PARAMETERS OF STREAMER BREAKDOWN IN XENON

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It is known from experiments [1-3] that the velocity of streamers, induced in the center of the interelectrode gap and propagating to the electrodes under conditions when the streamer length is comparable with the distance between the electrodes, increases linearly as the streamer length increases. This relationship is in qualitative agreement with theory [4]. Nevertheless, the velocity of streamers starting from the electrodes and propagating in a long interelectrode gap remains practically constant during the whole propagation process [5, 6]. In the case of short gaps (2-5 cm), constancy of the velocity is observed during the stage of the process when the length of the streamer is much less ($\simeq$20%) than the length of the gap [7]. Since the electric field at its end controls the streamer propagation, the constancy of the streamer velocity indicates that the controlling field is constant under these conditions. A number of theoretical models were proposed in [8-13] which describe uniformly moving anode- and cathode-directed streamers (henceforth called anode and cathode streamers). Comparison of experimental data with the corresponding theoretical model enables one to determine the streamer parameters: the electric field, the charged-particle density, the current density, the channel radius, etc. In the case of an anode streamer in Xe an attempt at such a comparison was made, in particular, in [6]. However, the lack of reliable data on the value of the drift velocity and the diffusion coefficient of electrons in Xe for $E/p \simeq (10^2-10^3)$ V/cm · mm Hg allowed only rough estimates to be made. In this paper a numerical calculation is made of the drift velocity, the diffusion coefficient of electrons in Xe, and the rate of excitation of Xe atoms in the resonance level in the range of values of $E/p \simeq (10^1-10^3)$ V cm · mm Hg, and the volt–ampere characteristic of the breakdown is measured under conditions described in [6] ($p_0 = 300$ mm Hg and $E \simeq 10^4-10^5$ V/cm). Using these results, the formulas for the velocity of anode [12] and cathode [13] streamers, and experimental data [6], the parameters of the streamers studied in [6] are determined.

§ 1. The macroscopic characteristics and transport coefficients of the electron components of a plasma required to determine the parameters of a streamer can be calculated knowing the electron distribution function. An estimate shows that under experimental conditions [6] the relation $Q_{ee}n_e \ll (2m/M)Q_{ea}n_a$ is satisfied, corresponding to a degree of ionization of the plasma $\simeq n_e/n_a \ll (2m/M) \cdot Q_{ea}\, Q_{ee} \sim 10^{-5}$ (n_e, n_a, and m, M are the density and mass of the electrons and atoms, respectively; Q_{ee} and Q_{ea} are the cross sections of electron–electron and electron–atom collisions, respectively). This means that when calculating the distribution function electron–electron collisions can be neglected. Under these conditions the time taken for the distribution function to become established $\tau' \sim (2m/M)Q_{ea}n_av_e \sim 10^{-7}$ sec (v_e is the thermal velocity of the electrons) is less than the characteristic duration of the process [6] which is $\sim 10^{-6}$ sec.

Under these conditions we can use the steady-state equation for the electron distribution function f(u) in a weakly ionized plasma [14]:

$$\frac{E^2}{3}\frac{d}{du}\left[\frac{u}{n_aQ_m(u)}\frac{df}{du}\right]+\frac{2m}{M}\frac{d}{du}\left[u^2n_aQ_m(u)f(u)\right]+\frac{2m}{M}T_a\frac{d}{du}\times$$

$$\times\left[u^2n_aQ_m(u)\frac{df}{du}\right]+n_a\sum_i(u+u_i)f(u+u_i)Q_i(u+u_i)-n_auf(u)\sum_i Q_i(u)=0, \qquad (1.1)$$

where $u = mv_e^2/2e$ is the electron energy, eV; E is the electric field strength, V/cm; Q_m is the transport cross section; T_a is the temperature of the atoms, eV; and Q_i are the cross sections of the inelastic processes; Q_m and Q_i are expressed in CGS units.

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Equation (1.1) can be reduced to the form [15]

$$f(u) = A\exp\left[-\int_0^u \frac{du'}{\Phi(u')f(u')}\sum_i \int_{u'}^{u'+u_i} \Psi_i(u'')f(u'')\,du''\right], \tag{1.2}$$

where

$$\Phi(u) = u\left[\frac{(E/n_a)^2}{3Q_m(u)} + u'\frac{2m}{M}T_aQ_m(u)\right]; \quad \Psi_i(u) = uQ_i(u).$$

Equation (1.2) was solved by an iterational method using the scheme

$$f_n(u) = A\exp\{-B[f_{n-1}(u'')/f_{n-1}(u')]\},$$

where the kernel

$$B = \int_0^u \frac{du'}{\Phi(u')f_{n-1}(u')}\sum_i \int_{u'}^{u'+u_i} \Psi_i(u'')f_{n-1}(u'')\,du'';$$

we took as the zeroth approximation the function $f_0(u) = 1$ for all values of u.

In the calculations we took into account 10 channels of inelastic interactions: excitation from the ground state $5p^6$ into the 6s, 7s, 8s, 6p, 7p, 8p, 5d, 6d, and 7d levels, and ionization from the ground state. The cross sections of elastic scattering [16] and ionization [17] are known from experiments, while the excitation cross section was calculated in the Born approximation using the method described in [18]. The normalizing factor A in Eq. (1.2) was found from the condition

$$\int_0^\infty \sqrt{u}\,f(u)\,du = 1.$$

From the known distribution function we found the electron drift velocity

$$v = -\sqrt{\frac{2e}{m}}\,\frac{E/n_a}{3}\int_0^\infty \left[u\frac{df}{du}\Big/Q_m(u)\right]du,$$

the diffusion coefficient

$$D = \sqrt{\frac{2e}{m}}\,\frac{1}{3n_a}\int_0^\infty [uf(u)/Q_m(u)]\,du,$$

and the rate of excitation by electron collision of the i-th level

$$K \equiv \langle \sigma_i v_e\rangle = \sqrt{\frac{2e}{m}}\int_{u_i}^\infty uf(u)Q_i(u)\,du.$$

All the calculations were made on the BÉSM-6 computer assuming $T_a = 0$. Figure 1 shows the drift velocity (curve 1 represents our calculations and curve 2 represents experiment [19]), the electron diffusion coefficient in Xe, and the rate of excitation of Xe atoms in the resonance level as a function of E/p.

§ 2. We will compare the value of the calculated drift velocity (Fig. 1) with the velocity of propagation of an anode streamer measured in [6]; it is shown in [12] that the velocity of an anode streamer can be found from the relation

$$u_a = \mu E + 2\sqrt{D\alpha\mu E}, \tag{2.1}$$

where μ and D are the mobility and diffusion coefficient of the electrons, and α is the first Townsend coefficient. The second term in Eq. (2.1) is the rate of diffusion of electrons, which cannot exceed the drift velocity $v = \mu E$ [12]. Hence, the measured values of u_a cannot differ from the calculated values by a factor of more than two. The electric field strength far from the electrodes of the discharge tube under the conditions described in [6] can be estimated from the relation

$$E \simeq \varepsilon U/2\ln\Delta/r_0, \tag{2.2}$$

where U is the voltage across the tube, $\Delta = 2$ mm is the thickness of the quartz walls of the tube, $r_0 = 0.4$ mm is the radius of the auxiliary electrode (a fine wire), and $\varepsilon = 3.75$ is the dielectric constant of quartz. For U = 10 kV, $E \simeq 100$ kV/cm and the drift velocity at a pressure of the xenon of 300 mm Hg is approximately $5 \cdot 10^7$ cm/sec (see Fig. 1), which agrees with the value $u_a = 4 \cdot 10^7$ cm/sec measured in [6].

TABLE 1

U, kV	E, kV/cm	$u_a \cdot 10^{-7}$, cm/sec	α, cm^{-1}	θ, %	$n_e \cdot 10^{-13}$, cm^{-3}	j, A/cm^2	J, A	$\bar{r}_a$, cm	$u_c \cdot 10^{-7}$, cm/sec	$\bar{r}_c$, cm
10	53	4	1270	16,6	1,06	38	84	0,84	4,6	0,07
15	107	8	2800	22,2	5,8	420	133	0,32	11,4	0,12
20	190	14	4500	20,2	16,6	2070	186	0,17	17	0,15

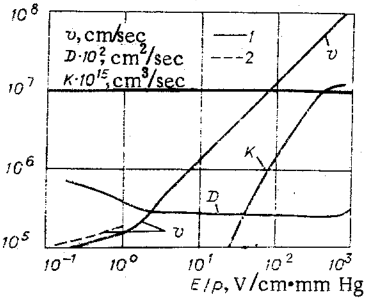

Fig. 1

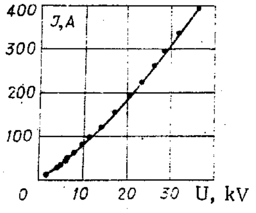

Fig. 2

Equation (2.2) only gives a rough estimate of the field E. In reality, the field at the end of the streamer, which depends not only on the applied voltage U but also on the radius of curvature of the end of the streamer, determined by the particle and radiation-transfer processes, which depends on the electric field, controls the propagation of the breakdown. Hence, there are serious difficulties involved in determining the controlling field directly. Nevertheless, by using the results of the above calculation (see Fig. 1) and experimental data on the streamer velocity [6], we can find E from Eq. (2.1). The results of such a calculation are presented in Table 1 for several values of the voltage under the conditions described in [6]. In the calculation we used the experimental values of $\alpha(E)$ for Xe given in [20].

Note that when E varied from 20 to 350 kV/cm the value of $2\sqrt{\alpha D/\mu E}$ lay within the limits $\simeq 0.6$–0.8, while the thickness of the leading edge of the streamer $\delta \simeq \sqrt{D/\alpha \mu E} \simeq 1.5 \cdot 10^{-3}$–$6 \cdot 10^{-5}$ cm. The last value is in good agreement with the estimate of δ obtained in [9] from experimental data [5] in which breakdown in atmospheric air with $E \simeq 400$ kV cm was studied.

Knowing E we can find the electron density n_e and the current density $j = en_e v$ in the streamer. The value of n_e was found from the relation [4]

$$n_e = \theta E^2/8\pi I,$$

where

$$\theta = \frac{2I}{E^2 \mu E} \int_0^\infty \alpha(E)\, \mu(E)\, E dE \tag{2.3}$$

is the fraction of the energy of the electric field expended in ionizing the gas per unit volume, and I is the ionization potential of the gas. The quantities θ for the values of E given in the table were found by numerical integration of Eq. (2.3). The approximate formula for θ obtained in [4] assuming $\alpha(E) = A' e^{-B'/E}$ (A' and B' are constants) gives values of θ under these conditions which are close to the results of the numerical integration.

The value of the radius of curvature of the end of the streamer is of considerable interest in the physics of streamer breakdown. If we know the total current in the streamer the average value of the radius of curvature of the end of the anode streamer $\bar{r}_a$ can be found using the value of j given in the table. For this we measured the volt–ampere characteristic of the breakdown under conditions corresponding to those described in [6]. The current J was measured using a low-inductive resistance of 1.8 Ω, connected in series with the discharge tube and the voltage U in the interelectrode space was measured using a divider consisting of resistances of 390 and 1.8 Ω. The volt–ampere characteristic of the breakdown in shown in Fig. 2. Within the limits of experimental error (an error not greater than 10%) the volt–ampere characteristics agreed for differently directed streamers. The current and voltage pulses under the conditions described in [6] had a rectangular form. The values of J in Fig. 2 and in Table 1 correspond to the flat top of the voltage pulse; assuming that the streamer is a channel of radius $\bar{r}_a$ with a uniformly distributed current density j, we can find the radius of the channel $\bar{r}_a = \sqrt{J/\pi j}$.

In the case of a cathode streamer the average radius of curvature was found from the expression for the streamer velocity [13]

$$u_c = \sqrt{K n_a \bar{r}_c^2 / 8\pi\tau}, \tag{2.4}$$

where $K = \langle o_i v_e \rangle$ is the rate of excitation of the atoms in the resonance level, and τ is the lifetime of an atom with respect to spontaneous radiation. Under the conditions considered $n_a = 1.06 \cdot 10^{19}$ cm^{-3} and $\tau = 3.74 \cdot 10^{-9}$ sec for the $5p^6 - 6s$ transition, the K(E) curve is shown in Fig. 1. The values of r_c obtained from Eq. (2.4) are shown in Table 1, where it is seen that under the conditions considered the relation $\bar{r}_a \geq \bar{r}_c$ is satisfied. If the situation after the formation of the streamer is regarded as breakdown between a point and an electrode [7] (the streamer connected to one of the electrodes and traveling toward the opposite electrode plays the part of the point), by means of the relation $\bar{r}_a \geq \bar{r}_c$ we can explain the higher velocity of propagation of a cathode streamer and also its ability to pass through a region of highly attenuated external field which the anode streamer cannot cross [6]. In this case the end of the cathode streamer corresponds to a positively charged point, while the end of the anode streamer corresponds to a negatively charged point. In support of this idea we have the well-known experimental fact that under similar conditions the breakdown voltage of the gap between a point and a plane is much lower in the case of a positively charged point [21].

The values of the radii of curvature of the ends of the streamers obtained in this investigation agree in order of magnitude with the experimental results obtained in [2], a study of streamer breakdown in neon. The results obtained in [2] also qualitatively confirm the conclusion regarding the difference in the radii of curvature of the ends of oppositely directed streamers. An additional confirmation of this difference is the observed difference in the velocities of the anode and cathode streamers [1, 2, 6], since the velocity of the streamer is determined by the electric field at its end, the value of which, other conditions being equal, increases as the radius is reduced.

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

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

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

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

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