CATHODIC VOLTAGE DROP IN A NON-SELF-SUSTAINED DISCHARGE

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The non-self-sustained discharge, maintained by an electron beam, is widely used in electric-ionization lasers (EIL). Theoretical and experimental studies of such a discharge are generalized in [1-3].

The cathodic space-charge layer has a determining effect on the current flow between the electrodes. The calculation of the parameters of the layer reduces to the solution of a system of nonlinear continuity and Poisson equations with the appropriate boundary conditions. In the simplest case (flat electrodes, absence of electronegative impurities) in the stationary state the system of equations with the boundary conditions has the form

$$dj_e/dx = -dj_i/dx = eq + \alpha j_e; \tag{1}$$

$$dE/dx = 4\pi e(n_i - n_e); \tag{2}$$

$$j_e(0) = \gamma j_i(0); \tag{3}$$

$$U_c \int_0^d E dx, \tag{4}$$

where j_e and j_i are the current density of the electrons and ions; q, rate of non-self-sustained ionization; E, intensity of the electric field; n_e and n_i, electron and ion densities; U_c, cathodic voltage drop; d, thickness of the space-charge layer at the cathode; e, electron charge; α, first Townshend coefficient; and, γ, coefficient of secondary emission of electrons from the cathode.

The computational results obtained by most authors differ substantially from one another. It is desirable to compare the calculations performed for a wide range of current densities j and gas pressures p on the basis of the dependence of the cathodic voltage drop U_c on the ratio j/p^2, since it is known that when the rate of self-sustained ionization in the cathodic layer is much higher than the rate of non-self-sustained ionization, the discharge for all practical purposes does not differ from the classical glow discharge [3], for which the similarity laws hold. These curves are constructed in Fig. 1, where the curves 1-5 correspond to the data from [1-5]. For curve 4 the similarity law is not obeyed, which indicates that the calculations are wrong. The disagreement between the curves 1-3 and 5 can be explained in part by the fact that different approximations for the Townshend ionization coefficient and different values of the mobilities were used. Curves 3 and 5 lie significantly higher than all computed curves and, especially, the experimental data. To construct these curves a voltage drop was added in the so-called transitional region, which was not taken into account in [1, 2].

The parameters of the cathodic layer can be very easily calculated using Thompson's formula [6], expressing the dependence of the ion current density j_i and the field intensity at the cathode E_c on the cathodic voltage drop:

$$j_i = e^{3/4}(b_i/\pi)^{1/4} q^{3/4} U_c^{j/2}; \tag{5}$$

$$E_c = 2(\pi e q/b_i)^{1/4} U_c^{1/2}, \tag{6}$$

where b_i is the ion mobility.

Thompson's formulas were obtained by solving the same continuity and Poisson equations (1) and (2), but for a completely non-self-sustained discharge. In the derivation it was assumed that the non-self-sustained ionization is uniform in the cathodic layer, the self-

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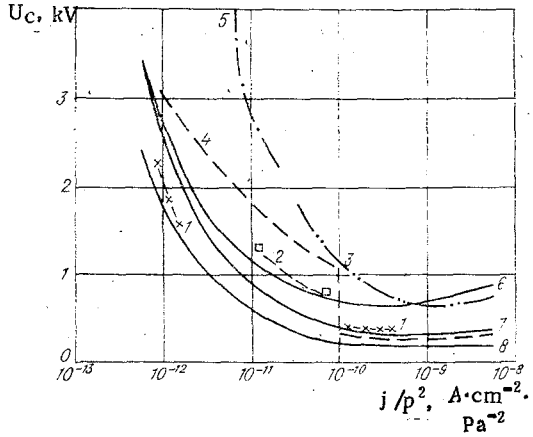

Fig. 1

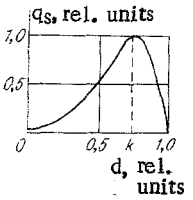

Fig. 2

sustained discharge is much weaker than it ($\alpha = 0$), and electrons are not emitted from the cathode ($\gamma = 0$). They can, however, be used when self-sustained ionization in the cathodic layer is appreciable and also for calculating the self-sustained glow discharge. At the same time, q is replaced by the sum of the rates of the non-self-sustained q_n and self-sustained q_s ionization or only by q_s.

The self-sustained ionization in the cathodic layer is nonuniform – it is minimum at the boundaries of the layers, and the position of the maximum depends on the current density. Figure 2 shows the distribution of the rate of self-sustained ionization in argon with $j/p^2 = 1 \cdot 10^{-8}$ A·cm^{-2}·Pa^{-2}.

To use Thompson's formulas, we shall replace the nonuniform rate of self-sustained ionization by an average value, which can be determined graphically or from the formula

$$q_s = (\gamma j_i \alpha_{av}/e) \exp(\alpha_{av} k d), \text{where} \alpha_{av} = \alpha_c/2, \quad (7)$$

where α_c is determined by the ratio E_c/p;

$$d = U_c/0.5\ E_c \quad (8)$$

is the working thickness of the cathodic layer; k is a coefficient that takes into account the position of the maximum of the rate of self-sustained ionization in the cathodic layer (see Fig. 2). For nitrogen its numerical values are equal approximately to 0.2, 0.3, 0.4, 0.5, and 0.6 with $j/p^2 = 10^{-11}$, 10^{-10}, 10^{-9}, 10^{-8}, 10^{-7} A·cm^{-2}·Pa^{-2}, respectively.

In the case of a non-self-sustained discharge q_n depends on the external source and is a constant. For fixed voltage on the discharge gap and q_n the current between the electrodes and E_c are calculated from the formulas (5) and (6), and then the thickness of the cathodic layer d is also calculated. If the discharge is self-sustained, then q_s depends on the discharge current and to calculate the parameters of the cathodic layer the self-consistent solution for (5)-(7) is obtained.

The calculation is carried out in the following order. The density of the discharge current j is chosen as an independent parameter. The ion current density at the cathode $j_i = j/(1 + \gamma)$, U_c is fixed and from (5) we find q. From (6) and (8) we calculate E_c and d, respectively. Assuming that the distribution of the field intensity in the cathodic layer is linear, we find the position of the maximum (the value of k in units of d) rate of self-sustained ionization, which is proportional to the product $\alpha(x) \exp[\int \alpha(x) dx]$. We iterate until q_s calculated from (7) is equal to q. Several iterations are usually sufficient.

The admissibility of replacing the nonuniform rate of ionization by its average value is confirmed by Table 1, where the results of the calculation based on the data of [7] and on the formulas (5)-(8) are compared for the subnormal, normal, and anomalous glow discharge in argon with $\gamma = 0.02$. In the calculation based on the formulas (5)-(8) we use the same values of the Townshend ionization coefficient, mobilities, and coefficient of secondary electron emission as those used in [7]. Table 1 also presents the value of the criterion for a self-sustained discharge

TABLE 1

j/p^2, $A \cdot cm^{-2} \cdot Pa^{-2}$	Calculation	U_c, V	E_c/p, $V \cdot cm^{-1} \cdot Pa^{-1}$	d, cm	Criterion for a self-sustained discharge
$3.3 \cdot 10^{-11}$	[7]	215	0,95	0.34	1,5
	(5)—(8)	195	0,91	0,33	1,15
$3.3 \cdot 10^{-10}$	[7]	180	1,90	0,15	1,15
	(5)—(8)	170	1.88	0,14	1,15
$1 \cdot 10^{-8}$	[7]	280	7,95	0.64	2,2
	(5)—(8)	240	6,30	0,58	1,28

TABLE 2

j_b, $\mu A/cm^2$	j_i, mA/cm^2	t_i, μsec	t_{ch}, μsec
40	0,6	830	270
85	1.0	520	160
150	1,5	180	105

$$\gamma \left\{ \exp \left[\int_0^d \alpha(x)\, dx \right] - 1 \right\},$$

characterizing the accuracy of the calculation (the closer this quantity to unity, the more accurate the calculation is). It is evident that the parameters of the layer calculated from the formulas (5)-(8) differ by not more than 10% from the computed values, obtained by Ward on a computer. The fine structure of the cathodic layer is not, of course, revealed in the approximate calculation, but this was not the purpose of the calculations.

This method was used to calculate the dependence $U_c = f(j/p^2)$ for a glow discharge in nitrogen. The results are presented in Fig. 1. Here we use the following values of the mobility and coefficients: $b_i = 2.65 \cdot 10^5$ $cm^2 \cdot Pa/(V \cdot sec)$ for curves 6-8. For curve 6, $\gamma = 10^{-2}$, α/p, as in [5]; for curve 7, $\gamma = 10^{-2}$, and the experimental value from [8] was used for α/p; for curve 8, $\gamma = 10^{-1}$, and the experimental value given in [8] was used for α/p.

The computational methods examined above are applicable to a discharge with perfectly clean electrodes ($\gamma \approx 10^{-2}$). To obtain reproducible results coinciding with the theoretical calculations, the parameters of the "classical" glow discharge at low pressure are measured in carefully degassed tubes after the cathode is cleaned by fast ions [9].

A similar technological preparation cannot be done for the discharge chamber of an EIL. In addition, especially pure and technically pure gases contain an oxygen impurity (up to 0.1 and 0.5%, respectively), whose absolute partial pressure is very high. As a result, an oxide film forms on the electrodes of the discharge chamber. In [9, 10] a glow discharge with an oxide film on the cathode, called by the authors diffuse, is singled out as a special form of the glow discharge. In this diffuse discharge the burning voltage is about 10 times lower than in the usual glow discharge, and the current density is approximately 1000 times higher than the normal current density. In addition, at low current densities the usual γ processes occur at the cathode, while at high densities the presence of the oxide film is felt.

In [9, 10] the absence of a cathodic voltage drop is explained by field emission, owing to the fact that the positive ions charge the external surface of the oxide film and create on the surface of the metal and in the dielectric a high electric-field intensity. The discharge used in EIL must have the characteristic features of precisely such a diffuse glow discharge.

We shall study the processes occurring in the discharge gap, keeping in mind the presence of an oxide film on the cathode. When voltage is applied to the electrodes of the discharge chamber, and when an external ionization source is switched on, an electron current, giving rise to a voltage drop in the volume of the discharge gap, flows toward the anode of the dis-

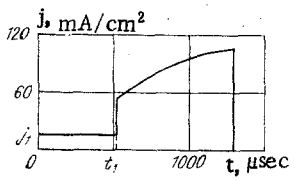

Fig. 3

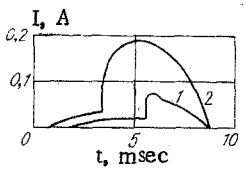

Fig. 4

charge chamber. An ionic current, whose density is calculated from (5), flows toward the cathode of the discharge chamber. The ion current charges the oxide film of the cathode; the charging time, neglecting leakage of charge, is expressed by the elementary formula [11, 12]

$$t_{ch} = \varepsilon\varepsilon_0 E/j_i, \tag{9}$$

where ε and ε_0 are the relative dielectric constant and the dielectric constant; E is the field intensity in the film.

When the charging process is completed, emission of electrons straight through the film appears. According to [13], when the gap width of the dielectric is equal to 2-3 eV, significant electron emission through the film occurs with field intensities of $(2\text{-}5)\cdot10^5$ V/cm.

After the appearance of the electron emission the cathodic voltage drop decreases. The formulas for j_i and E_c are no longer operative. The positive charge on the dielectric is neutralized by the electrons emitted from the metal into the dielectric, and also by the conduction electrons produced in the dielectric by the beam electrons. A value of U_c for which the ion current compensates the charge leakage is established.

The effect of the oxide film is confirmed most clearly by studies of the process establishing a steady discharge current in nitrogen at atmospheric pressure in the impulsive mode [14]. Table 2 was constructed based on these studies; here j_i is the ion current density calculated from (5) with U_c = 1 kV, t_1 is the delay time of the high-current stage of the discharge corresponding to the charging time of the oxide film, t_{ch} is the charging time calculated from (9) with $E = 2\cdot10^5$ V/cm.

A typical oscillogram of the discharge current with a beam electron current density of j_b = 85 μA/cm² is shown in Fig. 3. The ratio of the experimentally measured current density at the weak-current stage of the discharge with a reticular cathode j_1 to the computed ion current density, equal in this case to 15, characterizes the value of the coefficient γ. The ratio of these currents is lower for a flat cathode. The charging time is shorter than the experimentally measured time t_1, since the leakage of charge, whose effect on the increase in the ion current density, naturally decreases, was not taken into account in the calculation.

The studies of the process of establishing a steady-state current in the quasistationary discharge with a frequency of 50 Hz, performed on the same setup at atmospheric pressure but with a gas flow rate of 100 m/sec, are also revealing [15]. Figure 4 shows the oscillograms of the discharge current with a voltage of 1 kV. The curves 1 and 2 were measured with j_b = 100 and 200 μA/cm², respectively. The delay time of the high-current stage of the discharge in this case is somewhat longer than in the impulsive mode, since for small transverse dimensions of the electrodes (1 cm) the charges are displaced by the gas flow out of the discharge gap, as a result of which the ion current on the cathode decreases.

The delay of the high-current stage of the discharge is explained in [14, 15] by the time required for heating the gas in the cathodic layer. Estimates show, however, that the gas in this case is heated by only 20-30°, so that this explanation is not satisfactory.

In a stationary discharge the effect of the oxide film is manifested as follows. The computed and experimental values of the cathodic voltage drop differ significantly from one another [16]. As before, the disagreement between them is explained by the heating of the gas in the cathodic region. This explanation is, however, implausible, since at the beginning of the current–voltage characteristic the current density is low, and the gas is practically not heated. This disagreement is associated with the fact that under the conditions of the experiment the surface of the cathode is oxidized, so that the coefficient γ is equal not to 0.01, but is rather 2-3 orders of magnitude higher.

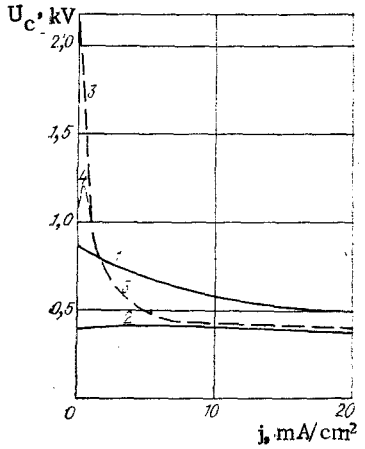

Fig. 5

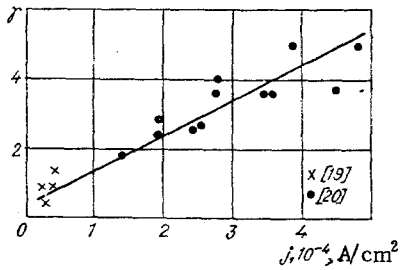

Fig. 6

The cathodic voltage drop depends on the electron current density in the beam (Fig. 5, curves 1 and 2, respectively, with j_b = 10 and 80 μA/cm², according to the data of [16], with a nitrogen pressure of 10 kPa). With a clean cathode ($\gamma \approx 0.01$), at some current density the rate of the self-sustained ionization in the cathodic layer is significantly higher than the rate of the non-self-sustained ionization, as a result of which the cathodic voltage drop is virtually independent of j_b (the curves 3 and 4 in Fig. 5 show the calculations performed by the author for the same conditions.

The current increases not proportionally to $U_c^{1/2}$, as follows from (5), but rather more rapidly. With a flat cathode the voltage of the transition of the non-self-sustained discharge into a self-sustained discharge is approximately two times lower than the computed value with $\gamma = 0.01$ [17].

The oxide layer must have a stronger effect on a cathode made of aluminum foil, whose oxide film exhibits better insulation properties. Indeed, from photographs of the cathodic region it is evident that the size of the glowing region on an oxidized-aluminum cathode is several times smaller than in the case of a copper cathode. The authors believe that the magnitude of the cathodic voltage drop on such a cathode is much higher than on a cathode prepared from pure metal. The observed phenomenon is not explained in the work. Apparently, the authors ignored the properties of a glow discharge with an aluminum cathode, coated by a thin oxide layer [9, 10].

The coefficient of secondary emission, determined from the condition determining the transition of the non-self-sustaining discharge into a self-sustained discharge

$$\gamma\left\{\exp\left[\int_0^d \alpha(x)\,dx\right]-1\right\}=1,$$

is equal to several units and increases with the ion current density (Fig. 6), which corresponds to [9]. To construct this curve the experimental values of the voltages for the transition of the non-self-sustained discharge into a self-sustained discharge from [19, 20] were used, and j_i and E_c were calculated from (5) and (6). Since the electrons are emitted from separate sections of the film [13], the discharge burns nonuniformly, especially with weak currents [16, 20].

In many studies the role of dielectric films is underestimated. For example, in [19] their effect on the characteristics of the discharge is not even considered, and in [20] a relationship between the formation of cathodic spots and the charging process and the breakdown of the films is rejected. The breakdown of the films could occur in strong-current impulsive discharges of short duration. In the work studied above electron emission straight through the dielectric film is more likely.

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