	1.7	0.6	0.56
Aluminum	NaCl	Center of the substrate	NII	444.7	8(4)	—	1.4	1.1	1.2	1.1	0.95	1.1	1.3	—
			AlIII	452.9	4(8)	—	—	—	1.1	1.1	1.1	1.2	1.1	—
Aluminum	NaCl	Anode	NII	444.7	2(12)	—	—	—	—	1.8	1.3	1.5	1.4	—
			AlIII	451.2	7(5)	—	—	—	1.7	1.4	1.2	1.4	1.5	1.1

Note: *t* is the time elapsed from the instant a glow appeared, the time in parentheses is the time it takes for

Analysis of the data obtained under the above-described experimental conditions has shown that the concentration of charged particles is higher in the case where the material of the substrate and electrodes contains atoms of elements possessing a higher ionization potential. The maximum electron concentration, equal to $(5.6–7)\cdot10^{18}$ cm^{-3}, was obtained for the copper electrodes and the fluoroplastic substrate (see Table 1).

A large portion of the energy of a discharge occurring under the conditions of an evaporating wall is expended for the plasma formation. Since ionization and excitation of atoms and ions are among the main processes leading to the plasma formation, the parameters of the erosion plasma are determined by the parameters of the plasma-forming material. In our opinion, the atoms of chemical elements influence the plasma formation in the following way. A higher energy is required for a higher degree of ionization of atoms. For example, in the case where a comparatively small portion of the discharge energy is expended for the first degree of ionization of atoms, they can be ionized to the second degree if not very high energy is required for this purpose. It is known that the energy regime of a discharge depends on the experimental conditions. For example, a higher energy is required for ionization of FI, CI, and CII atoms than for ionization of SiI, CaI, and AlI atoms. In the first case, the energy stored can be insufficient for the second degree of ionization of atoms and, therefore, the first-degree ionization will be continued. In the second case, because of the relatively small expenditure of energy in the first-degree ionization and the relatively small potential of the second-degree ionization, double ionization can occur. However, in this case, a much higher energy is expended for the first- and second-degree ionization than for the first-degree ionization in the first case. Because of this difference, the rate of ionization (the number of ionization acts in a unit volume in a unit of time) in the first case can be much higher than that in the second case, which was observed in the measurements of the electron concentration.

A qualitative analysis of the emission spectra obtained with the copper electrodes and the fluoroplastic substrate has shown that the lines of the atoms ionized to the first degree are the most intense. In the case where the aluminum electrodes and the fluoroplastic substrate were used, the lines of the atoms ionized to the second degree were the most intense.

The data of our investigations suggest the following physical pattern of ignition and development of a surface discharge at the prebreakdown stage. The ignition of a surface discharge is determined by a number of factors [20], in

particular by the distance between the electrodes and the initial voltage, and is initiated by a sharp change in the electric field in the electrode spacing. In the present work, a field inhomogeneity was created by a high-voltage initiating pulse that strengthened the field. The electrons emitted from the cathode surface under the action of this pulse are accelerated in the electric field created by the voltage across the main electrodes and the starting electrode. Fast electrons reach the anode and slower electrons are decelerated by the field just beyond the starting electrode. The deceleration of slow electrons near the starting electrode leads to the formation of an uncompensated negative space charge. At this time, as the photographic frame scans of the discharge glow show, a low-intensity glow appears in the gap between the electrodes (in the cathode–starting electrode region) due to the impact action of electrons emitted by the cathode. With time, the low-intensity glow region widens toward the anode. Evidently, an uncompensated negative space charge behaves analogously. When the distance between the low-intensity glow (and, apparently, the uncompensated negative space charge) and the anode decreases to a certain value, a partial electrical breakdown occurs between the anode and the charge. This breakdown was detected on photographic frame scans in the form of an intense light strip. The partial breakdown is evidenced by the high rate of formation of the intense light strip ($>> 5 \cdot 10^3$ m/sec), the fairly high intensity of the lines of the air elements and the electrode material at the prebreakdown stage, and the appearance of a low-intensity continuous radiation. An intense glow appearing as a result of the partial breakdown widens toward the cathode, with the result that an anode torch is formed.

The prebreakdown development of a pulsed surface discharge in the case where a starting electrode is used can be divided into four stages:

1) appearance of a low-intensity glow between the starting electrode and the cathode and near the anode, which then widens, predominantly, toward the anode;

2) formation of an intense glow or a partial breakdown in the region between the anode and the starting electrode (one intense light strip) for a time that is much smaller then 2 μsec;

3) propagation of the intense light strip toward the cathode for ~10 μsec;

4) complete breakdown of the surface.

The prebreakdown stage of a surface discharge fired with the use of a starting electrode differs from that of a discharge fired without this electrode. The main difference is that [20], in the case where a starting electrode is used, an additional low-intensity glow arises in the gap between the electrodes and then a single intense light strip appears, apparently due to the partial breakdown, unlike the streamer stage, where several low-intensity strips appear.

In the case where a surface discharge is fired without a starting electrode, "the change from the streamer stage to the spark stage is accompanied by a sharp increase in the conduction of the spark channel as a result of the change from the impact ionization to the thermal ionization of the gas in the discharge channel, which leads to a rapid increase in the spark length" [20]. In the case where a discharge is fired by a pulse, a sharp increase in the conduction of the discharge channel as a result of the change from the impact ionization to the thermal ionization of the gas in the discharge channel occurs when the discharge is transformed from the first to the second stage. In this case, the glows arising at the second and third stages are nearly equal in brightness, and the length of the discharge channel increases at a higher rate at the second stage than at the third stage.

The processes of plasma formation change correspondingly when a discharge is transformed from the first to the second stage of its development. At the first stage, the impact mechanism of excitation and ionization mainly acts: atoms of the air elements are excited and ionized for the most part. At the second stage, the thermal mechanism begins to act: in addition to the atoms of the air elements, anode-material atoms participate in the plasma-formation processes. At the third stage, the dielectric material atoms begin to participate in the plasma formation. The role of the air atoms in the near-surface and, especially, near-electrode regions decreases significantly; however, they, as before, exert a fairly large effect on the plasma-formation processes.

It has been established that the pressure of the ambient gas (air) plays a decisive role in the ignition of the discharge considered. When this pressure is low (as low as $\sim 10^{-1}$ N/m^2), an intense prebreakdown glow does not appear. We did not detect a dependence of the prebreakdown stage on the substrate material; however, this material significantly influences the plasma formation.

Thus, an intense prebreakdown glow appears in the case where a plane surface discharge is fired with the use of a starting electrode in a relatively large (~2 cm) electrode spacing at a high pressure close to the atmospheric pressure; such a glow is also characteristic of an open (without a substrate) discharge. The duration of this glow is, on

average, 10 μsec under the experimental conditions considered. It increases when the electrode spacing increases and the initial voltage decreases and when aluminum electrodes are replaced by copper ones, which is explained by the fact that factors hampering the electrical breakdown activate in this case. An intense prebreakdown glow arises, apparently, as a result of the partial breakdown between the uncompensated negative spatial charge formed near the starting electrode and the anode. The partial breakdown influences the parameters of the plasma at the prebreakdown stage of the discharge: the electron concentration increases to $\sim 10^{18}$ cm^{-3} and the temperature near the anode surface increases to $(14–25)\cdot 10^3$ K (C = 24 μF, U = 6 kV, l = 2 cm); in this case, an anode torch is formed at the prebreakdown stage and a cathode torch begins to form at the instant the gap between the electrodes is broken down. The composition of the plasma at atmospheric pressure is determined by the material of the substrate and the electrodes and the air elements. It has been established that the substrate material influences the space-time intensity distribution of the spectral lines and the continuous radiation. At the beginning of the prebreakdown stage, the maximum intensities of the spectral lines and the continuous background were detected at a distance of $(5–8)\cdot 10^{-2}$ cm from the surface of the fluoroplastic and textolite substrates and near the surface of the crystalline-salt substrate.

NOTATION

C, capacity of the capacitor, μF; E_∞, ionization energy, eV; E_{up} and E_{low}, energies of excitation of the upper and lower levels of a spectral line, eV; F, focal distance, cm; h, distance from the surface, mm; I_{rel}, radiation intensity, rel. units; k, Boltzmann constant; l, distance, m; N_e, electron concentration, cm^{-3}; T, temperature, K; t, time, sec; U, voltage, V; $\sim$, order of magnitude. Subscripts: up, upper; low, lower; e, electron; rel, relative.

REFERENCES

1. G. Shardin and F. Fyunfer, Principles of spark cinematography, *Voprosy Raketn. Tekh.*, No. 3, 89–123 (1953).
2. J. Romand and V. Vodar, Contribution á l'étude de l'ultraviolet lointain, *Spectrochim. Acta*, **8**, Nos. 4–5, 229–248 (1956).
3. S. I. Andreev, Use of spark discharge for obtaining intense light flashes of duration 10^{-7}–10^{-8} sec. III. Study of capillary, surface, and resistance-addition-damped spark discharges in air, *Zh. Tekh. Fiz.*, **32**, No. 8, 967–974 (1962).
4. B. Vodar, Absorption spectra of gases and reflection spectra of solids, *J. Quant. Spectrosc. Radiat. Transfer*, **2**, Oct.-Dec., 393–412 (1962).
5. M. P. Vanyukov and E. V. Daniél', On the problem of development of the channel of a surface discharge, *Zh. Tekh. Fiz.*, **37**, No. 8, 1529–1532 (1967).
6. S. A. Andreev, M. P. Vanyukov, and E. V. Daniél', Use of a surface spark discharge for laser pumping, *Zh. Tekh. Fiz.*, **37**, No. 8, 1527–1529 (1967).
7. *Encyclopedia of Low-Temperature Plasma* [in Russian], Vol. 2, Nauka, Moscow (2000), pp. 350–357.
8. V. I. Belosheev, Special features of formation of a spark discharge on the surface of water, *Zh. Tekh. Fiz.*, **66**, No. 8, 50–58 (1996).
9. I. A. Kossyi, V. P. Silakov, and N. M. Tarasova, Combustion of methane–oxygen and methane–oxygen–freon mixtures initiated by a high-current sliding surface discharge, *Fiz. Plazmy*, **27**, No. 8, 757–768 (2001).
10. V. B. Avramenko, B. B. Davydov, and L. Ya. Min'ko, Study of near-electrode plasma formations of a high-current pulse discharge with separated torches at atmospheric pressure. II, *Teplofiz. Vys. Temp.*, **7**, No. 1, 19–26 (1969).
11. V. B. Avramenko, G. I. Bakanovich, and L. Ya. Min'ko, Study of near-electrode and near-wall plasma formations of a pulsed surface discharge, in: *Proc. 2nd All-Union Conf. on Plasma Accelerators* [in Russian], 2–5 October 1973, Institute of Physics, Minsk (1973), pp. 61–62.
12. M. A. El'yashevich, V. B. Avramenko, G. I. Bakanovich, and L. Ya. Min'ko, Possibilities of using high-speed spectrography for diagnostics of pulsed erosion plasma accelerators, *Zh. Prikl. Spektrosk.*, **16**, No. 3, 422–425 (1972).
13. H. R. Griem, *Plasma Spectroscopy* [Russian translation], Atomizdat, Moscow (1969).

14. L. S. Polack (Ed.), in: *Outlines of Physics and Chemistry of Low-Temperature Plasma* [in Russian], Nauka, Moscow (1971), pp. 386–410.
15. V. B. Avramenko, G. I. Bakanovich, and L. Ya. Min'ko, Special features of the spectroscopic diagnostics of pulsed erosion plasma accelerators, in: *Proc. 2nd All-Union Conf. on Plasma Accelerators* [in Russian], 2–5 October 1973, Institute of Physics, Minsk (1973), pp. 323–324.
16. V. B. Avramenko, A. P. Burmakov, A. A. Labuda, and L. Ya. Min'ko, Study of the plasma jet of a pulsed erosion plasma accelerator by holographic interferometry, in: *Proc. 2nd All-Union Conf. on Plasma Accelerators* [in Russian], 2–5 October 1973, Institute of Physics, Minsk (1973), pp. 325–326.
17. V. B. Avramenko, Study of the dynamics of development and processes of plasma formation of a pulsed surface discharge, in: *Proc. 2nd All-Union Conf. on Plasma Accelerators* [in Russian], 2–5 October 1973, Institute of Physics, Minsk (1973), pp. 63–64.
18. N. K. Sukhodrev, Spectrum excitation in a spark discharge, in: *Studies on Spectroscopy and Luminescence* [in Russian], Proc. of the Institute of Physics of the USSR Academy of Sciences, Vol. 15, Izd. AN SSSR, Moscow (1961), pp. 123–177.
19. Yu. S. Shaulkauskas, Estimation of the radial temperature distribution and determination of the relative chemical composition of the plasma of a low-voltage pulsed discharge, *Zh. Prikl. Spektrosk.*, **28**, No. 3, 388–392 (1978).
20. P. N. Dashuk, L. S. Zaientz, V. S. Komel'kov, G. S. Kuchinskii, N. N. Nikolaevskaya, P. I. Shkuropat, and G. A. Shneerson, in: V. S. Komel'kov (Ed.), *Technique of High Pulsed Currents and Magnetic Fields* [in Russian], Atomizdat, Moscow (1970), pp. 268–303.