PRIMARY AND SECONDARY PROCESSES IN THE NANOSECOND RANGE IN THE PRODUCTION OF A DISCHARGE IN A SHORT GAS GAP

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It has been shown [1-3] that the discharge buildup time τ for initiation by single electrons substantially exceeds the time expected from the one-avalanche streamer mechanism in the case of gaps about 1 mm long breaking down in 10^{-9} sec or so. This indicates that the mechanism involves many avalanches. If the discharge is initiated by many electrons (10^4), the current rise is due to avalanche multiplication of initiating electrons [4]. Then τ equals the time for an avalanche to build up to about 10^8 electrons [5].

Little is known about electron multiplication in one-electron initiation, except that a diffuse glow occurs throughout the gap during the initial buildup, together with narrow channels of low luminosity [6], while the stage of rapid current rise can be ascribed to avalanche multiplication of secondary electrons [4]. Here we consider electron multiplication in the primary process, and also the mechanism of secondary-electron extraction in one-electron initiation in strong fields.

1. Electron spread in an avalanche. An electron appearing at the cathode leads to production of an electron avalanche. If the field is strong, many electrons are formed in the avalanche as it advances a distance much less than the gap width. The field produced by the electrons and ions begins to influence the behavior of the avalanche. The ion field retards the tail of the electron avalanche, while the electron field will accelerate the electrons at the head, i.e., the electrons begin to spread out. This effect appears even during the exponential growth of the avalanche.

The electron density n_e^* and ion density n_e^* are as follows in a cylindrical coordinate system r, z:

$$n_e{}^* = \pi^{-3/2} r_d{}^{-3} \exp\{\alpha_0 v_- t - [r_2 + (z - v_- t)^2]\, r_d{}^{-2}\}, \qquad (1.1)$$

$$n_i{}^* = \alpha_0 v_- \int_0^t n_e{}^*(t')\, dt', \quad r_d = \sqrt{4Dt}. \qquad (1.2)$$

Here r_d is the diffusion radius, D is diffusion coefficient, α_0 is the coefficient of collisional ionization, and v_- is electron drift velocity.

The following are [7] the electron and ion fields in an avalanche as functions of z:

$$E_e{}^z = -E_0 M(y), \quad E_i{}^z = E_0 a e^{ay} \int_y^\infty e^{-ax} M(x)\, dx,$$

$$E_0 = \frac{q_e \exp(\alpha_0 v_- t)}{4\pi\varepsilon_0 r_d{}^2}, \quad y = \frac{z - v_- t}{r_d}, \quad a = \alpha_0 r_d,$$

$$M(y) = \frac{\operatorname{erf}(y)}{y^2} - \frac{2}{\pi}\,\frac{\exp(-y^2)}{y}, \qquad (1.3)$$

in which q_e is electron charge.

We normalize the expressions for the fields and space-charge densities:

$$n_e = \frac{n_e{}^*}{\pi^{-3/2} r_d{}^{-3} \exp(\alpha_0 v_- t)}, \quad E_e = \frac{E_e{}^z}{E_0},$$

$$n_i = \frac{n_i{}^*}{\pi^{-3/2} r_d{}^{-3} \exp(\alpha_0 v_- t)}, \quad E_i = \frac{E_i{}^7}{E_0}. \qquad (1.4)$$

Figure 1 shows n_e, n_i, E_e, and E_i as functions of $(z - v_- t)/r_d$.

To the right of the point where $E_e = E_i$ we have $E_e > E_i$. The field $E_e + E_i$ is added to the external field and will tend to detach electrons from the head. The sum field is reduced to the left of $E_e = E_i$ and the electrons are retarded. Consider the number of electrons in a field exceeding the external field, for which we determine the surface at which $E_e + E_i = 0$ and take the integral over the entire volume in the direction of increasing r an z. For approximate purposes we restrict consideration to determination of the surface at which the projection of $E_e + E_i$ on the z-axis is zero.

We assume the distribution of n_i and n_e to be spherically symmetrical. The center of density for the ions lies at $y = -\beta$, where β is defined by

$$E_i(-\beta,\ a) = 0.$$

Then for the critical surface whose coordinates are $\rho(y)$ we have

$$\frac{y + \beta}{\sqrt{(y+\beta)^2 + \rho^2}}\, E_i\left[\sqrt{(y+\beta)^2 + \rho^2},\ a\right] + \frac{y}{\sqrt{y^2 + \rho^2}}\, E_e\left(\sqrt{y^2 + \rho^2}\right) = 0 \quad \left(\rho = \frac{r}{r_d}\right). \qquad (1.5)$$

Numerical solution of (1.5) for $a = 1$ and 2 shows that $\rho(y)$ may be approximated by a parabola:

$$\rho = 2.4(y - b)^{0.5}, \qquad (1.6)$$

in which $b = 0.495$ for $a = 1$ and $b = 0.645$ for $a = 2$.

The proportion of electrons within the paraboloid is

$$N^{(1)} = \exp(-\alpha_0 v_- t) \int_{z_0}^{\infty} \int_0^{r(z)} n_e 2\pi r\, dr\, dz,$$

where z_0 is deduced from (1.6) with $\rho = 0$ and r(z) from (1.6) with the substitution

$$\rho = r / r_d, \quad y = (z - v_- t)/r_d.$$

The $N^{(1)}$ for $a = 1$ and 2 are, respectively, 0.18 and 0.13.

The number N of electrons in the avalanche increases as time passes, while α decreases and r_d increases. Calculations [7-9] were made for $a = \alpha r_d$ at p = 760 mm Hg and E/p = 150 V/cm-mm Hg in order to estimate $N^{(1)}$. As α increased from $0.7\alpha_0$ to $0.98\alpha_0$ there was about a 10% increase in a, and Fig. 1 shows that this leads to increase in $N^{(1)}$. This result agrees with measurements of avalanche radius in vapors of

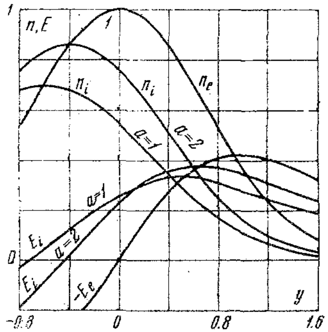

Fig. 1. Normalized n_e, n_i, E_e, and E_i at the z-axis near the center of the electron cloud.

organic liquids [10], but these data indicate that the avalanche radius is greater than r_d for $N \geq 5 \cdot 10^7$ on account of Coulomb repulsion between the electrons. This reduces E_e and correspondingly reduces the electron spread.

This means that more than 10% of the electrons will be moving with a velocity exceeding v_- even at the start of retardation of the avalanche by E_i, while the rest will move at less than this velocity.

2. Avalanche chains. When E_i becomes comparable with the external field, the electron head becomes detached from the avalanche and starts to form a new avalanche, and so on. The proportion of electrons lost from the avalanche will be less than the N(ι) derived in the previous section because only electrons whose speed considerably exceeds v_- will be lost.

Consider the total number of electrons in such a chain. We neglect overlap between the electron and ion clouds, and we also assume that the avalanche broadens by free diffusion. If we also assume that the avalanche grows exponentially with α = const, the following is the number of electrons in the avalanche for one initiating electron when $E_i = E$:

$$N_0 = \frac{16\pi\varepsilon_0 u_T \mu_+ \ln N_0}{q_e \alpha}, \qquad (2.1)$$

in which u_T is the thermal velocity of the electrons.

Electrons detached from the head move in the field

$$E^* = k_E E \ (k_E > 1),$$

since the field of the electron cloud will be superimposed on the external field E. The number of avalanches in a path z is

$$z/z_k = z\alpha / \ln N_0 \,/\, N^*,$$

in which z_k is avalanche length and N^* is the number of electrons ejected from the avalanche. Then the total number of electrons in such a chain is

$$N_1 = N_0 \frac{z}{z_k} \quad \text{or} \quad N_1 = \frac{16\pi\varepsilon_0 u_{T+} z}{q_e}. \qquad (2.2)$$

The conductivity of an avalanche chain across the gap ($z = \delta$) is $N_1 \mu_- q_e \delta^{-2}$. It is found [8,9] for nitrogen at $E/p > 10^2$ V/cm-mm Hg that $u_T \approx 0.3(E/p)^{0.62}$, i.e., the conductance is ~ $2.5 \cdot 10^{-6} (p\delta)^{-1}$ ohm^{-1}.

Chains of avalanches such as those described above should take the form of thin weakly luminescent channels at the stage at which there is still no potential drop in the gap; such channels would appear to have been observed [6].

In fact, narrow channels within about 10^{-9} sec acquired a diameter of about 10^{-2} cm and crossed the gap in not more than 10^{-9} sec for $\delta =$ $= 0.4$ cm, p = 46 mm Hg, and $E/p = 1.43 \cdot 10^3$ V/cm-mm Hg.

An avalanche chain under such conditions should have a diameter of about $d_1 \approx 2\sqrt{6Dt}$ and should bridge the gap in a time $t_1 \approx \delta / k_v v_-$, in which $k_v > 1$ takes account of the increase in the speed of the avalanche chain relative to v_-. If the electrons are ejected for $E_i = E$ we have $k_v \approx 2$. For nitrogen [8,9]

$$D \approx {}^2/_3 \, u_T \mu_- \approx 3.10^4 \text{ cm}^2 \text{ sec}^{-1},$$

so we get

$$d_1 \approx 3 \cdot 10^{-2} \text{ cm} \ t_1 \approx 1{,}5 \cdot 10^{-9} \text{ sec}.$$

These agree with observed values in order of magnitude [6].

Secondary electrons are produced by photons from the primary avalanches. If we assume that these photons are emitted by excited molecules with a mean lifetime τ_b, the time of discharge buildup should be of the order of τ_b, as is observed [3,12].

The concept of avalanche chains is confirmed by the presence of many channels in the final stage of breakdown. An avalanche chain is of low conductivity and is quasi-neutral, so the time of spark voltage drop related to avalanche electron multiplication should not be dependent on the number of original initiating electrons, as is found [4].

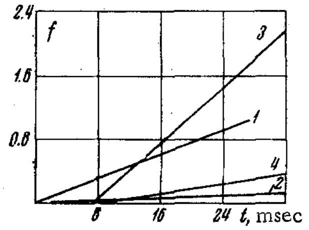

Fig. 2. Change in photoelectric emission from copper for δ = 1 mm, p = 760 mm Hg, and U (kV) of: 1) 30, clean electrodes, 2) 30, after 4000 sparks, 3) 10, clean electrodes, spark illumination, 4) 10, after 4000 sparks, spark illumination.

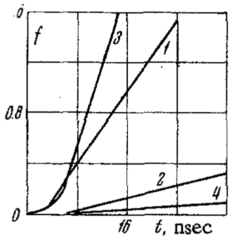

Fig. 3. Field emission from copper with δ = 1 mm at U = 30 kV and p (mm Hg) of: 1) 20, clean electrodes, 2) 760, clean electrodes, 3) 20, after 4000 sparks, 4) 760, after 4000 sparks.

3. Secondary processes. The distribution in the discharge delay was examined in relation to the surface state of the cathode in order to investigate the role of the cathode in the secondary process. The method of measurement was as previously described [3]. We plotted $f(t) =$ $= |\ln n_t/n_0|$, $f(t_1) = 1$ (n_t is the number of discharges with a delay of t or more, and n_0 is the total number of discharges). If $t_1 \gg 10^{-9}$ sec, the $f(t)$ curves become straight lines. Copper and tungsten cathodes gave a marked dependence of t_1 on the number of previous discharges. Numerous measurements of t_1 showed that t increases with the number of sparks. The effect is slight for the first few hundred sparks, but it becomes marked for $n > 10^3$. These effects are not observed for aluminum cathodes [13].

There are two reasons for increase in t_1: 1) the photoelectric emission from the cathode may deteriorate, which reduces the effects of secondary processes, 2) if the discharges reduce the field emission from the cathode, this will reduce the electron current i_0 that initiates the breakdown and thus will increase t_1, because $t_1 \propto 1/i_0$ for E, p, and δ constant.

The following tests were performed to establish which of these two effects governs $t_1(n_0)$. With $E = 3 \cdot 10^5$ V/cm, $\delta = 0.1$ cm, p = 760 mm Hg (air), and clean copper electrodes, we measured the delay and drew up $f(t)$ curves. The same electrodes were then used with the same p and δ at $E = 10^5$ V/cm with illumination from an auxiliary spark via a quartz window (curves 1 and 3 in Fig. 2). Then 4000 sparks were passed, followed by recordings with and without the spark illumination (curves 2 and 4 in Fig. 2).

Curves 1 and 2 are to be compared with 3 and 4, which characterize the photoelectric emission. Line 4 is much less steep than line 3, which shows that the cathode emissivity is much reduced by 4000 sparks. The $f(t)$ for low pressures similarly serve to characterize the change in field emission in response to a number of discharges.

It has been found [3] that for $\delta \leq 0.1$ cm at atmospheric pressure there is a certain probability $P < 1$ of electron emission from the cathode even at high overvoltages. The ratio E/p had to be increased to produce $P \approx 1$. We therefore recorded two distributions at $E = 3 \cdot 10^5$ V/cm for clean copper electrodes, one at 20 mm Hg and the other at 760 mm Hg (curves 1 and 2 in Fig. 3). The curves were again recorded after 4000 sparks (curves 3 and 4). As $P = 1$ implies that $i_0 \approx q_e/t_1$ for the electron current from the cathode that initiates breakdown, the slopes of the $f(t)$ curves for 20 mm Hg (1 and 3 in Fig. 3) characterize i_0 at the start and end. The sparking tends to increase the field emission [14].

Photoelectric emission from the cathode is thus an important secondary process in the production of discharges in the nanosecond range.

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