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TRANSFER PROCESSES IN LOW-TEMPERATURE PLASMA

DIAGNOSTICS OF SURFACE-PLASMA FORMATIONS IN A PULSED SURFACE DISCHARGE

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The main parameters (temperature and electron concentration) of the plasma formed in the near-wall and near-electrode regions of a high-current pulsed surface discharge with separate torches at atmospheric and lower pressures have been determined and analyzed. The mechanism of failure of the face (working) surface of cylindrical electrodes and a dielectric surface has been investigated on the basis of analysis of heat flows. The surface and open discharges were compared.

The near-surface (near-electrode and near-wall) regions of an electric discharge are regions responsible for the plasma formation. The thermal-ionization processes occurring in these regions lead to the formation of a plasma possessing specific properties ([1–7]). However, there is no strict theory of the indicated processes and the amount of experimental data available is insufficient to make theoretical generalizations. Further investigations of the near-surface regions of an electric discharge are of importance not only for theoretical study of plasma-formation processes but also for practical purposes. For example, reliable space-time characteristics of the plasma formed in the near-surface regions of an electric discharge can be used for optimization of discharge devices since, despite the differences in their design, similar plasma-formation processes occur in them.

Electrode spots have been the objective of most experimental and theoretical investigations devoted to plasma-formation processes (see, e.g., [1–3, 5, 6]). In this case, the following parameters of an electrode spot were investigated: the diameter of the spot, the velocity of its travel, the depth of the hole, the density of the current at the spot, the lifetime of the spot, the weight erosion, and the temperature regime. A much smaller number of works were devoted to the study of surface plasma formations, and the parameters of the plasma formed in the near-surface regions of a high-current pulsed discharge on a dielectric surface were practically not investigated.

Apparatus, Experimental Conditions, and Investigation Methods. A pulsed surface discharge was experimentally investigated using a plane-configuration discharge device with a parallel placement of electrodes [2, 4]. 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 separate and free to flow, which eliminates the contribution of the torch component to the electrode erosion and the collision of supersonic electrode torches.

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 near the center of the discharge gap. 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 was controlled using a light ray.

The electric characteristics of the device were described in [8].

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. Copper and aluminum wires 0.2–0.3 cm in diameter were used as the electrodes. Aluminum electrodes and fluoroplastic and crystalline-salt substrates were used in experiments carried out at a low pressure ($\sim 10^{-1}$ N/m^2).

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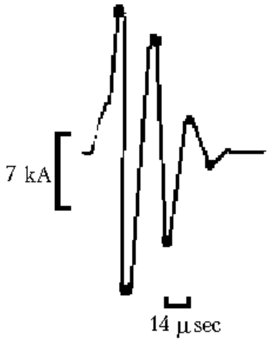

Fig. 1. Typical oscillogram of the current of a surface discharge fired on a fluoroplastic substrate with the use of copper electrodes at atmospheric pressure (C = 24 μF, l = 2 cm, and U = 6 kV).

The space-time characteristics of the plasma formed in the near-electrode and near-wall regions of a discharge were investigated with the use of an ISP-51 spectrograph connected to an SPA through a Jupiter-3 objective. The plasma radiation spectra were photographed with a speed of $5 \cdot 10^5$ 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. Time-resolved spectra of plasma formations were obtained on a highly sensitive aerial photographic film. The instrumental broadening was determined by narrow lines in the emission spectrum of a gas-discharge tube filled with hydrogen. The electron concentration was determined by the Stark broadening of spectral lines. The error of the method could reach 35–40% [9, 10]. This error was decreased by averaging over several lines equal for analysis [9–12].

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 temperature determined in this way 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 even 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 spectral lines represents the electron temperature. The absorption of different-wavelength radiation was determined by the intensity and width of faint and strong lines of a multiplet. The relative error in determining the temperature by the relative intensities of spectral lines was (in the case where the thermal energy kT was approximately equal to the difference between the energies of the upper and lower levels of spectral lines) 25–30% [9, 10].

Experimental Data and Their Analysis. The continuous photographic scans and discharge-current oscillograms obtained by us show that, in the case of a parallel placement of electrodes, the intense glow of the plasma formed in the near-surface regions of a plane surface discharge changes in accordance with the oscillations of the discharge current. In a discharge at atmospheric pressure between electrodes of diameter 0.2–0.3 cm, the half-period of the current was equal to ~14 μsec and the discharge duration was ~70 μsec (Fig. 1). The afterglow time was much longer than the discharge time. At a lower pressure, the duration of the first half-period of the glow was different for different substrates: ~30 μsec for the NaCl substrate and ~25 μsec for the fluoroplastic substrate. The other half-periods were equal to ~16 μsec for all the substrates.

A qualitative analysis of the emission spectra has shown that, at atmospheric pressure, an intense continuous background and intense lines of the electrode material appear in the spectra of the plasma formed in the near-electrode regions at the instant of electrical breakdown and after it (Fig. 2). The lines of the air elements appearing at the prebreakdown stage disappear rapidly. In the spectrum of the plasma formed near the surface of a substrate, a continuous background and lines of the substrate material, the electrode material, and the air elements appear. At a lower pressure, at the instant of electrical breakdown and after it, electrode-material lines and a continuous background appear in the emission spectra of the plasma formed in the near-electrode regions. The electrode-material and substrate-material lines of the plasma formed were photographed near the surface of a substrate without time scanning on a highly sensitive aerial photographic film.

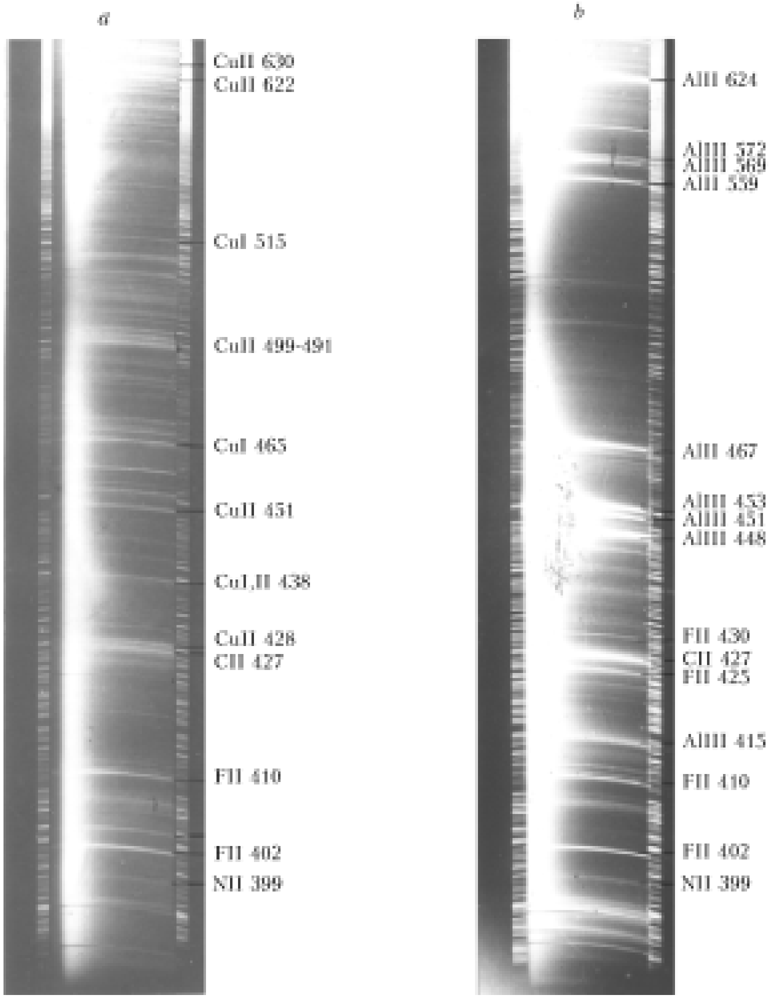

Fig. 2. Radiation spectra of plasma torches formed in the near-anode regions of a surface discharge fired on a fluoroplastic substrate (l = 2 cm, U = 6 kV, the radiation wavelength is given in nanometers) with the use of copper electrodes (a) and aluminum electrodes (b).

The investigation of the space-time distribution of the discharge plasma radiation at the breakdown stage has shown that, just as at the prebreakdown stage, the substrate material and the material of the electrodes influence the spectroscopic characteristics of the discharge. Note that it is difficult to determine the space-time intensity distribution of the spectral lines of the plasma formed in the near-electrode regions after the breakdown because of the very intense continuous radiation, which is especially intense at atmospheric pressure. The intensity of the lines and continuous radiation of the plasma formed in the near-electrode regions increased with increase in the distance from the surface of the electrodes for all the substrates investigated. For the near-wall plasma, unlike the plasma formed at the prebreakdown stage, radiation was detected near the surface of the crystalline-salt, fluoroplastic, and textolite substrates (Fig. 3).

The space-time characteristics of the discharge plasma were determined by the spectral lines of the dialectric-material atoms and ions, the lines of nitrogen ions and double aluminum ions for the plasma formed near the substrate surface at atmospheric pressure, and by the lines of the double aluminum ions for the plasma formed near the surface of the electrodes at atmospheric and lower pressures.

The electron temperature at atmospheric and lower pressures was determined by the method of relative intensities. At atmospheric pressure, the electron temperature in the first half-period after the breakdown was equal, in order of magnitude, to that in the prebreakdown stage. For example, in the case where the aluminum electrodes and the tex-

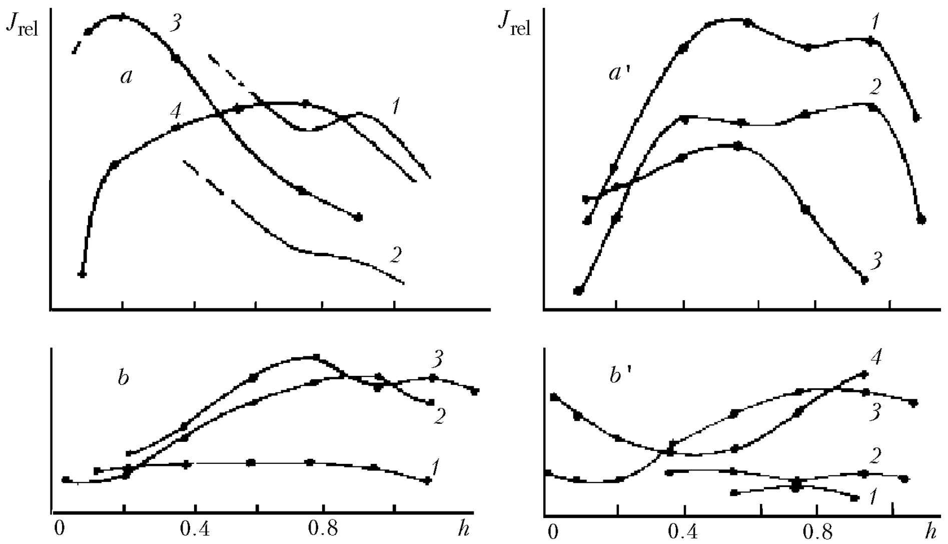

Fig. 3. Change in the intensities of the spectral lines and the continuous radiation of surface plasma formations [a, b) NaCl substrate; a', b') fluoroplastic substrate]; a, a') afterglow stage [a) near the anode: 1) AlIII 452.9 nm, 2) AlIII 451.1 nm, 3) continuous radiation; near the cathode: 4) continuous radiation; a') near the anode: 1) AlIII 569.6 nm, 2) AlIII 572.3 nm; near the cathode: 3) continuous radiation]; b, b') near the dielectric surface [b) CIII 481.9 nm: 2 (1), 6 (2), and 10 (3) μsec; b') FI 623.9 nm: 6 (1), 10 (2), 14 (3), and 18 (4) μsec]. $J_{\rm rel}$, rel. units; *h*, mm.

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

Discharge conditions		Discharge region investigated	Diagnostic line	λ, nm	*t*, μsec	*h*, mm								
Electrodes	Substrate					0.05	0.09	0.2	0.4	0.55	0.7	0.9	1.1	1.3
Copper	Fluoroplastic	Substrate center	FI	623.9	17(4)	0.89	1.1	1.2	0.83	1.1	1.0	0.66	1.3	—
					21(8)	0.5	0.63	1.0	1.3	0.93	1.5	1.2	1.0	1.4
			NII	566.6	13(2)	6.5	—	—	8.0	—	—	8.0	—	—
Copper	Textolite	Substrate center	SiII	634.7	15(8)	1.0	1.0	0.76	1.0	0.63	—	0.93	0.98	1.1
			NII	566.6	13(2)	3.8	—	—	—	—	—	—	—	—
Alimunum	Fluoroplastic	Substrate center	FI	623.9	17(4)	1.7	1.3	1.5	1.1	0.72	1.3	1.0	1.3	1.3
			NII	566.6	13(3)	3.4	—	—	—	—	—	—	—	—
Aluminum	NaCl	Substrate center	ClII	481.9	13(2)	—	—	—	5.9	1.7	2.8	3.0	3.1	3.5
Aluminum	NaCl	Anode	A1III	451.2	22(11)	—	—	2.3	—	—	—	—	—	—
		Cathode	A1III	451.2	14(3)	—	—	1.2	1.2	1.7	—	—	—	—

Note. *t* is the elapsed time from the appearance of a glow; the parenthetical time is the elapsed time from the instant of breakdown; *h* is the distance from the substrate (electrode) surface; λ is the wavelength.

tolite substrate were used, this temperature was ~$2\cdot10^4$ K near the anode surface in the middle of the first half-period. At a lower pressure, the electron temperature (averaged over the observation ray) at the beginning of the first half-period was $(13–16)\cdot10^3$ K near the cathode surface in the case where the fluoroplastic substrate was used and $(20–24)\cdot10^3$ near the anode surface and $(20–30)\cdot10^3$ K near the cathode surface in the case where the crystalline-salt substrate was used.

The charged-particle concentrations determined by the Stark broadening of the spectral lines of the near-surface plasma formed in the first half-period at atmospheric pressure are presented in Table 1. The analogously deter-

TABLE 2. Electron Concentration in Plasma Formations at a Low Pressure (N_e, 10^{18} cm^{-3})

Substrate	Discharge region investigated	λ, nm	t, μsec	h, mm						
				0.05	0.09	0.2	0.4	0.55	0.7	0.9
NaCl	Anode	451.2	3	1.2	1.3	1.4	1.2	1.3	1.3	0.9
		452.9	3	1.6	1.8	1.7	1.0	1.1	1.4	0.9
NaCl	Cathode	451.2	3	1.5	2.5	2.7	3.1	2.5	3.5	2.3
		452.9	3	2.5	2.4	—	3.9	1.2	3.2	4.5
Fluoroplastic	Anode	452.9	3	—	—	3.6	2.7	—	—	—
Fluoroplastic	Cathode	452.9	3	—	—	—	—	—	2.3	—
		452.9	11	—	—	—	3.0	2.2	2.0	—

Note. t is the elapsed time from the instant of breakdown and h is the distance from the electrode surface.

mined concentrations of charged particles in the near-electrode regions at a lower pressure are presented in Table 2. The broadening constants of the line of AlIII at 451.25 nm were taken from [13] and the broadening constants of the other lines were taken from [9]. It should be noted that the concentrations of charged particles were determined in those regions of plasma formations that have intense spectral lines. The differences in the concentrations determined by different spectral lines are explained, besides the theoretical and experimental errors, by the differences between these lines in the ionization potential and the broadening constant. The spectral lines, except for the line of AlIII at 451.25 nm, used in the present work for determining the electron concentration by their broadening, give equal ranges of this concentration. As is seen from Table 1, the concentration of charged particles in the near-surface regions of a surface discharge at atmospheric pressure after the breakdown of the gap between the electrodes, just as at the prebreakdown stage, depends on the substrate material and the material of the electrodes. This dependence becomes weaker at the afterbreakdown stage as compared with that at the prebreakdown stage. A maximum electron concentration was detected in the case where the fluoroplastic substrate and copper electrodes were used.

Comparison of the electron concentrations determined by the broadening of the spectral lines of the AlIII ion, detected in the near-anode region before the breakdown of the electrode spacing and after the breakdown, shows that this concentration somewhat increases after the breakdown. When the electron concentrations in the near-anode and near-cathode regions are compared, it is apparent that the electron concentration in the near-anode region is somewhat higher than that in the near-cathode region.

As is seen from Table 2, the electron concentration (determined by the line of AlIII) in the near-electrode regions of a discharge at atmospheric pressure depends on the substrate material in the case where the aluminum electrodes are used. However, this dependence is not simple in character: the electron concentration is minimum in the near-anode region and is maximum in the near-cathode region in the case where the crystalline-salt substrate is used. The electron concentrations in the near-anode and near-cathode regions differ insignificantly when the fluoroplastic substrate is used.

The data of our investigations show that, in the general case, the influence of the substrate material on the near-surface processes occurring in a pulsed surface discharge depends on the ambient pressure and the current. At the prebreakdown stage of a discharge at atmospheric pressure, the current is much lower than the discharge current and the charged-particle concentration is strongly dependent on the chemical composition of the substrate material. The existence of impurities of easily ionized elements and elements with a relatively low potential of ionization of atoms to the first and second degree leads, evidently, to a decrease in the electron concentration. After the breakdown of the gap between the electrodes, the discharge current is relatively high and the electron concentration is weakly dependent on the substrate material.

At a low pressure the dependence of the electron concentration in the near-anode region on the substrate material is the same; it is somewhat stronger in the case where the fluoroplastic substrate is used. The inverse dependence is observed for the near-cathode region.

To determine the role of a substrate in the processes occurring in the near-cathode region of a pulsed surface discharge, we compared the data of investigations of surface and open discharges. Special emphasis has been concentrated on the study of the dependence of the electron concentration in the near-cathode region on the ambient pressure

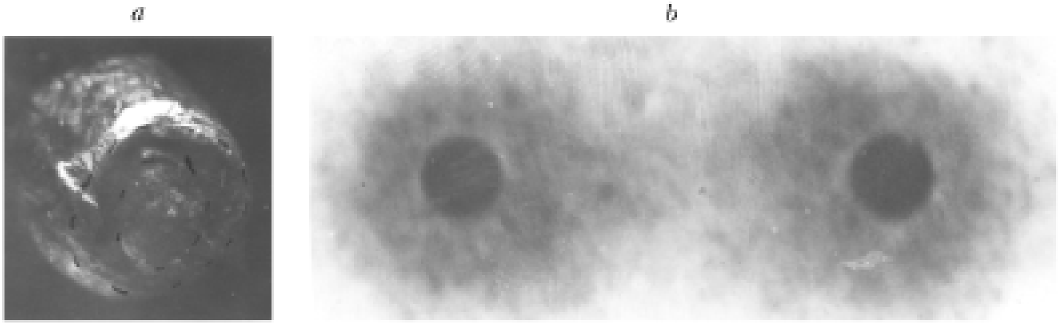

Fig. 4. Photographs of a surface subjected to a pulsed surface discharge: a) surface of an aluminum electrode ~0.24 cm in diameter (the outer circle is the electrode perimeter, the inner circle is the bulge perimeter); b) surface of a fluoroplastic substrate.

and the current. These experiments were carried out with a plane copper cathode and a molybdenum anode (counter-electrode) made of a wire 0.2 cm in diameter. The cathode spots formed in the process of discharge were free to move over the cathode surface. In the experiments, the discharge current changed in the range 2–3 kA and the ambient pressure was $5.33 \cdot 10^4$, $1.33 \cdot 10^2$, $13.3 \cdot 10^{-2}$, and $1.33 \cdot 10^{-2}$ N/m^2. Optical-spectroscopic investigations were carried out using a photoelectric recording technique with a high time resolution (~$5 \cdot 10^{-8}$ sec) [6].

Analysis of the data obtained has shown that the electron concentration in the near-cathode region of a high-current discharge increases with increase in the ambient pressure or in the current [6].

Comparison of the dependences of the electron concentrations in the near-cathode region of the surface and open discharges on the pressure has shown that the electron concentration in the near-cathode region of the surface discharge increases with decrease in the pressure (Tables 1 and 2), while the electron concentration in the near-cathode region of the open discharge decreases in this case. This allows the conclusion that the substrate material significantly influences the plasma-formation processes at the afterbreakdown stage of a surface discharge.

Unlike an open discharge, the failure of the electrodes in the process of a surface discharge with separate electrode-plasma torches is peculiar in character because of the complex dynamics of the electrode plasma torches comprising normal and oblique compression shocks of cask-like configuration. Examination of the electrode faces subjected to a discharge has shown (Fig. 4a) that they have a bulge in the central zone and their ring zone is damaged to a larger extent. A peculiarity of the erosion discharge studied is that, because of the movement of the discharge channel along the torches, the discharge current flows predominantly in the oblique shocks and the current channel is shaped as an outer ring relative to the electrode center in the region of the plasma–metal contact. The electrode spots that, as is known [1], are responsible for the active failure of the electrode material are evidently grouped in the region of this ring.

Examination of a dielectric surface subjected to a discharge has shown (Fig. 4b) that its ring region around the electrodes suffered the largest structural failure. This failure is apparently due to the complex gas dynamics of the electrode torches and is caused by the radiative transfer of heat energy from the torches to the dielectric along the tangent to the oblique shocks.

Since the failure of the electrodes and the dielectric is thermal in character, we have done rough, but simple, estimations of the heat flowing over the electrodes and the substrate. The foregoing points to the fact that a surface discharge has a relatively high electron concentration and a high-intensity radiation. The energy transfer from the bulk of the plasma to the substrate can be due to both the electron and radiative-heat conductivity. Estimation of the heat transferred to the substrate surface by these two mechanisms has given the following results. The heat flow transferred by electrons in a surface discharge in the air was estimated at ~$1.8 \cdot 10^4$ W/cm^2. The radiative-heat flow estimated using the Stefan–Boltzmann law was ~$4.5 \cdot 10^5$ W/cm^2. As is seen, the heat flow transferred by electrons accounts for 4% of the flow transferred by radiation. These estimations support the qualitative conclusion made on the basis of experimental data that heat energy released in a surface discharge in the air is transferred to the substrate surface predominantly by radiation. Higher energies (higher than $6 \cdot 10^6$ W/cm^2 according to the estimates) are achieved at the electrodes. This supports the assumption made on the basis of experimental data that, in the case of a plane surface discharge between electrodes positioned in parallel, the peripheral ring zone of the electrodes experiencing discharge current suffers the largest structural failure.

Thus, we have shown that the substrate material and the material of the electrodes influence the plasma-formation processes occurring in a pulsed plane surface discharge after the breakdown of the gap between the electrodes. A maximum electron concentration was detected in the case where the fluoroplastic substrate and copper electrodes were used; it was equal to $8 \cdot 10^{18}$ cm^{-3} in the near-wall region at the first half-period ($U = 6$ kV, $l = 2$ cm, atmospheric pressure). The influence of the substrate material is stronger at the prebreakdown stage than at the afterbreakdown stage, which is explained by the fact that the current increases after the breakdown of the electrode spacing. After the breakdown, the electron concentration somewhat increases and the temperature remains the same in order of magnitude.

It has been established that the substrate material also influences the near-electrode processes. As the discharge current and the ambient gas (air) pressure decrease, the electron concentration in the near-electrode regions also decreases due to the decrease in the energy supplied to the discharge, except in the near-electrode region of the discharge on the surface of the crystalline-salt substrate. Comparison of the near-cathode regions of the surface and open discharges shows that the electron concentration in the open discharge increases with increase in the current or pressure, while the electron concentration in the surface discharge on the crystalline-salt substrate decreases with increase in the pressure.

We have revealed the dependence of the duration of the glow in the first half-period of a surface discharge at a low pressure on the substrate material; the glow duration was 30 μsec in the case where the crystalline-salt substrate was used and ~25 μsec for the fluoroplastic substrate. The glow duration in the other half-periods was approximately equal to 14 μsec for all the substrates. The glow intensity changes in accordance with the oscillations of the current.

NOTATION

C, capacity of a capacitor, μF; F, focal distance, cm; h, distance from the electrode surface (wall), mm; I, current, kA; $J_{\rm rel}$, radiation intensity, rel. units; l, length, cm; $N_{\rm e}$, electron concentration per cm^3; T, temperature, K; t, time, sec; U, voltage, kV.

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