GROWTH OF A NANOSECOND PULSED DISCHARGE IN A GAS WITH ONE-ELECTRON INITIATION

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Pulse breakdown on gaps of millimeter order at substantial overvoltages is explained in terms of a discharge mechanism involving photoelectric emission from the cathode followed by collisional multiplication in the gas to give avalanches. The mechanism is used to deduce a theoretical equation for the time of discharge buildup in one-electron mutation, which is compared with experiment.

1. Gas Gap Breakdown at High Fields. The usual theories of gas breakdown are the avalanche (Townsend) one and the Streamer one [1, 2]. The buildup time τ is a basic criterion in deducing the discharge type. This time is usually defined as extending from the instant when the first electron appears that causes collisional ionization in the gap up to the point where the voltage has fallen to a definite level, e.g., 10% of the amplitude. It is considered that the streamer mechanism applies for pulse breakdown at substantial overvoltages [1, 2], for which

$$\frac{\delta}{v_-} > \tau \approx \frac{x_*}{v_-} \qquad (1.1)$$

Here v_- is the speed of electron drift to the anode, x_* is the avalanche length for the critical number of electrons, and δ is the gap length.

Also, the condition for an electron avalanche to become a streamer should apply to the streamer mechanism:

$$x_* = \frac{\ln N_*}{\alpha} < \delta \qquad (1.2)$$

Here N_* is the critical number of electrons for the space-charge field to approach the strength E of the external field, while α is the collisional-ionization coefficient.

The object of the present study was pulse discharges in gases at high E, when $x_* \ll \delta$.

Values of τ have been obtained [2] that satisfy (1.1) and (1.2) for E around 10^5 V/cm, E/p around 100 V/cm-torr, and 1 cm > δ > 0.1 cm with the cathode exposed to strong UV. Detailed analysis shows [3, 5] that the discharge begins with the simultaneous formation of about 10^4 avalanches, which are due to the presence of about 10^4 photoelectrons at the cathode before arrival of the pulse.

As there were many avalanches, one can calculate correctly the current curve, including the stage of rapid growth [5, 6]. It has been shown [4, 6] that τ increases as the number of initiating electrons decreases, whereas the time for the pd to fall is unaffected.

Many-electron initiation is the name given to initiation by a large number of initial electrons, while single-electron initiation is the term used when there are many electrons. The two types of cases can be distinguished by comparing the time for an avalanche to reach a critical size with the mean time between production of successive initiating electrons at the cathode. For the above two mechanisms we have, respectively,

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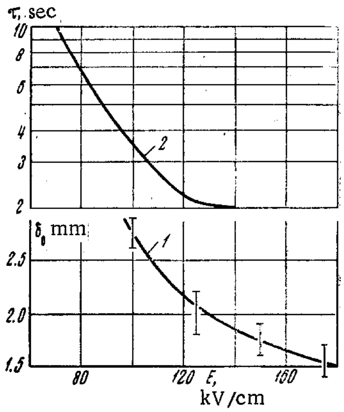

Fig. 1

$$i_0 \gg \frac{eav_-}{\ln N_*}, \qquad i_0 < \frac{eav_-}{\ln N_*} \tag{1.3}$$

where i_0 is the electron current from the cathode, and e is electron charge.

Values of τ considerably larger than those implied by (1.1) have been obtained [4] for $E \geq 10^5$ V/cm, $E/p \geq 100$ V/cm-torr, and $\delta < 0.1$ cm in air with one-electron initiation. A detailed study has been made [5] on $\tau(E)$ for air with $\delta = 0.2$ cm, p = 760 torr, and one-electron initiation. It was found that τ (curve 2 of Fig. 1) for E of $0.8\text{-}2 \cdot 10^5$ V/cm was substantially larger than the discharge buildup time with many-electron initiation. The excess was by an order of magnitude of the highest E (around 160 kV/cm) with τ about 2 nsec.

It has been shown [7] that δ has little effect on τ for a given E and for $\delta > \delta_0$ (a certain limiting value), while $\delta < \delta_0$ results in a rapid rise in τ from a few nsec to some μsec. Curve 1 of Fig. 1 shows $\delta_0(E)$.

The rapid current rise takes a time independent of the breakdown mechanism [6], so one naturally supposes that the final stage of the discharge is independent of the initial number of electrons. The larger τ for one-electron initiation is due to the more prolonged accumulation of avalanches in the gap [6], but one needs to assume that the growth rate of the number of electrons in the avalanches subsequently decreases.

This fall has been observed in studies on the growth of single avalanches and is due to avalanche retardation by the field of the ion space charge [1]. Direct observations [8, 9] at 10^5 V/cm and atmospheric pressure reveal a continuous propagation of a diffusion light emission from the cathode to the anode at about 10^8 cm/sec, with subsequent formation of channels. This has been ascribed [10] to each retarded avalanche generating a new one ahead of itself, with production of an avalanche chain. If $x_* \ll \delta$, we can assume a linear increase in the number of electrons in such a chain. The drift speed for such a chain should be greater than the drift speed for an avalanche.

Subsequent avalanche chains are produced via the photoelectric effect at the cathode [10] on account of emission by excited molecules which are formed at the same time as ions and electrons in the avalanches [1].

2. Time Dependence of the Current. Each successive retarded avalanche may develop either by repulsion of the frontal electrons by the space-charge field [10] or by photoionization in the gas near the head of the avalanche. It is also possible that fast electrons run ahead, these electrons having acquired more energy from the field than they have lost by collision [11]. This process is especially important in breakdown of air at atmospheric pressure and $E > 10^6$ V/cm [17], but we shall not consider these very high E here.

The experimental evidence indicates that a fresh avalanche forms ahead of the previous one, and so we get a chain of retarded avalanches extending towards the anode. A simplified model was used for avalanche growth in the calculations. The number of electrons in an avalanche ceases to grow when a critical number N_* is reached. It is assumed that the current is due only to the electron component of the leading avalanche. The analysis for $\delta \gg x_*$ and $\tau \gg x_*/v_-$ is simplified by taking the mean growth rate as the same for the number N_e of the electrons in each avalanche chain. Then the growth rates for the ion and electron numbers are

$$\frac{dN_i}{dt} = \frac{dN_e}{dt} = a \tag{2.1}$$

where a is a coefficient considered later on. The mean rate of production of excited particles is proportional to the mean rate of production of electrons and ions [1], i.e., from (2.1)

$$\frac{dN^*}{dt} = Qa \tag{2.2}$$

The mean avalanche-chain current $\langle I^* \rangle$ is then constant.

Consider the particle-balance equations when the gap contains M growing avalanche chains. We restrict consideration to the case where none of the chains reaches the anode during τ, i.e., $\tau < \delta/v$, where v is the speed of a chain. We assume that each avalanche produces the same numbers of electrons and excited particles.

The mean rate of increase in the number of excited particles (with allowance for light emission) is as follows:

$$\frac{dN_+^*}{dt} = QaM - \frac{N_+^*}{\tau^*} \tag{2.3}$$

Here τ^* is the excited-state lifetime; N_+^* is the total number of excited particles at a given instant; and Q is the number of excited particles per avalanche electron. The total number N_+° of photons produced is taken as equal to the number of excited particles that have emitted light:

$$N_+^\circ = Qa\int_0^t Mdt - N_+^* \tag{2.4}$$

We neglect photon absorption in the gas, which is permissible for $\mu\delta < 1$, where μ is the absorption coefficient. The number N_-° of photoelectrons produced at the cathode by the avalanche photons is proportional to N_+°:

$$N_-^\circ = q\sigma N_+^\circ \tag{2.5}$$

where σ is a geometrical factor and q is the quantum yield of the cathode, which is dependent on the wavelength λ. The emission spectrum of an avalanche is unknown, so we take as a rough approximation the mean q for the response range of the cathode.

The total number of avalanche chains in the gap is

$$M = N_-^\circ + N_{e-}$$

where N_{e-} is the number of electrons produced in time t by the external factors (field emission, photoelectric emission, etc.). Then (2.4) and (2.5) give

$$M - N_{e-} = \sigma q\left(Qa\int_0^t Mdt - N_+^*\right) \tag{2.6}$$

and the gap current is

$$I = M\langle I^*\rangle \tag{2.7}$$

where $\langle I^*\rangle$ is the mean current from an avalanche chain, which is taken as constant.

We eliminate N_+^* and N_-° from (2.3), (2.6), and (2.7) to get

$$\frac{dM}{dT} + M - \psi\int_0^T MdT = \frac{dN_{e-}}{dT} + N_{e-} \quad \left(N_{e-} = \frac{i_0 t}{e}\right) \tag{2.8}$$

$$T = \frac{t}{\tau^*}, \quad M = \frac{I}{\langle I^*\rangle}, \quad \psi = a\tau^*\gamma, \quad \gamma = \sigma qQ$$

where i_0 is the current due to the initiating electrons, and e is the electronic charge. The solution is

$$M = \frac{B}{p_2 - p_1}\left[\frac{p_2}{p_1}(e^{p_1T} - 1) - \frac{p_1}{p_2}(e^{p_2T} - 1)\right] \tag{2.9}$$

where

$$B = \frac{i_0}{e}\tau^*, \quad p_{1,2} = -0.5 \pm \sqrt{0.25 + \psi}$$

Equation (2.9) allows one to calculate the gap current up to the time when some avalanche chain reaches the anode, i.e., while $t \leq \delta/v$, where v is avalanche-chain speed.

3. Discharge Buildup Time. Preliminary estimates show that $\sqrt{\psi} \gg 1$ for air and argon, so (2.9) for $I \gg i_0$ simplifies to

$$I \approx \frac{i_0 \langle I^* \rangle \tau^*}{2e \sqrt{\psi}} \exp(\sqrt{\psi} T) \tag{3.1}$$

If we assume [5] that the current rises to I_* during τ, this current corresponding to the onset in the fall in the pd across the gap, then (3.1) implies that

$$\tau \approx \left(\frac{\tau^*}{a\gamma}\right)^{1/2} \ln \frac{2I_* e \sqrt{\psi}}{i_0 \tau^* \langle I^* \rangle} \tag{3.2}$$

Before we can compare (3.2) with experiment, we must determine a and the mean electron current in an avalanche chain. To estimate a we assume that an avalanche grows exponentially up to $N = N_*$, after which there is no further increase. It is also assumed that an avalanche expands by free diffusion. We derive N_* from the condition that the external field equals the field due to the ionic space charge:

$$N_* = \frac{16\pi\varepsilon_0 u_T}{e\alpha} \ln \frac{N_*}{N_0} \tag{3.3}$$

where U_T is the thermal electron energy, N_0 is the initial number of electrons for the formation of the subsequent avalanches, and ε_0 is the dielectric constant. In general, the subsequent avalanches grow in a field that exceeds the external field on account of superposition of the field from the electron space charge. The number of avalanches in a path length x is

$$\frac{x}{x_*} = \frac{x\alpha}{\ln (N_*/N_0)}$$

where x_* is the critical length of an avalanche. The following is the total number of electrons in an avalanche chain of length x:

$$\frac{x}{x_*} N_*$$

or with (3.3)

$$N_e = \frac{16\,\pi\varepsilon_0 u_T\, v}{e} t \tag{3.4}$$

where t is time. It follows from (3.3) and (3.4) that

$$a = \frac{16\,\pi\varepsilon_0 u_T\, v}{e} \tag{3.5}$$

The mean avalanche-chain current is

$$\langle I^* \rangle = \frac{1}{t_*} \int_0^{t_*} I^*(t)\, dt = \frac{ev_-}{\delta} \frac{N_*}{\ln (N_*/N_0)} \tag{3.6}$$

where $I^*(t)$ is the instantaneous current in a growing avalanche.

Then we get for τ from (3.2), (3.3), (3.5), and (3.6) that

$$\tau = \left(\frac{e\tau^*}{16\pi\varepsilon_0 u_T\, v\gamma}\right)^{1/2} \ln A, \quad A = \frac{I_* \delta e\alpha}{16\pi\varepsilon_0 u_T\, i_0 \tau^* v_-} \tag{3.7}$$

4. Comparison with Experiment. This model and the calculated τ allow us to explain the available experimental evidence.

The τ for air at E around 10^5 V/cm and $\delta < \delta_0$ increase rapidly as δ is reduced, while δ has little effect for $\delta > \delta_0$. Some of the chains reach the anode within τ for $\delta < \delta_0$, while I_* is attained before any chain reaches the anode if $\delta > \delta_0$, so τ is independent of δ. This is confirmed by (3.7), since δ appears within the logarithm and has no marked effect on τ.

It has been shown [7] that $\delta_0(E) \approx 2.7 \cdot 10^4/E$ (curve 1 in Fig. 1). Our model gives the same relation between δ_0 and E, as it implies $\delta_0 = v\tau$. The $\tau(E)$ for air at 760 torr and $80 < E < 140$ kV/cm is $\tau(E) \approx$

$0.12E^{-3/2}$ [5] for copper electrodes (curve 2 in Fig. 1). If $v \approx v_- = 3.3 \cdot 10^6 (E/p)^{1/2}$ [15], we get for atmospheric pressure (with $v/v_- \approx 2$) that $\delta_0 \approx 2.7 \cdot 10^4/E$, i.e., as in [7].

To derive the theoretical $\tau(E)$ we need to know $U_T(E/p)$ and $\gamma(E/p)$. We have $U_T = 0.3(E/p)^{2/3}$ [14] for E/p of 10-1000 V/cm·torr in nitrogen. For air and copper electrodes at E/p of 50-100 V/cm·torr we have [16] $\gamma \propto (E/p)^{1.6}$. As $v \sim (E/p)^{1/2}$, substitution for U_T, v, and γ in (3.7) gives $\tau \sim E^{-1.4}$ for p = const. The power of E agrees satisfactorily with experiment because $\tau \sim E^{-3/2}$.

It is difficult to verify these calculated τ quantitatively because γ is very much dependent on the surface state of the cathode, and we also do not know the balance between the ionic and photon components of the γ of [16]. We assume $\gamma \approx 10^{-4}$ [12, 16], $\tau_* = 4 \cdot 10^{-9}$ sec [12], $v \approx 10^8$ cm/sec [8], and $U_T \approx 5$ eV [14] for p = 760 torr and $E \approx 10^5$ V/cm in order to estimate τ. Also, $A \approx 10^5$ for the conditions of [5], i.e., $\ln A \sim 11.5$. Then $\tau = 10^{-9}$ sec, which agrees satisfactorily with the measured value [5].

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