15. R. E. Bellman and R. Kalaba, Quasilinearization and Nonlinear Boundary Problems [Russian translation], Mir, Moscow (1968).
16. A. A. Samarskii and E. S. Nikolaev, Methods for Solution of Grid Equations [in Russian], Nauka, Moscow (1978).
17. J. J. Lowke, A. V. Phelps, and B. W. Irwin, "Predicted electron transport coefficients and operating characteristics of CO_2–N_2–He laser mixtures," J. Appl. Phys., 44, No. 10 (1973).
18. R. S. Galeev, "Calculation of a steady-state glow discharge in a CO_2–N_2–He gas mixture," in: Mathematical Modeling in Physical Gas Dynamics [in Russian], Kazan. Inst., Kazan' (1985).

FORMATION OF AN ELECTRON BEAM-INDUCED SPARK DISCHARGE AT MINIMAL VOLTAGES

A. A. Aliverdiev, A. Z. Éfendiev, and K. A. Éfendiev

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Entire monographs [1, 2] have already been dedicated to study of electron beam-induced spark discharges in gases. However, some features of the phenomenon remain insufficiently studied. In particular, it is not clear in what manner the discharge forms at minimal voltages. This question will be considered in the present study.

Studies were performed in technically pure nitrogen and air at atmospheric pressure. A beam of electrons with 1-MeV energy was injected into the gas chamber perpendicular to the electric field. The length of the discharge gap d = 0.4 cm, with a discharge capacitance of 0.25 μF, and brass electrode diameter of 2 cm. The lower traces of Fig. 1 show typical oscillograms of discharge current vs time in technically pure nitrogen (a) and air (b), while the upper traces are the electron beam pulse. Time scale is 1 μsec/division. Values of electron flux intensity P_e, dependent discharge combustion voltage U_{dd}, electron concentration in the discharge gap n_e for the steady-state period of the independent discharge, combustion voltage of the quasisteady-state discharge U_{qd}, and spark discharge formation time t_f, measured from the moment of irradiation until appearance of the spark for an active external circuit resistance of 7575 Ω and electron beam pulse duration t_{ep} of 0.5 μsec are presented in Table 1. Similar data for air at an active resistance of 45,075 Ω and electron pulse durations of 0.5 and 1.5 μsec are given in Table 2. It is evident that the values of U_{dd}, n_e, U_{gd}, and t_f depend (for other conditions equal) on R and t_{ep}. This is controlled by the number of ionization acts and circuit time constant. Upon development of the independent discharge the voltage in the discharge circuit is redistributed. The value of n_e can be calculated from the condition $n_e = I/Sq_ev_e$, written in the form

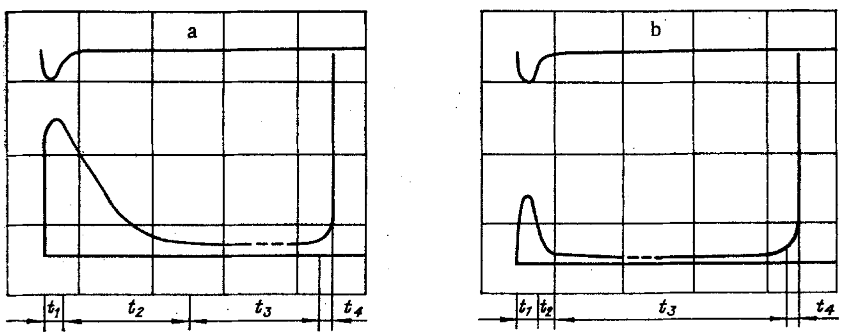

Fig. 1

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TABLE 1

$P_e \cdot 10^{-16}$, $1/(cm^2 \cdot sec)$	U_{dd}, kV	$n_e \cdot 10^{-10}$, cm^{-3}	U_{qd}, kV	t_f, msec
		Nitrogen		
1	4,4	6,1	5,0	0,10
2	3,0	23,4	4,8	0,125
5	3,0	23,4	4,8	0,15
10	1,1	136,3	4,8	0,15
20	0,8	201,4	4,8	0,15
50	0,8	201,4	4,8	0,15
		Air		
1	7,9	2,7	8,6	0,013
2	6,0	8,0	7,6	0,032
5	4,1	16,1	6,4	0,10
10	3,0	31,7	6,3	0,10
20	2,4	46,0	6,3	0,10
50	2,4	46,0	6,3	0,10
125	1,1	134,5	6,3	0,10

TABLE 2

$P_e \cdot 10^{-16}$, $1/(cm^2 \cdot sec)$	U_{dd}, kV	$n_e \cdot 10^{-10}$, cm^{-3}	U_{qd}, kV	t_f, msec
		Electron beam pulse duration 0.5 μsec		
1	8,0	1,2	9,5	0,004
2	5,0	3,6	7,7	0,080
5	3,0	12,6	8,7	0,015
10	2,7	14,8	9,0	0,010
20	2,0	21,9	8,9	0,015
50	0,2	284,9	8,9	0,015
		Electron beam pulse duration 1.5 μsec		
1	2,8	7,8	6,3	0,12
2	2,3	11,1	6,3	0,12
5	1,6	17,8	6,3	0,10
10	1,1	29,8	6,4	0,10
20	0,5	70,1	6,4	0,10
50	0,5	70,1	6,4	0,10

$$n_e = U_R d / R S q_e b_e (U_0 - U_R),$$

where I is the current flowing in the circuit, v_e is the electron drift velocity, U_R is the voltage drop across the active resistance, S is the electrode area, q_e and b_e are the charge and mobility of the electron, U_0 is the voltage across the discharge capacitance. U_R is determined with the oscilloscope.

The dynamics of discharge development can be divided into four stages:

– the dependent discharge caused by the presence of external ionization (time interval t_1);

– plasma decay (time interval t_2);

– quasisteady-state discharge (time interval t_3);

– transition to spark-type discharge (time interval t_4).

In the first stage a gas-discharge plasma develops within the discharge gap. As a result of electrical drift electrons depart from the plasma to the anode. Hence a steady-state discharge in this first stage is possible only when electron removal is compensated by secondary processes in the discharge gap. We will consider this process in more detail. In air and nitrogen at atmospheric pressure for a field intensity E_0 the shock ionization coefficient α is small (for $E_0 < 15.2$ kV/cm in air $\alpha < 0.02584$ cm^{-1}, while in nitrogen $\alpha <$ 0.06612 cm^{-1} [3]). Therefore, avalanche electron multiplication in the discharge gap is possible when the excess positive ion concentration Δn_i reaches a certain value, which can be determined from Poisson's equation, knowing the functional dependence $\alpha/p = f(E_{ef}/p)$, where $E_{ef} = E_0 + \Delta E$ is the effective field intensity, $E_0 = U_{dd}/d$, ΔE is the field intensity caused by the presence of Δn_i, and p is gas pressure. An evaluation performed with experimental data on the dependence $\alpha/p = f(E/p)$ in [3] showed that avalanche electron multiplication in the discharge gap at $E_0 \le 10$ kV/cm is possible when the excess positive ion concentration reaches the order of $4 \cdot 10^{10}$ cm^{-3} or more. It was assumed that positive ions are uniformly distributed through the discharge gap. The process of shock ionization in the effective field leads to accumulation of excess positive space charge in the cathode region, and upon satisfaction of the condition

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

(where ℓ_c is the length of the cathode region, γ is a generalizing coefficient, considering all "γ-processes" at the cathode [4]), the discharge achieves steady state. Thus, the time for establishment of the steady state for minimal voltages increases significantly from the case considered in [1]. Judging from the experimental n_e values (Tables 1 and 2), it may reach the order of or exceed the electron transit time through the discharge gap.

After passage of the electron beam plasma decay occurs. In the cathode region the excess positive ion concentration in the steady state of the dependent discharge Δn_{ic} is approximately an order of magnitude (or more) greater than the charged particle concentration in the discharge gap, as can easily be proved from the balance of discharge currents, written in the form

$$\Delta n_{ic}/n_e = \left[v_e - v_{ec}\exp\left(-\int_0^{l_c} \alpha(x)\,dx\right) - v_{ic}\right] \Big/ v_{ic},$$

where v_{ec} and v_{ic} are drift velocities of electrons and positive ions in the cathode region (the balance is written without consideration of negative ion currents and in the absence of additional anode region voltage drop). The presence of Δn_{ic} leads to a situation where after completion of the electron beam the total time of joint stay of electrons and positive ions in the discharge gap (because of departure of electrons produced by shock ionization in the cathode region) significantly exceeds the electron transit time through the discharge gap. This leads to an increase in recombination processes. The discharge current decreases and the voltage across the discharge gap increases. In air, aside from recombination of electrons and positive ions, a significant role is played by the process of electron attachment [3] (at $E_0 \simeq 10$ kV/cm the attachment coefficient is greater than α [5]), so that after the electron beam is finished the discharge current falls more abruptly.

The drop in current continues until recombination processes are compensated by ionization ones, i.e., at $n_e = \alpha v_e/\beta$ (where β is the recombination coefficient) a quasisteady independent discharge develops.

It follows from the experimental data (Tables 1 and 2) that for electron flux intensities greater than $5 \cdot 10^{16}$ 1/(cm$^2\cdot$sec) the spark discharge formation time remains constant. This indicates that a significant role in spark discharge formation is played by processes occurring in the third stage of the discharge. The combustion voltage of the quasisteady discharge in air is higher than in nitrogen, while the current is lower (in air, of the order of 7 mA, in nitrogen, 26.6 mA), while the spark formation time in air is less than in nitrogen. With increase in combustion voltage of the quasisteady discharge the spark formation time decreases in both gases.

Qualitatively, these principles do not differ from already known ones [1, 2]; therefore they may be interpreted in an analogous manner. The transition of the quasisteady discharge to a spark is apparently related to development of electrode spots with subsequent extension of "streamer" channels [6]. One possible mechanism of cathode spot development is dielectric breakdown of any sort of dielectric inclusions on the cathode surface after charging by positive ions to field intensities at which autoemission is possible [1, 2].

The electric field intensity for charging of a dielectric inclusion is related to the discharge current density by the expression [2]

$$\varepsilon\varepsilon_0 E(t) = \exp\left[-\left(\int_0^t \sigma dt\right)\Big/\varepsilon\varepsilon_0\right]\int_0^t i(t)\exp(\sigma t/\varepsilon\varepsilon_0)\,dt, \tag{1}$$

where ε and ε_0 are the relative and absolute dielectric constants of the dielectric, σ is the conductivity of the dielectric, i is the discharge current density. With consideration of the fact that autoemission processes in the dielectric occur at field intensities of the order of 10^6 V/cm, the time required for development of cathode spots given by Eq. (1) for nitrogen is of the order of microseconds, so that the channel growth velocity v_c for field intensities in the discharge of 12-12.5 kV/cm are of the order of $2 \cdot 10^3$-$4 \cdot 10^3$ cm/sec. Such velocities are supported by the experimental fact that v_c depends significantly on field intensity in the discharge [1, 2]. For example [2], for nitrogen at E/p = 13.2 V/mPa, $v_c = 9 \cdot 10^4$ cm/sec, while for E/p = 8.5 V/mPa, $v_c = 10^4$ cm/sec. Naturally for values of E/p ≈ 0.9-0.94 V/mPa, as in the present experiments, v_c should be significantly smaller.

In air the discharge current is less than in nitrogen. This fact is apparently caused by electron attachment. Formation of negative ions leads to a series of consequences: decrease in discharge current density (due to decrease in the electron component) and effective field intensity within the discharge gap (due to anode screening by negative ions), increase in anode region voltage drop, and the probability of various electrochemical processes. Each of these factors may have a significant effect on the electrode spot formation process. Therefore, an indirect estimate of spot formation time and channel growth velocity is quite difficult. Nevertheless, judging from the data of Tables 1 and 2, the general principle of dependence of v_c on field intensity in the discharge is apparently maintained in air, too.

The processes occurring in the fourth stage of the discharge are, in our opinion, analogous to the process which occurs after a streamer bridges the discharge gap in single-avalanche breakdown [4].

LITERATURE CITED

1. Yu. D. Korolev and G. A. Mesyats, Autoemission and Explosive Processes in a Gas Discharge [in Russian], Nauka, Novosibirsk (1982).
2. Yu. I. Bychkov, Yu. D. Korolev, G. A. Mesyats, et al., Injection Gas Electronics [in Russian], Nauka, Novosibirsk (1982).
3. V. L. Granovskii, Electric Current in Gas. Steady-State Current [in Russian], Nauka, Moscow (1971).
4. J. Mick and J. Cregs, Electrical Breakdown in Gases [Russian translation], IL, Moscow (1960).
5. G. N. Aleksandrov, V. L. Ivanov, and V. E. Kizeveniper, Electrical Strength of External High-Voltage Insulation [in Russian], Énergiya, Leningrad (1969).
6. A. Z. Éfendiev and A. A. Aliverdiev, "Multichannel discharge in helium in an inhomogeneous field," Izv. Vyssh. Uchebn. Zaved., Radiofiz., 20, No. 8 (1977).