Properties of a space discharge excited by an electron beam of 10^{-5} sec duration

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A space discharge maintained by a fast-electron beam of 10^{-5} sec duration is investigated. Volt-ampere characteristics in CO_2+N_2 gas mixtures are obtained at different pressures and modes of energy delivery to the discharge volume. The conditions are found for which the space discharge is stable (does not become a spark discharge).

The investigation of space discharges in high-pressure gases is of interest in view of their utilization in gas lasers. Here the gas-discharge plasma is produced through the ionization of molecules by high-energy electron beams from high-voltage accelerators. The capabilities of such accelerators and the corresponding properties of the gas discharge depend strongly on the type of electron emitter that is employed.

Multi-point cold cathodes operating on the principle of explosive emission provided electron current pulses having durations from 10^{-8} to 10^{-6} sec.[1,2] In [3] more prolonged electron beams produced with the aid of heated cathodes were used for gas ionization. The aim of the present investigation has been to determine stable sparkless discharge regimes and to study their energy properties.

Figure 1 shows the experimental apparatus schematically. To produce an electron beam we used a sectional high-voltage accelerator with a gas-discharge electron source based on a plasmatron with a Penning tube.[4] The electron source can produce beams of practically any duration with controllable current density and is long-lived in the pulsed regime. This source also possesses an advantage over guns having a thermionic cathode in that it does not require a separate heating circuit at a high potential and can be fed from the active voltage divider that distributes the potential along the accelerating tube. The plastic tube was 45 cm long. A negative accelerating voltage of 250-kV amplitude was applied to the voltage divider by an Arkad'ev-Marks voltage pulse generator. The electron beam, of density $j = 10$ mA/cm^2 and 1.2×10^{-5} sec pulse duration was introduced into the gas gap through a 4×8-cm window made of 130-μm lavsan polyester film with mesh reinforcement. A 2-μF capacitor C applied a constant voltage to the discharge gap of the gas chamber 3. The electron beam ionized the gas, making the gap conductive. At sufficiently high electron densities ($n_e > 10^{12}$ cm^{-3}) the conduction mechanism of the discharge gap resembled that of a glow discharge.

The time dependence of the electron density is obtained from the balance equation of electrons in the positive column:

$$dn/dt=\psi-\beta n^2, \qquad (1)$$

where $\psi = j_b\langle\sigma\rangle/e$ is the rate of ionization by the fast-electron beam, j_b is the beam current density, e is the electron charge, $\langle\sigma\rangle$ is the mean cross section for ionization by fast electrons, and β is the recombination coefficient.

If $\psi = \text{const}$ and $E = \text{const}$ (i.e., C is large) the stationary discharge current density is obtained from

$$j_{st}=e\sqrt{\psi/\beta}\,v_-, \qquad (2)$$

and the characteristic time for establishing a stationary concentration is

$$\tau\sim1/\sqrt{\psi\beta}. \qquad (3)$$

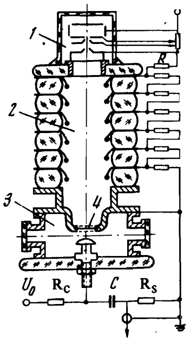

FIG. 1

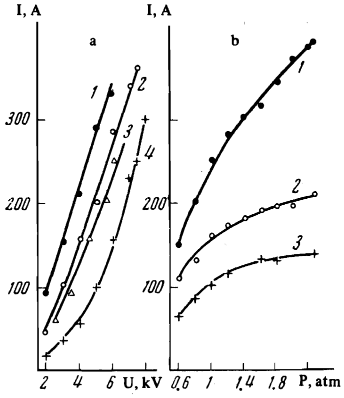

FIG. 2

FIG. 1. Schematic diagram of experimental apparatus. 1—plasma source of electrons, 2—accelerating chamber, 3—gas discharge chamber, 4—lavsan film window, R_C—charge resistance, R_S—shunt resistance.

FIG. 2. Dependence of discharge current on (a) gap potential and (b) pressure at constant beam current $I_b = 0.3$ A. (a) d = 0.9 cm, P = 1 atm, gas composition: 1—pure N_2, 2—CO_2+N_2 in 1:3 ratio, 3—CO_2+N_2 – 1:2, 4—pure CO_2; (b) d = 1.05 cm, E/P = 5 V/cm-Torr, gas composition: 1—pure N_2, 2—CO_2+N_2 – 1:3, 3—pure CO_2.

Thus the fluctuation of the beam current with a time constant smaller than or commensurable with τ has a weak effect on the discharge current. This was observed experimentally.

Figure 2a shows the volt-ampere characteristics for sparkless discharge regimes in the case of 1-atm gas pressure and 30 cm^2 active area of the cathode. The linear growth of the current as a function of the voltage is attributed to the growth of the drift velocity as E/P increases. The highest discharge current occurs in pure N_2 and decreases as the partial pressure of CO_2 is increased. This indicates that the recombination coefficient is higher in CO_2 than in N_2. For N_2 the recombination coefficient β, determined from the relation (1) for the known value of ψ and subject to the condition $dn/dt = 0$, equals 10^{-7} cm^3/sec. In CO_2 (curve 4) a slight deviation of the current growth from the linear rate is possible because of the attachment of electrons to CO_2 molecules.

Figure 2b shows the dependence of the discharge

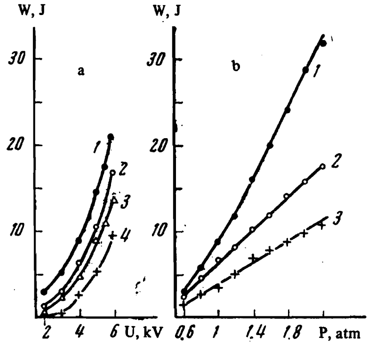

FIG. 3. Dependence of energy put into the gas by a single pulse (a) on voltage and (b) on pressure, at constant beam current $I_b = 0.3$ A. The conditions for the curves are the same as in Fig. 2.

current on the gas pressure at a constant value of E/P. The increase of the current with the pressure confirms that recombination is the main process causing the loss of electrons at pressures in the range of one or two atmospheres.

Figure 3 shows how the energy put into the gas, for different mixtures, depends on voltage and pressure. The specific energies are seen to reach 0.5–0.6 J/cm^3.

We also tested experimentally the region in which a space discharge exists. At fields up to 8 kV/cm in the cases of N_2 and CO_2 at atmospheric pressure the discharge is not self-maintained. At higher fields E ~ 8–11 kV/cm the nature of the space discharge is not changed, but after some tens or hundreds of microseconds a spark discharge occurs. The time lag of spark breakdown decreases sharply as the field is increased. It can be assumed that the formation of the spark channel is here associated with field distortion in the gap, caused by the space charge of positive ions in the course of recombination decay of the plasma. After the beam is terminated the density of electrons and ions in the positive column falls off with the time constant $\tau \sim 1/\beta n$. This obviously increases the thickness of the cathode fall as the result of charge separation, so that at certain low densities (~10^{11} cm^{-3} according to estimates) the field is enhanced near the cathode because of positive-ion space charge within a distance that is sufficient to satisfy the condition for Townsend breakdown. In this case the time lag of the spark channel will consist of two terms—the recombination time of the plasma and the formation time of the Townsend discharge; its order of magnitude can be ~10^{-4} sec.

With further increase of the field (E > 11 kV/cm) the spark breakdown is observed while the beam exists. In this case the mechanism of spark channel formation is apparently of a different nature and results from ionization instabilities in the plasma of the space discharge.[5,6]

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