VOLT-AMPERE CHARACTERISTIC AND TRANSITION CURRENT OF A GAS GAP WHEN ACTED UPON BY PULSED IONIZING RADIATION

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The problem of the reduction of the breakdown voltage of a gas gap when it is acted upon by a high-power ionizing pulse is considered in [1]. The prebreakdown transition currents are calculated for argon and air in the case of a wide gap (the distance between the electrodes d = 1 cm). The problem of the form of the volt-ampere characteristic in the high-current range (the "glow" discharge mode) was not considered.

The purpose of the present paper is to calculate the volt-ampere characteristics of a narrow gas gap ($d = 2 \cdot 10^{-2}$ cm) in both the high- and low-current regions (the range of currents limited by space charge).

§1. We will assume that the external source of radiation produces uniform ionization in the interelectrode gap. This assumption is satisfied quite well when the electrodes are fairly close to one another. We will direct the x coordinate from the cathode to the anode. Then the initial system of equations and boundary conditions have the form [1-3]

$$\partial q_-/\partial t = \alpha(E)j_- - \partial j_-/\partial x + Q; \tag{1.1}$$

$$\partial q_+/\partial t = \alpha(E)j_- + \partial j_+/\partial x + Q; \tag{1.2}$$

$$\partial E/\partial x = (4\pi/\varepsilon)(q_- - q_+); \tag{1.3}$$

$$j_-(0, t) = \gamma_i j_+(0, t) + \gamma_* \cdot \int_0^d \alpha(E)\, j_-(x, t)\, dx; \tag{1.4}$$

$$j_+(d, t) = 0; \tag{1.5}$$

$$\int_0^d E(x, t)\, dx = U = \text{const}, \tag{1.6}$$

where q_- and q_+ are the charge densities of electrons and positive ions, j_- and j_+ are the current densities of electrons and positive ions, E is the electric field, $\alpha(E)$ is the impact ionization coefficient, γ_i and γ_* are the coefficients of secondary ionization at the cathode due to the action of ion collision and photoeffect, ε is the dielectric constant of the gas, U is the applied external voltage, and Q is the rate of generation of charges by the external source per unit volume.

Equations (1.4) and (1.5) describe the boundary conditions for the electron current density at the cathode and the current density of the positive ions at the anode, respectively; Eq. (1.6) reflects the fact that the external voltage across the discharge gap is maintained constant.

We used the following empirical expressions in the calculations:

1) in the case of nitrogen from [4] $v_- = \mu_- E/p$, $v_+ = \mu_+ E/p$ are the drift velocities of the electrons and positive ions in the electric field E(x, t); $\alpha(E) = cp\exp(-Dp/E)$, where $\mu_- = 2.9 \cdot 10^5$ cm^2·mm Hg/V·sec, $\mu_+ = 2 \cdot 10^3$ cm^2·mm Hg/V·sec, c = 7.6 (cm·mm Hg)$^{-1}$, p = 760 mm Hg, and D = 260 V/cm·mm Hg;

2) in the case of air we used the empirical expression from [5] for $\alpha(E)$, μ_-, and μ_+.

§2. To solve the system of equations (1.1)-(1.6) an explicit calculation scheme [6] was used in [1-3]. The stability of the calculations using this approach is ensured if the Courant condition [2]

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$$1 > r = v_- \tau / h$$

is ensured, where τ is the time step, h is the coordinate step, and r is the Courant number. Since the electron velocity v_- is large, the time step τ is small which leads to a considerable calculation time. An implicit calculation scheme is described in [7] in which the equations of motion of the electrons are integrated along the characteristics. In this scheme there is no local limitation on the time step, but a large number of iterations have to be carried out at each step.

In the present paper we use an implicit continuous calculation scheme [4]. In this case it is necessary to iterate with respect to the boundary condition at the cathode. In fact, a single iteration was carried out in the calculations. Comparative calculations showed that the scheme gives acceptable results for a Courant number r=5. This enables one to economize considerably on computing time as compared with explicit schemes. In the region of the anode and cathode, regions of high gradients of the defined quantities arise. Hence, we chose a nonuniform step with respect to the spatial coordinate (small at the cathode and anode and coarser in the remaining region). The minimum step at the cathode was chosen to be $h=4\cdot10^{-4}$ cm.

§3. Consider the results of the calculations describe above. Figures 1-4 represent graphically the results of a calculation for nitrogen for a radiation dosage power $\dot{D}=3.32\cdot10^{-7}$ R/sec ($Q=1.1\cdot10^{-2}$ Cl/cm$^3\cdot$sec), an interelectrode distance $d=2\cdot10^{-2}$ cm, a gas pressure p=760 mm Hg, and $\gamma_i=0.02$.

Figure 1 shows the volt-ampere characteristic of a gas gap. Two parts can be distinguished in this characteristic: a region of relatively small currents ($U < U_*$) and a region of relatively high currents ($U > U_{**}$). These two qualitatively different parts of the volt-ampere characteristic correspond to two different electric field distribution patterns in the interelectrode gap.

Figure 2 shows curves of the electric field distribution at the point on the volt-ampere characteristic $U=1200$ V $< U_*$. Curves 1-3 correspond to times $t=35\cdot10^{-9}$, $70\cdot10^{-9}$, and $210\cdot10^{-9}$ sec after the beginning of the radiation pulse. The distortion of the field by the positive space charge is small ($\Delta E/E_0=2\cdot10^{-2}$), and the field in the cathode layer is insufficient for impact ionization [$Q > \alpha(E) j_-$]. Under these conditions the current through the gap is determined by ionic conductivity. For a voltage $U=U_*$ the electric field in the cathode layer depleted by electrons reaches values exceeding the ionization threshold. Due to impact ionization the ionic conductivity in the cathode layer becomes equal to the electronic conductivity in the remaining volume, which leads to a reduction in the potential drop in the cathode layer and in the thickness of the latter.

Figure 3 shows electric field distribution curves at a point on the volt-ampere characteristic where $U=1400$ V $> U_{**}$; curves 1-3 correspond to the instants of time $t=2.9\cdot10^{-7}$, $3.06\cdot10^{-7}$, and $3.25\cdot10^{-7}$ sec after the beginning of the radiation pulse. In this case the electric field in the cathode layer considerably exceeds the ionization threshold ($\Delta E/E_0=20$). A narrow cathode region, characterized by considerable electric field and charge gradients, and a wide positive column in which the field is uniform are formed. The cathode layer plays the role of an unlimited electron emitter, the value of whose emission is automatically maintained at a level assigned by the conductivity of the positive column. The discharge acquires lines characteristic of a glow discharge when there is no radiation. When the change into the glow discharge mode occurs, the current increases by five orders of magnitude.

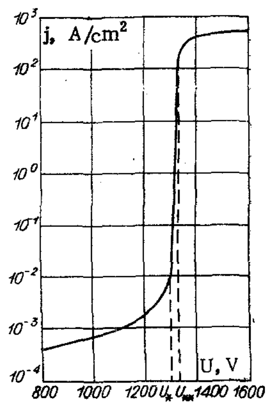

Fig. 1

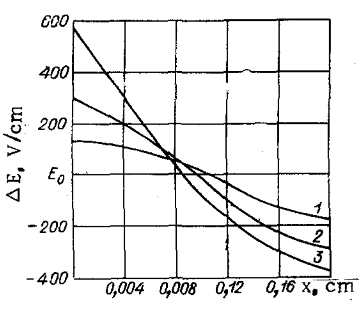

Fig. 2

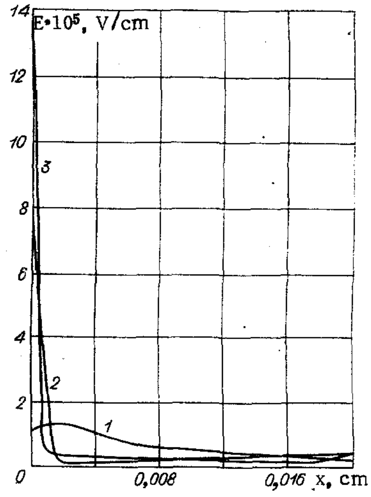

Fig. 3

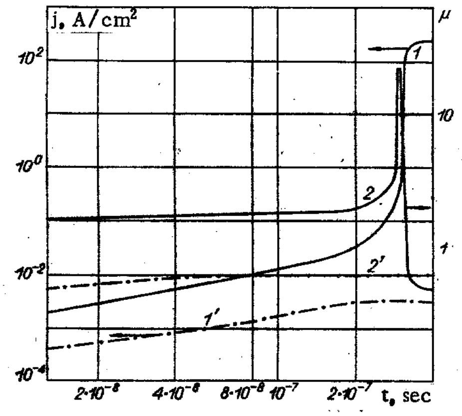

Fig. 4

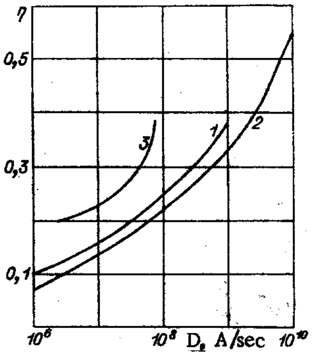

Fig. 5

Figure 4 shows calculated curves of the transition current (curves 1) and also shows (curves 2) the time dependence of the coefficient

$$\mu(t) = \gamma_i \left[\exp\left(\int_0^d \alpha[E(x, t)]\, dx \right) - 1 \right].$$

The continuous curves correspond to the point on the volt–ampere characteristic in Fig. 1 where $U = 1400$ V, while the dotted lines correspond to the point where $U = 1250$ V. It is seen from these curves that when $U = 1400$ V $> U_{**}$, the coefficient $\mu(t)$ is greater than 1 when $t > 15$ nsec, but there is no sharp increase in current. At the instant when the transition to the glow-discharge mode occurs (the instant of sharp current increase) $\mu(t)$ increases rapidly, reaching its maximum value $\mu_* = 22$. Then μ decreases just as sharply.

The reduction in μ is accompanied by a slowing down in the increase in current, and when μ reaches its steady-state value $\mu_\infty = 0.48$, the increase in current ceases. When the applied voltage is increased, μ_∞ increases, and at a certain voltage $U = U^*$ reaches a value of unity, which corresponds to Townsend breakdown. In the case of low discharge currents ($U = 1250$ V $< U_*$) the coefficient $\mu(t)$ is always less than unity and there is no sharply pronounced maximum.

§4. We made an experimental check of the theoretical method. To do this we calculated the volt–ampere characteristics of an air gap for an interelectrode spacing $d = 2 \cdot 10^{-2}$ cm at a pressure $p = 760$ mm Hg and a radiation dosage power $\dot{D} = (10^6 - 10^9)$ R/sec. From these characteristics we found the voltage U_* at which transition to the glow-discharge mode occurs. We then drew graphs of the coefficient of relative reduction in breakdown voltage $\eta = (U_0 - U_*)/U_0$ as a function of the radiation dosage power (Fig. 5, curve 1), where U_0 is the breakdown voltage of a nonirradiated air gap. This relation was also found experimentally. The gas was irradiated from a generator of the type described in [8]. The experimental results are shown in Fig. 5 (curve 2). The agreement between the experimental and theoretical curves can be regarded as satisfactory. For comparison, Fig. 5 (curve 3) also shows the results of numerical calculations of the coefficient η carried out in [1].

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