Pulse discharges in gases under conditions of strong ionization by electrons

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A review is given of investigations of pulsed high-pressure volume discharges excited by fast-electron beams. The following topics are discussed: classification of discharges; methods for calculating the current-voltage characteristics; analysis of the optimal ways of depositing energy in the gas in the volume stage of the discharge; discharge instability mechanisms and the corresponding experimental observations; applications of discharges. The results are given of calculations of the electric field in the cathode and anode regions, and also in the discharge column in the case of a spatially inhomogeneous ionication of the gap. It is shown that a stable volume flow of the current in molecular gases in which the specific deposited energy is 0.1–1 J/cm^3 may be attained in a nonself-sustaining discharge and in a discharge with ionization multiplication. In both cases a spark channel appears in two stages: formation of spark-initiating centers in the form of plasma regions with a higher density near the electrodes is followed by growth of the spark channel from such initiating centers. In some cases the spark channel growth can be described by the available mathematical models. Discharges in mixtures of rare gases with halogen-containing compounds, when electrons are lost mainly by capture by complex molecules, are considered separately. Applications of volume discharges in laser pumping, switching of pulsed currents, plasma chemistry, etc., are described.

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CONTENTS

1. INTRODUCTION

a) General description of a discharge

The interest in gas discharges under conditions of strong volume ionization by an electron beam[2,3] is due to extensive applications of such discharges in high-power gas lasers, various types of current switches and interrupters, plasmotrons, etc. Such discharges differ from those with weak ionization[1] primarily because the conduction mechanism is similar to that in a glow discharge. At high gas ionization rates (exceeding 10^{16} cm$^{-3}\cdot$sec^{-1}) and high pressures (10^2–10^4 Torr) the electric field is enhanced in narrow electrode regions but remains practically constant in the discharge column (Fig. 1). The potential drops in the cathode and anode regions are then slight compared with the total voltage applied to the discharge gap. Thus, the rate of gas ionization in the discharge column effectively determines the gap conductance and, because the use of electron beams ensures high ionization rates, the discharge

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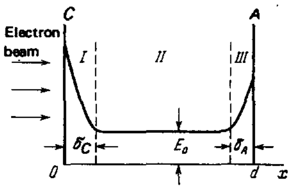

FIG. 1. Qualitative distribution of the field between electrodes.

current density can be high.

Pulsed volume discharges with gas ionization by electron beams[2,3] have been used initially to pump CO_2 lasers[4,6,7] and to switch pulse currents.[3,5,8,9] Detailed investigations have been made of discharges excited by electron beams in the form of pulses of less than 10^{-7} sec duration.[6-10] Studies of quasisteady and steady discharges at atmospheric pressure are reported in a paper by Velikhov *et al.*[11]

Volume discharges under conditions of strong ionization by electrons have a number of remarkable properties. Firstly, it is possible to achieve nonself-sustaining volume discharges at gas pressures of tens of atmospheres. This provides means for independent control of the discharge-initiating voltage, discharge current, and discharge column area; the discharge current is controlled by altering the current in the fast-electron beam. Secondly, in the case of strong inhomogeneity of the ionization of a bulk gas by an electron beam the electric field in the discharge column becomes strongly distorted and this facilitates the stable (~10^{-9} sec) formation of a spark channel. Thirdly, the use of electron beams in the form of short pulses makes it possible to initiate volume discharges with ionization multiplication of the pulse glow discharge type when the initial voltage across the gap is less than the breakdown value. The role of the electron beam is to create, at the selected moment, a plasma of the required density inside the gap. This method improves greatly the homogeneity of the discharge because in the conventional systems with discharge initiation by ultraviolet radiation it is necessary to apply initially a voltage above the breakdown value. Moreover, it is then easy to initiate a pulse glow discharge in the subnormal, normal, and anomalous regions. These principal properties of the discharges in question are responsible for their extensive applications.

b) Main equations

If we consider only the volume stage and ignore the discharge stability, we find that the principal processes in a discharge can be described by the equations of continuity and by the Poisson equation for the electric field. In the one-dimensional case we have

$$\frac{\partial n_-}{\partial t}-\frac{\partial n_-v_-}{\partial x}=\alpha v_- n_- -\beta n_- n_+ +\Psi+q, \quad (1)$$

$$\frac{\partial n_+}{\partial t}+\frac{\partial n_+v_+}{\partial x}=\alpha v_- n_- -\beta n_- n_+ +\Psi, \quad (2)$$

$$\frac{\partial E}{\partial x}=-\frac{e(n_+-n_-)}{\varepsilon_0}, \quad (3)$$

$$v_-=\mu_- E, \quad (4)$$

$$v_+=\mu_+ E. \quad (5)$$

These equations have to be supplemented by the initial and boundary conditions

$$n_-(0,\ t)\,v_-(0,\ t)=\gamma n_+(0,\ t)\,v_+(0,\ t), \quad (6)$$

$$n_+(d,\ t)=0, \quad (7)$$

$$\int_0^d E(x)\,dx=u_0. \quad (8)$$

The following notation is used in Eqs. (1)–(8): n_- and n_+ are the electron and ion densities; v_-, v_+, μ_-, and μ_+ are the drift velocities and mobilities of electrons and ions; E is the electric field intensity; u_0 is the potential difference between the electrodes; d is the length of the gap; Ψ is the rate of ionization of the investigated gas by the beam electrons; q is the rate of thermalization of the fast electrons; γ is the coefficient of secondary electron emission from the cathode; α and β are the impact ionization and recombination coefficients; ε_0 is the permittivity; e is the electron charge.

The diffusion of charged particles is ignored in Eqs. (1)–(5) since it is usual to consider the case of high pressures when this process is negligible. The volume losses of electrons and ions are governed by recombination. This is true, for example, of a discharge in nitrogen. In electronegative gases and in mixtures containing these gases we may expect a considerable loss of electrons due to the capture by neutral molecules. We shall consider the role of capture in some specific cases but the majority of the results will be given for the gases in which this process does not occur.

A rigorous allowance for the gas ionization by electrons would require supplementing the system (1)–(8) by the transport equation describing the motion of fast electrons in matter and considering two subsystems in a self-consistent manner: these subsystems are the electrons and ions in the gas discharge, on the one hand, and the beam electrons, on the other. The self-consistency involves allowance for the fact that both Ψ and q depend on the fast-electron flux, which is influenced by the field E, and, consequently, by the value of (n_+-n_-). However, in this case the problem becomes highly complex and the solutions are no longer easy to understand. Therefore, we shall assume that Ψ and q are governed by the beam electrons and by the external field E. The order-of-magnitude relationship is $q/\Psi \sim \langle\varepsilon\rangle/\langle T\rangle$, where $\langle\varepsilon\rangle$ is the average energy lost in the formation of a single electron–ion pair and $\langle T\rangle$ is the average energy of the beam electrons. The function $\Psi(x)$ is found from

$$\Psi(x)=\frac{j_b D(x)}{e\langle\varepsilon\rangle}, \quad (9)$$

where j_b is the current density of the injected electron beam; x is the distance from the cathode; $D(x)$ is the distribution of the energy losses in the gas (per one electron). The distribution $D(x)$ depends on the initial energy of the beam electrons and also on the electric field in the gas-filled discharge gap.[12-14]

A calculation of the energy lost by fast electrons in a gas-filled gap reduces to the problem of their transport in a gas allowing for the electric field, which can be solved by the multistep method.[14,15] The influence of a foil, which separates the acceleration gap and the gas-filled region, is allowed for by performing the calculations in two stages.[14] In the initial stage the transport of electrons across the foil is considered and then an analysis is made of the motion of electrons in an infinite gaseous medium in which the electric field is uniform. The results of studies of the influence of the foil material and thickness, and of the electric field in the gas on the energy distribution $D(x)$ in nitrogen are plotted in Fig. 2. The energy distribution behind a sufficiently thick foil is nearly linear. The electric field redistributes considerably the energy D improving the homogeneity of the distribution.

Another fairly widely used method of calculating the ionization rate involves numerical simulation of the passage of fast electrons through a dense medium; this simulation is carried out by the Monte Carlo method. The method is time-consuming and requires sophisticated computer facilities, but its advantage is the ability to solve the problem allowing for the three-dimensional spatial distribution. Examples of the Monte Carlo calculations can be found in Refs. 16 and 17.

2. DISTRIBUTION OF THE ELECTRIC FIELD IN A DISCHARGE GAP

a) Cathode region

We shall initially assume that the ionization of the gap is longitudinally homogeneous. The qualitative form of the field distribution between the electrodes is similar to that in the weak ionization case[1] (see Fig. 1). In the discharge column (II) the field is homogeneous, the space charges of electrons and ions equal and opposite, and ionization is balanced out by volume recombination. In the cathode (I) and anode (III) regions the field intensity is higher than in the column because of predominance of the space charges of ions and electrons, respectively.

The processes in the cathode region ensure the supply of electrons to the discharge column. If the field in the cathode region is insufficient for impact ionization, the length of this region δ_C and the field intensity on the cathode E_C are found from[1]

$$\delta_C = \frac{\mu_- E_0}{\sqrt{\beta\Psi}}, \tag{10}$$

$$E_C = E_0 \sqrt{\frac{e\mu_-^2}{\varepsilon_0 \beta \mu_+}}. \tag{11}$$

Since the potential drop in the cathode region is $u_C \approx E_C\delta_C/2$, it follows from Eqs. (10) and (11) that there is a reduction in δ_C and U_C on increase of Ψ, which is an important property of discharges occurring under conditions of strong ionization by electrons. Consequently, we usually have $\delta_C \ll d$ and $U_C \ll u_0$, i.e., practically the whole of the potential drop is concentrated in the discharge column and, consequently, the field in the column is $E_0 \approx u_0/d$. This conclusion applies also when impact ionization by electrons takes place in the cathode region.

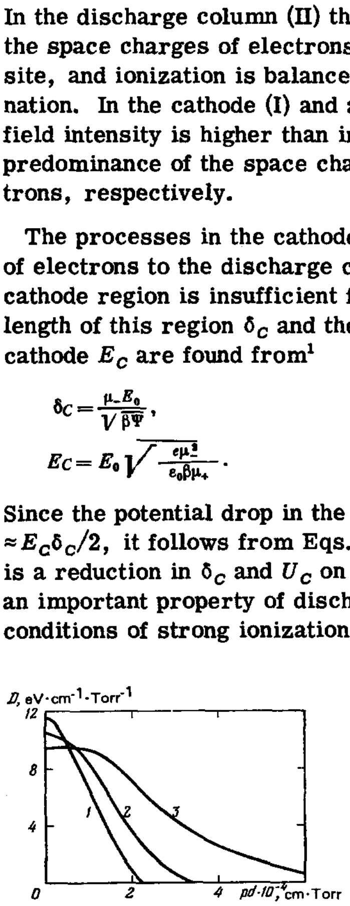

FIG. 2. Distribution of the energy lost by fast electrons in nitrogen after passage through aluminum foil 50 μ thick. Electron energy in front of the foil 200 keV. E/p($V \cdot$cm$^{-1} \cdot$Torr^{-1}): 1) 0; 2) 2.5; 3) 5.

There have been many studies of the cathode region of discharges subjected to high electric fields and exhibiting impact ionization.[5,8-12,18-22] It has been found that even when the rate of external ionization is relatively low,[11] the electric field is not screened by the cathode layer. This is why large currents can pass through a nonself-sustaining volume discharge.[10] Analytic expressions for the field intensity at the cathode and for the cathode potential drop are obtained in Ref. 10, where a linear dependence of $E(x)$ is assumed. This problem is solved in Ref. 12 on the assumption that the current in the cathode region is carried by ions. In both cases the gas ionization by the beam electrons is ignored and, therefore, the scaling laws apply as in the case of a glow discharge. The values of E_C, U_C, and $p\delta_C$ depend on the ratio of the current density to the square of the gas pressure j/p^2. This is confirmed by the experimental results[20] plotted in Fig. 3.

Numerical calculations[19,22] indicate that when the field in the column is weak, there is a transition region between the column and the layer where ionic conduction predominates; in this layer the creation of electrons by an external beam plays an important role. The existence of a transition region is characteristic of nonself-sustaining discharges maintained by an electron beam. However, in most cases this does not alter significantly the estimates of the cathode layer parameters obtained on the basis of the theory of glow discharges, because the transition region makes no significant contribution to the cathode potential drop.

The results considered above apply to steady discharges. When the electron beam is switched on and off, the distribution of the electric field in the cathode region varies with time. The solution of the transient problem of establishing the cathode drop after the application of a voltage to the gap can be found in Refs. 21 and 22.

b) Anode region

The length of the anode region and the electric field on the anode in a steady discharge are given by the fol-

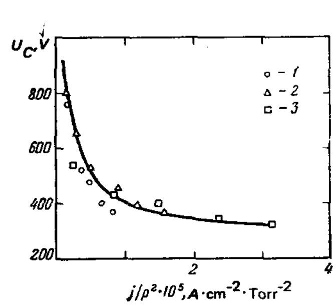

FIG. 3. Experimental dependence of the voltage drop across the cathode layer on the parameter j/p^2 for discharges in a CO_2:N_2:He = 4:1:12 mixture at pressures p(Torr): 1) 450; 2) 300; 3) 150.

lowing relationships which apply when there is no impact ionization:

$$\delta_A = \frac{\mu_+ E_0}{\sqrt{\beta\Psi}}, \tag{12}$$

$$E_A = E_0 \sqrt{1 + \frac{e\mu_+(\mu_+ + \mu_-)}{\varepsilon_0 \beta \mu_-}}. \tag{13}$$

In high anode fields when the impact ionization process can no longer be ignored, we can still obtain fairly simple expressions by assuming a linear rise of the field in the anode region[23] and using the relationship between the impact ionization coefficient α, pressure, and field E

$$\frac{\alpha}{p} = A e^{BE/p}, \tag{14}$$

where $E/p \leqslant 40$ V · cm^{-1} · Torr^{-1}, $A = 3.3 \times 10^{-7}$ cm^{-1} · Torr^{-1}, and $B = 0.26$ cm · Torr · V^{-1} for nitrogen. If

$$\alpha_A \delta_A \ll \frac{B(E_A - E_0)}{p} = \ln \frac{\alpha_A}{\alpha_0}$$

we can find δ_A and E_A from the system

$$E_A^2 = E_0^2 + \frac{e\Psi\delta_A^2(\mu_+ + \mu_-)}{\varepsilon_0 \mu_+ \mu_-}, \tag{15}$$

$$\delta_A = \frac{\mu_+ E_0}{\sqrt{\beta\Psi}} \left[1 + \frac{pE_0\alpha_A(\mu_+ + \mu_-)}{\sqrt{\beta\Psi}\, B(E_A - E_0)}\right]^{-1}. \tag{16}$$

If $\alpha_A = 0$, Eqs. (15) and (16) transform to Eqs. (12) and (13). It follows from the dependence of E_A on E_0 (Fig. 4) that an increase in the field E_0 and the appearance of impact ionization lowers the ratio E_A/E_0 because the field due to the negative charge of electrons is compensated by the positive charge of ions. At atmospheric pressure the impact ionization in the anode region begins to play a role in an electric field E_0 exceeding 4×10 V/cm, i.e., under typical nonself-sustaining discharge conditions.

c) Electric field in a column under inhomogeneous ionization conditions

The electric field in the discharge column remains constant along its length only in the case of homogeneous ionization of the bulk by electrons $[\Psi(x) = \text{const}]$ and in the absence of thermalized electrons ($q = 0$). The steady-state distribution of an electric field under inhomogeneous ionization conditions has been analyzed qualitatively.[5,12,17,24] A quantitative allowance has also been made for the influence of impact ionization and thermalized electrons on the field distribution in a discharge column.[25] If we ignore the thermalized electron current, i.e., if we assume that $n_+ \approx n_-$, $q \ll \Psi$, we find that the field distribution in the column is given implicitly by

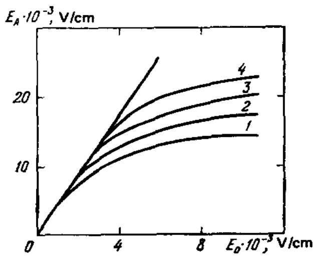

FIG. 4. Field intensity at the anode for discharges in nitrogen ($p = 760$ Torr) plotted as a function of the field in the column.[23] Ψ(cm^{-3}·sec^{-1}): 1) 10^{16}; 2) 10^{17}; 3) 10^{18}; 4) 10^{19}. The straight line corresponds to the assumption that $\alpha = 0$.

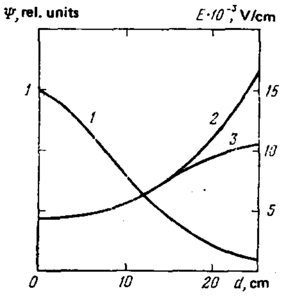

FIG. 5. Field distribtuion in the discharge gap for inhomogeneous ionization and $E_{min} = 4$ kV/cm: 1) $\Psi(x)$; 2) $E(x)$ without allowance for impact ionization; 3) $E(x)$ with allowance for impact ionization.

$$e\Psi(x) + \alpha(E)\, j = \frac{\beta j^2}{e\mu_-^2 E^2}. \tag{17}$$

We shall bear in mind that in the region of minimum field E_{min} near the cathode we can ignore impact ionization. Then, Eq. (17) can be written in the form

$$\frac{\Psi(x)}{\Psi(x_{min})} = \frac{\alpha(E)\mu_- E_{min}}{\sqrt{\beta\Psi(x)}} = \frac{E_{min}^2}{E^2(x)}. \tag{18}$$

Figure 5 shows an example of the field distribution across the gap for the case of ionization of nitrogen at atmospheric pressure by 150 keV electrons crossing an aluminum foil 50 μ thick.[25] In the region of weaker ionization there is an increase in the electric field and in the specific power dissipated per unit volume of the gas.

Another reason for the distortion of the field in a discharge column is the presence of thermalized beam electrons, which produce an uncompensated space charge in the gap. We shall now consider the influence of thermalized electrons on the field distribution in the case of short discharge times when $t < (\beta\Psi)^{-1/2}$. If the range of electrons in a gas is $R \ll d$, the field created by thermalized electrons in the course of their injection can be found from

$$E_t \approx \frac{j_b R t}{2\varepsilon_0 d}, \tag{19}$$

where j_b is the current density of the beam of the injected electrons. For example, if $R/d = 0.5$, $j_b = 1$ A/cm^2, and $t = 10^{-8}$ sec, this field is $E_t \approx 3 \times 10^4$ V/cm.

If $R > d$, it follows from the system (1)–(5) that the space charge of electrons ρ is found from[25]

$$\frac{\partial\rho}{\partial t} + \frac{e\mu_-\Psi\rho t}{\varepsilon_0} = eq + e\mu_- E t \frac{\partial\Psi}{\partial x}. \tag{20}$$

It is clear from Eq. (20) that a space charge is established by thermalized electrons and a gradient of the rate of carrier generation. We shall ignore the influence of the gradient $\partial\Psi/\partial x$ on ρ and obtain

$$\rho = eqt \int_0^1 \exp[at^2(1 - y)]\, dy, \tag{21}$$

where $a = e\mu_-\Psi/2\varepsilon_0$. The value of ρ at a time $t = \sqrt{\varepsilon_0/e\mu_-\Psi}$ reaches its maximum value

$$\rho_{max} = \frac{eq}{2\sqrt{a}} \tag{22}$$

corresponding to the maximum field

$$E_{t,\max} = \frac{j_b \alpha}{4R\varepsilon_0 \sqrt{a}}. \quad (23)$$

The initial rise of the field after beam injection is due to the accumulation of electrons and the subsequent fall is due to an increase in the plasma conductivity and in the rate of dispersion of the space charge. For $j_b = 1\ A/cm^2$, $d/R = 1$, $\mu = 5\times 10^2\ cm^2 \cdot V^{-1} \cdot sec^{-1}$, and $\Psi = 10^{21}\ cm^3/sec$, we have $E_{t,\max} = 4.5\times 10^3$ V/cm. These estimates indicate that the influence of thermalized electrons on the electric field is significant when the injected electron current densities are of the order of $1\ A/cm^2$ or higher.

3. DISCHARGES WITHOUT IONIZATION MULTIPLICATION

a) Classification

It follows from the above analysis that in the case of strong homogeneous ionization of a gas the major part of the discharge gap is occupied by a column in which the ion and electron densities are $n_+ \approx n_-$, where $dn_\pm/dx = 0$, and the electric field is $E_0 \approx u_0/d$. These assumptions simplify greatly the calculation of the current-voltage characteristics of the discharge, because—bearing in mind the low ion mobility—the total current is $j = env$ and the electron density is found from Eq. (1):

$$\frac{dn}{dt} = \alpha v n - \beta n^2 + \Psi; \quad (24)$$

Here and later, we shall assume that $n_- = n$, $v_- = v$, $\mu_- = \mu$, and $E_0 = E$. A nonself-sustaining discharge or a discharge without ionization multiplication occurs if $\alpha v/n \ll \beta$. Then, solving Eq. (24), we obtain

$$n = \sqrt{\frac{\Psi}{\beta}}\, \mathrm{th}\sqrt{\beta\Psi}\, t_{st}, \quad (25)$$

where $t_{st} = 1/2\sqrt{\beta\Psi}$ is the characteristic time of the rise of the concentration to its steady-state value. Depending on the relationship between the duration of the electron beam pulses t_b and the time t_{st}, a discharge may be transient ($t_b < t_{st}$) or quasitransient ($t_b \geq t_{st}$).

Historically the first volume discharge excited by an electron beam was observed in a transient nonself-sustaining form in nitrogen.[2,3] Detailed experimental studies of this discharge were made later.[5-10,26,27] The results obtained confirmed the above theory: for example, in agreement with the theory, the current-voltage characteristics were found to be linear because $j = e\Psi t_b \mu E$ (Fig. 6). Since $\mu \propto p^{-1}$ and $\Psi \propto p$, the current amplitude for constant values of E and t_{st} should be independent of the gas pressure (Fig. 6).[5,8] The linear dependence of the discharge current on the beam current was also confirmed experimentally.

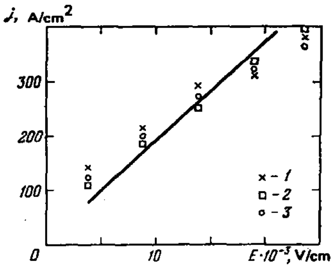

FIG. 6. Current-voltage characteristic of a discharge in nitrogen ($t_b = 2\times 10^{-8}$ sec, $j_b = 10$ A/cm²) obtained at various pressures[5] p (atm): 1) 4; 2) 7; 3) 10.

Experimental studies of quasisteady discharges have also been made.[28-33] One of the tasks in these studies was to achieve long discharge durations (10^{-4}–10^{-3} sec), because this made it possible to change a gas in a cell during one pulse and thus make the discharge continuous. The possibility of initiating continuous discharges at atmospheric pressure was demonstrated by Velikhov *et al.*[11] The main results on continuous discharges were reported in a review by Velikhov *et al.*[34]

b) Energy parameters of nonself-sustaining discharges

The energy deposited in a gas is an important parameter of systems based on volume discharges. In the case of a transient nonself-sustaining discharge the energy is mainly dissipated in a gas in the course of recombination decay of the plasma. The specific energy can then be found from

$$W = \frac{e\mu E^2}{\beta} \ln\frac{n_0}{n_{cr}}, \quad (26)$$

where n_0 is the initial electron density and n_{cr} is the critical density at which the gap conduction process becomes ionic and the transfer of energy to the gas ceases.

We can thus see that practically the only way of increasing the deposited energy is to increase the electric field. However, in high fields E, discharges become self-sustaining and, therefore, unstable. The problem of the maximum energy that can be deposited in a gas under transient conditions has been investigated in detail.[10,21,26] The idea of selecting the discharge parameters is based on the fact that the field across the discharge gap should decrease during the recombination decay of the plasma so as to ensure that the discharge is still nonself-sustaining.[35] In practice, this is done by selecting the external circuit elements in accordance with the geometry of the discharge gap and the electron beam characteristics. A method for calculating the energy characteristics[21,35] has been confirmed by experimental results, which indicate that in a time of 10^{-7}–10^{-6} sec the specific energy deposited in CO_2:N_2 mixtures can reach $0.5\ J\cdot cm^{-3}\cdot atm^{-1}$.

In the quasisteady case a discharge gap is usually subjected to a voltage known to ensure that the discharge is nonself-sustaining. The energy supplied to the gas can be increased, retaining the stability of the volume discharge, by increasing the field, fast-electron beam current, and discharge duration. Certain special features associated with the contraction of discharges are encountered in dealing with the problem of supplying the maximum energy to a unit volume of the gas.[29,30,34,36] Typical energy characteristics of a discharge excited by an electron beam in the form of 10^{-4} sec pulses are shown in Fig. 7 (Ref. 33). The curves are plotted for voltages under which the discharge does not become a spark channel. In higher fields, sparking is observed and the breakdown delay time may be considerably greater than the electron-beam current dura-

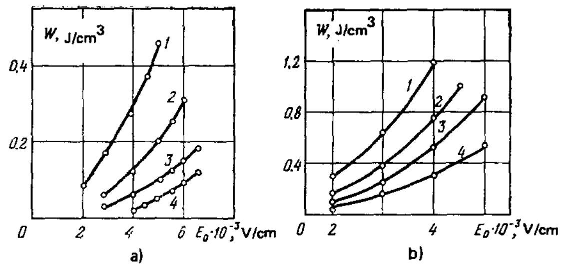

FIG. 7. Specific energy deposited in a discharge plotted as a function of the electric field intensity in two densities of the beam current (mA/cm^2): a) 0.14; b) 1.4. 1) $CO_2:N_2=0:1$; 2) 1:4; 3) 1:1; 4) 1:0.

tion[30] but it decreases on increase of the voltage. We can see from Fig. 7 that the discharge stability is influenced not only by the specific energy but also by the electric field. For example, in the case of nitrogen with $j_b=0.14\times10^{-3}$ A/cm^2 the attained field intensity is $E+5\times10^3$ V/cm and the specific energy is $W=0.46$ J/cm^3, whereas in the field $E=4\times10^3$ V/cm an increase in the beam current to 1.4×10^{-3} A/cm^2 increases the specific energy deposited in the gas to 1.2 J/cm^3. It follows that for each field there is a certain energy which can be introduced into a gas for a given duration of an electron-beam pulse without initiating a spark channel. The question of maximum field intensities corresponding to various discharge current densities when the pulse duration is 0.8×10^{-3} sec is considered in Ref. 29. Figure 8 gives the relevant dependences, which demonstrate that lowering of the discharge initiation voltage and increase in the beam current can increase the maximum energy supplied to a unit volume of the gas.

Another way of increasing the maximum energy is to reduce the duration of a nonself-sustaining quasisteady discharge and increasing the current density. In this case the required effect is achieved by selecting the discharge time shorter than the time needed to form a spark channel.[37]

4. DISCHARGES WITH IONIZATION MULTIPLICATION

a) Characteristics of current flow

If the field applied to a discharge gap is sufficiently high and the condition for nonself-sustaining operation

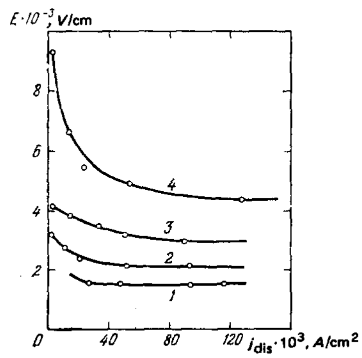

FIG. 8. Dependence of the maximum field intensity on the density of the discharge current in nitrogen ($t_b=0.8\times10^{-2}$ sec) at pressures p (Torr): a) 150; 2) 300; 3) 500; 4) 760.

is not satisfied, the process of impact ionization plays a significant role in the balance of charged particles in a discharge column. This makes the discharge excited by an electron beam similar to a self-sustaining volume discharge in which the initial electrons are created by ultraviolet radiation on the surface of a cathode or in the interior of a gap.[38] A characteristic feature of such discharges is that their formation and maintenance are affected strongly by elements of an external electric circuit because an increase in the current due to the ionization multiplication process is accompanied by a drop of the voltage across the external elements and a reduction of the field in the plasma. This stabilizes the electron density and plasma conductivity during the volume stage.[38-41] Discharges of this kind can be described by the electron balance equations and the Kirchoff equation for the electric circuit.[39,42] The results of calculations for a circuit with a limiting resistance are shown in Fig. 9, which gives the time dependence of the current in nitrogen for various initial field intensities.[42] Similar calculated dependences are in agreement with the experimental results.[39,40] The operation conditions under which the plasma is initially created by an electron beam and then a given concentration is maintained or increased by ionization multiplication[21,35,43-47] are of interest from the point of view of ensuring the maximum deposited energy for the minimum expenditure of energy in producing an electron beam.

b) Delay times and energy characteristics

If at a time $t=0$ the electron density induced by electron bombardment of a discharge gap is n_0, the dependence $n(t)$ is found by solving Eq. (24):

$$n(t)=\frac{n_{st}e^{\alpha vt}}{e^{\alpha vt}-1+\lambda}, \tag{27}$$

where $n_{st}=\alpha v/\beta$ is the steady-state electron density and $\lambda=n_{st}/n_0$. It follows from Eq. (27) that after the end of electron-beam injection, the initial electron density n_0 rises or falls to its steady-state value. This steady-state intensity increases rapidly when the ratio E/p is made larger. After a delay time t_d a volume discharge is converted into a spark channel. Figure 10 gives the values of the steady-state electron density and spark-breakdown delay time for the case of discharge initiation by electron-beam pulses 1.5×10^{-8} sec duration when the voltage in the discharge plasma remains constant throughout the pulse.[21,46] We can see that in the volume stage the specific energy deposited in the gas is $0.1-0.2\ J\cdot cm^{-3}\cdot atm^{-1}$ and the duration of the discharge

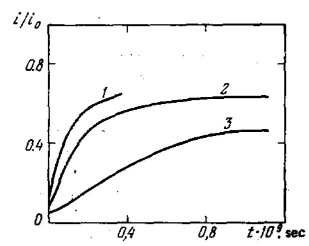

FIG. 9. Oscillograms of the discharge current in atmospheric nitrogen calculated for various initial values of $E(0)/p$. $E/p\,(V\cdot cm^{-1}\cdot Torr^{-1})$: 1) 160; 2) 130; 3) 90.

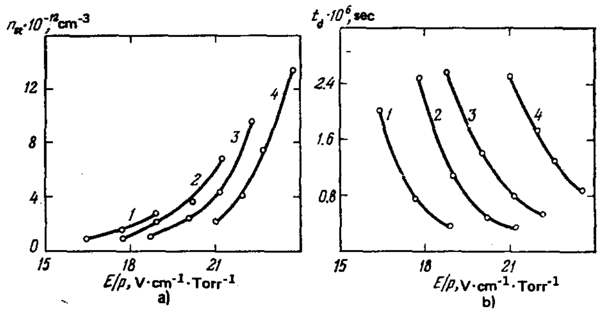

FIG. 10. Dependence of the steady-state electron density (a) and delay time of spark breakdown (b) on E/p in a discharge initiated by electron-beam pulses of 1.5×10^{-8} sec duration. Pressure p (atm): 1) 4.8; 2) 3; 3) 2.4; 4) 1.

is 10^{-6}–10^{-5} sec. The current is maintained by impact ionization in the gas and this makes it possible to reduce by an order of magnitude or more the electron-beam current, compared with the case of a nonself-sustaining discharge. Discharges with impact ionization lasting less than 10^{-6} sec are discussed in Ref. 47. It is noted that a reduction in the discharge time and a simultaneous increase in the power make it possible to increase the specific energy.

A distinguishing feature of this case is that a discharge transforms into a spark much faster. Conditions avoiding this change are considered in Refs. 35 and 43 by analyzing the case of a falling voltage across the discharge plasma. In this case the storage capacitance and voltage are selected in such a way that initially the ionization multiplication process increases the electron density, but subsequently (during the flow of the current) the capacitance is discharged through the plasma. A suitable selection of the conditions should make it possible to achieve a specific energy of ~0.1 J/cm³ at atmospheric pressure.

The idea of fast reduction of the voltage across the gap was also put into practice by other workers[35,43-45] who used special power-supply systems. A discharge gap was subjected to a constant voltage u_0 on which a pulse was superimposed and the amplitude of this pulse Δu was sufficient for ionization multiplication. It was found[35,43] that for $u_0 < 0.3\ u_{br}$ (u_{br} is the breakdown voltage) there was no spark breakdown. Here, a high-power electron injector was effectively replaced by a low-power accelerator with a special circuit for supplying energy to the discharge gap. A pulse could be applied to the discharge gap several times during the interval equal to the plasma recombination decay time and in this way a quasisteady discharge could be obtained.[35,44]

5. DISCHARGES IN MIXTURES OF RARE AND ELECTRONEGATIVE GASES

a) Nonself-sustaining discharges

The interest in discharges in such mixtures is due to the use of these discharges as the active media of lasers utilizing rare-gas halides. Stimulated emission from such halides was first obtained when a mixture of gases was pumped by an electron beam.[48-52] Stimulated emission as a result of pumping with a nonself-sustaining discharge lasting 0.2×10^{-6} sec was reported in Ref. 53 and a similar result was then reported in Ref. 54 for a discharge lasting 10^{-6} sec. A series of investigations of nonself-sustaining discharges[53,55-59] has been carried out with the aim of ensuring the highest specific energy deposition under stable discharge conditions and with the selection of the best conditions for the formation of the ArF, XeF, KrF, etc. excimer complexes which can emit stimulated radiation.

When a volume discharge takes place in the presence of an electronegative gas, the electron losses are due to the capture by halogen-containing compounds and the charge-particle losses are due to the ion–ion recombination process.

In the case of such discharges we have to supplement Eq. (24) with a term allowing for the capture:

$$\frac{dn}{dt} = \Psi + nn_a\left(\alpha - \frac{\eta n_i}{n_a}\right) - \beta n n_+, \qquad (28)$$

where n_a and n_i are the concentrations of atoms of the main gas and of the molecules of an electronegative impurity; η is the capture constant.

Since α rises strongly on increase of E/p, it follows from Eq. (28) that, beginning from a certain critical field E_{cr}, ionization multiplication begins to exceed the electron losses due to capture and the discharge becomes self-sustaining. Figure 11 shows the dependence of E_{cr} on the percentage content of SF_6 in Ar:SF_6 mixtures[58] at $p = 1$ atm, $j_b = 1.5$ A/cm², and $t_b = 1.5\times 10^{-7}$ sec. This figure gives the specific energy for electric fields of $0.8E_{cr}$ and $0.9E_{cr}$ across the gap. The specific energy rises linearly with the current density in the fast-electron beam. For $j_b = 20$ A/cm² and $t_b = 2\times 10^{-7}$ sec, the specific energy deposited in a nonself-sustaining discharge can reach 0.1 J/cm³ (Refs. 25 and 26).

b) Self-sustaining high-current discharges

In fields exceeding E_{cr} a discharge initiated by an electron beam is of a new volume high-current type with ionization multiplication.[58,59] In the discharges known earlier the volume stage is terminated by the formation of a spark channel which shunts the gas discharge gap. In the new discharge we can expect formation of diffuse channels in the gap which can fill the whole gap if the storage capacitance is sufficiently large so that a homogeneous discharge can be produced throughout the region between the electrodes and the electron density can be of the order of 10^{16}–10^{17} cm⁻³. Such a discharge can appear in pure argon and in

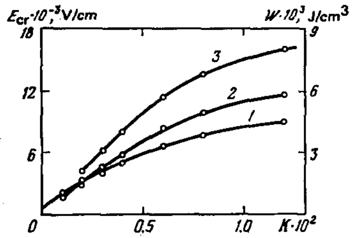

FIG. 11. Dependence of the critical electric field (1) and specific deposited energy (2, 3) on the percentage content of SF_6 in argon.

mixtures of argon with various halogen-bearing substances such as F_2, NF_3, SF_6, or CCl_4.

Figure 12 shows photographs of the radiation emitted from a discharge in an $Ar:Xe:SF_6 = 100:1.2:0.12$ mixture, and the corresponding oscillograms of the current and radiation emitted from the XeF molecule ($\lambda = 351$ nm), as reported in Ref. 59. It is clear from these photographs that at low values of E there is a nonself-sustaining discharge, whereas in the range $E > E_{cr}$ these are separate diffuse channels, whose number increases with E; these channels merge forming a homogeneous plasma filling the volume between the electrodes. The intensity of the radiation emitted from the XeF molecule ($\lambda = 351$ nm) increases on increase of E.

The electric field in a discharge plasma is low and, consequently, the processes of multistage ionization should play an important role in the maintenance of the electron density.

The duration of a volume high-current discharge in the experiments described above exceeded 5 μsec. However, the duration of the electron beam pulses was 10^{-7} sec.

The energy supplied to such a discharge depended on the percentage content of the electronegative gas and on the voltage applied to the discharge gap. For an $Ar:SF_6$ mixture the specific energy ranged from 0.2 to 6 J/cm^3. A summary of the results of an analysis of the current oscillograms, obtained for $L = 1.1 \times 10^{-7}$ H and $C = 0.41 \times 10^{-7}$ F, are given in Table I (Refs. 58 and 59), where the following notation is used: J_m is the maximum current; W is the specific energy dissipated in the gas; n_m is the electron density corresponding to $J = J_m$; u_0 is the voltage applied to the gap; k is the relative proportion of SF_6 in the $Ar:SF_6$ mixture; d is the distance between the electrodes; D is the transverse dimension of the plasma. It follows from Table I that an increase in the percentage content of SF_6 increases the electron density and the specific energy deposited in the gas. The rate of fall of the voltage across the plasma can be controlled by altering the inductance and capacitance of the discharge circuit. This may be of importance in selection of the optimal parameters of laser pumping.

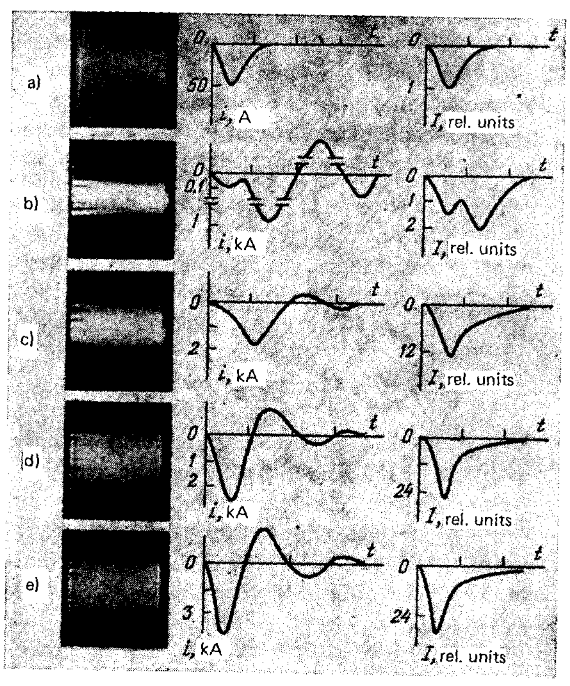

FIG. 12. Photographs of the radiation emitted from an interelectrode gap, oscillograms of the discharge current, and oscillograms of the radiation emitted from the XeF molecules at a wavelength of 351 nm (p=1 atm, d=2 cm, C=0.041 μF, $L = 1.1 \times 10^{-7}$ H, scan 250 nsec/div). U(kV): a) 4; b) 4.25; c) 5; d) 7.5; e) 9.

A study was made of the spectra of the radiation emitted from self-sustaining high-current discharges in mixtures composed of a buffer gas (argon) containing xenon or krypton admixtures and various halogen-bearing compounds. In all cases the brightest parts of the spectra coincided with the emission bands of the excimer molecules. Moreover, the atomic lines of argon at 515.1, 415.8, and 356.3 nm as well as others were observed. Figure 13 shows parts of the radiation spectra obtained for the KrF, XeF, and XeCl molecules. In the case of XeF there are sharp edges at the wavelengths of 353.1 and 351.0 nm. Moreover, there is a band in the region of 260–265 nm and its maximum intensity corresponds to 263.7 nm. The XeCl molecule has the brightest band in the 290–315 nm range.

In mixtures of rare gases with halides we can expect not only nonself-sustaining and self-sustaining high-current discharges but also discharges with ionization multiplication similar to that described in the preceding section. In this case, as well as in discharges used in CO_2 lasers, the initial voltage applied to a gas-discharge gap is sufficiently large to ensure effective ionization and the storage capacitance is selected to ensure that the stored energy is dissipated entirely in the gas before the formation of diffuse channels. In fields $E > E_{cr}$ such a discharge occupies the whole volume which is ionized by the beam. The current is aperiodic. Ionization multiplication of electrons occurs initially after the beam injection and then the rate of impact ionization decreases as the voltage across the capacitor falls. The specific energy deposited in a gas under spark-free conditions can then reach 0.1 J/cm^3.

6. INSTABILITY OF VOLUME DISCHARGES IN GASES

a) Experimental observations of the appearance and growth of spark channels

Stable three-dimensional flow of the current can occur only for a limited time and this is followed by contrac-

TABLE I.

	$K = 0.025 \cdot 10^{-2}$, $d = 2$ cm		$K = 0.12 \cdot 10^{-2}$, $d = 2$ cm				$K = 0.38 \cdot 10^{-2}$, $d = 1.4$ cm	
$u_0 \cdot 10^{-3}$, V	8.5	10	6.0	7.5	9.0	10	10.5	12
$J_m \cdot 10^{-3}$, A	3.63	4.96	1.45	2.30	2.86	3.75	3.75	4.96
D, cm	1.6	1.8	0.7	0.8	1.0	1.1	0.6	0.7
$n_m \cdot 10^{-16}$, cm^{-3}	1.8	2.8	4.7	5.0	4.3	3.5	6.1	6.0
W, J/cm^3	0.35	0.39	2.1	2.6	2.8	2.8	5.8	6.0

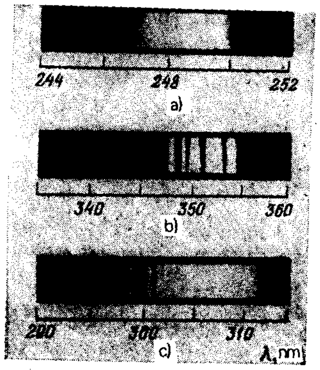

FIG. 13. Radiation spectra of excimer molecules of KrF, XeF, and XeCl in a high-current diffuse discharge: a) $Ar:Kr:SF_6 = 100:1:0.1$; b) $Ar:Xe:SF_6 = 100:1:0.1$; c) $Ar:Xe:CCl_4 = 100:5:0.1$.

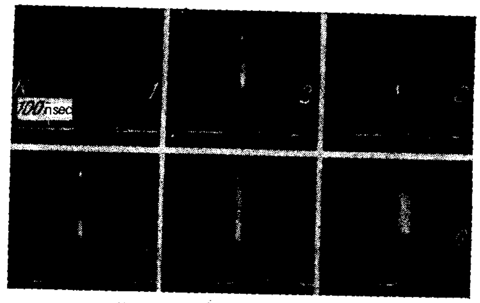

FIG. 14. Development of spark channels in a nitrogen discharge with ionization multiplication ($p = 1$ atm, $E = 23$ kV/cm, $t_b = 2 \times 10^{-8}$ sec). An oscillogram of the discharge current is shown under each photograph.

tion, which sets the upper limit to the energy evolved in a discharge during the volume stage. Therefore, considerable attention has been paid to instabilities of the volume discharge.

Studies of the kinetics of formation of a spark channel in hydrogen at pressures of $p = 500$–2700 Torr in a volume discharge, initiated by short ultraviolet radiation pulses, are reported in Refs. 60–62. During the volume stage the voltage was approximately 20% lower than the breakdown value and the discharge conditions were similar to those described in Sec. 4.b in the present review. The diameter of the luminous region during the volume stage was 10^{-1} cm and there was a correspondingly high current density of ~800 A/cm^2 and a short spark-breakdown delay time of ~70 nsec. Formation of a spark channel occurred in two stages. The first stage consisted of growth of a filamentary channel from the anode side. The dark anode drop region was not penetrated by this channel. An increase in the current density and dissociation of the hydrogen molecules along the discharge axis were observed before the appearance of the filamentary channel. During the second stage a bright plasma bunch appeared at the cathode and this developed into a highly conducting spark channel. Spectroscopic methods were used to determine the electron density and temperature in the high-conductivity channel.

A volume discharge in nitrogen at 50–100 Torr was studied in Ref. 63 under similar conditions, i.e., in the case of strong ionization multiplication in discharges lasting tens of nanoseconds. A study was made of a discharge with a "low" current density 10^2 A/cm^2 and a "high" current density 10^3 A/cm^2. In the former case the conductivity rise occurred in two stages: the formation of a diffuse channel which grew from the anode side was followed by the development of a channel from the cathode region. At high current densities the intermediate stage of a diffuse channel was not observed and a highly conducting spark channel appeared directly in the cathode layer. Spectroscopic studies demonstrated that the appearance of a plasma bunch near the cathode, intersecting the dark cathode space, was accompanied by the appearance of lines of the electrode material in the spectrum. This indicated formation of a cathode spot. As shown earlier,[24,64] a spot could form on increase of the field on the cathode because of the space charge of the ions. This was the direct reason for the appearance of a cathode spot which eliminated microprojections by explosion.[65] The explosion was followed by the formation of a plasma bunch which initiated a high-conductivity spark channel.

Photographs in Fig. 14 show the development of breakdown and the corresponding oscillograms of the current in a field of $E = 23 \times 10^3$ V/cm applied to nitrogen at atmospheric pressure.[66] A discharge is initiated by an electron-beam pulse of 1.5×10^{-8} sec duration. Frame 1 shows uniform radiation across the gap. The oscillogram of the current is typical of a volume discharge. The discharge time in frame 2 is 30 nsec longer than in frame 1. In addition to the volume radiation, there are weakly conducting channels growing toward the anode. Pronounced rise of the current is observed when a plasma region with a high concentration forms near the cathode and a channel grows from it (frame 3). After a time a similar channel grows also from the anode side (frame 4). Estimates of the electron density in this channel give 10^{16} cm^{-3}. The channel grows toward the anode at a velocity of 10^7 cm/sec.

Figure 15 shows the development of breakdown recorded by the method of terminated discharge in nitrogen at atmospheric pressure. In contrast to the conditions in the preceding case, the photographs show the development of a nonself-sustaining discharge with an initiation voltage of $E = 4$–6 kV/cm. The duration of the electron beam current is now $t_b \approx 10^{-3}$ sec and typical durations of the volume discharge are 60–300 μsec; the current density is 2.5–4 A/cm^2 and the electron density is 8×10^{12} cm^{-3}. Frame 1 shows the radiation pattern

FIG. 15. Growth of a spark channel for a nonself-sustaining discharge in nitrogen[74] ($E = 5$ kV/cm). The voltage oscillograms have a time scale 50 μsec/div.

obtained 35 μsec from the beginning of flow of the volume discharge current. There are characteristic precursors of spark channels over the whole cathode area where the beam is injected. During the early stages the radiation emitted from the anode region is weak. There are practically no bright plasma regions of the type which act as initiating centers of the channel growth. However, such centers are clearly visible in frame 2, showing the development of the discharge after 70 μsec. In spite of the fact that the regions of spark initiation appear on the anode later than on the cathode, the spark channel grows from the anode side. The growth velocity depends strongly on the field intensity. In a field of $E = 5$ kV/cm it is 4.7×10^4 cm/sec, whereas for $E = 6$ kV/cm it is $v = 9 \times 10^4$ cm/sec. The energy injected into the gas up to the moment of appearance of the channels at the anode also depends on the field in the column and for values of 4, 5 and 6 kV/cm this energy is 0.7, 0.55, and 0.25 J/cm^3. Oscillograms of the current and the corresponding photographs make it possible to estimate the electron density in a channel at the moment when the gap is closed. Such an estimate gives $n \sim 10^{15}$ cm^{-3}.

An analysis of the dynamics of a transition from a bulk discharge to narrow channels, carried out over a wide range of discharge maintenance voltages, reveals the following general regularitieis. The channel formation (instability) begins near the electrodes and then the ionization front moves toward the opposite electrode. A highly conducting spark channel may, depending on the conditions, form as a result of appearance of several ionization fronts. At some specific stage a cathode spot is formed and the anode conductance rises steeply. The formation of a cathode spot at high current densities is the factor which is directly responsible for the contraction of a discharge.[63]

b) Models of instability of volume discharges

The mechanism of transition from a volume to a spark discharge can be explained and the breakdown delay time can be estimated on the basis of several theories which show that the flow of a current in a discharge column is unstable and has a tendency to contract. The physical factors responsible for such contraction vary with conditions. Consequently, an analysis must be based on model representations of the processes occurring in a discharge plasma. A systematic analysis of the kinetic equations for volume discharges from the point of view of stability is given in Ref. 67, where use is made of the small-perturbation method. Dispersion relationships governing the conditions for the appearance of various types of instability are obtained in the linear approximation. The most general are the thermal[10,67-72] and ionization[73-80] contraction mechanisms. In the thermal mechanism the necessary condition is strong heating of a gas during the flow of the volume-discharge current. Then, neutral particles drift out of a current filament where the heating is faster. Consequently, the ratio of the field intensity to the density of neutral particles increases and the conductivity rises. The problem of thermal instability is considered in Refs. 10 and 68 assuming a constant gas pressure in a current filament and also in Ref. 69 without making this assumption. Numerical calculations relating to the thermal regime of formation of diffuse channels can be found in Ref. 71.

If fluctuations of the Joule heating of an electron gas exceed the energy lost by electrons in collisions with heavy particles, ionization instabilities of various kinds may appear. Such conditions are encountered in the case of strongly saturated vibrational states of molecules[76,79,80] or in the presence of multistage ionization processes.

A detailed review of instabilities in discharge columns is given in Ref. 34, where it is pointed out that different models of instabilities give the same orders of magnitude of the breakdown delay time. This makes it difficult to identify the appropriate mechanism on the basis of one specific model. Moreover, it should be mentioned that the models of contraction of a discharge column imply a volume increase of the conductivity in a current filament[68] or throughout the column.[78-80] However, experimental investigations practically all revealed a two-stage channel formation process: perturbations are nucleated near the electrodes and ionization waves grow deeper into the discharge gap.

c) Instability due to electric field inhomogeneity in discharge columns

In the case of instabilities discussed here the main reason for the increase in the electron density is the evolution of a considerable amount of energy in the discharge column. However, it is known that the discharge maintenance voltage has a very strong influence on the discharge stability even in the nonself-sustaining case. We shall consider the cases in which breakdown is governed mainly by spatial distortion of the electric field and a spark channel appears because of enhancement of the field. Instabilities of this kind are known as the electric-field type.[24]

A field may be enhanced in a discharge column during injection of electrons into the gas. As shown in Sec. 3, the field which appears in a column near the anode under inhomogeneous ionization conditions may reach 10^5 V/cm. Then, a channel develops by an avalanche-streamer process with a characteristic delay time

$$t_d = \frac{\ln N_{cr}}{\alpha v}, \qquad (29)$$

where $N_{cr} \approx 10^8$ is the critical number of electrons in an avalanche. If a discharge develops in atmospheric nitrogen, the characteristic growth time of an instability is $\sim 10^{-9}$ sec. Such instabilities have been observed experimentally[81] for injected-electron-beam pulses of 10^{-8} sec duration. Figure 16 shows how the amplitude of the injected electron beam, varied by altering the acceleration voltage, affects the time of development of an instability.[81] Reduction in the maximum energy of the injected electrons from 180 to 100 keV lowers considerably the instability growth time although the amplitude of the electron current falls from 50 to 10 A.

If the duration of the injected current pulses is 10^{-4} sec, a discharge in an $N_2:CO_2$ mixture contracts[33]

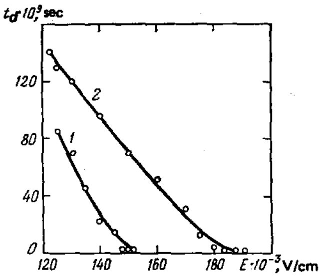

FIG. 16. Delay time of a spark breakdown in nitrogen t_d plotted as a function of the field intensity ($p=7$ atm, $d=1$ cm) for two values of the beam current density j_b(A/cm^2): 1) 2; 2) 10.

when the relative inhomogeneity of the volume ionization is 50%, due to reduction in the acceleration voltage. A spark channel grows from that electrode near which the discharge is weakly ionized and, consequently, where the electric field is higher in the column.

The electric field inhomogeneity in a discharge column is particularly strong in the front of a voltage pulse accelerating the injected electrons.[82] Then, the density of thermalized electrons is particularly high because the electron range varies from zero to some value corresponding to the maximum energy of the accelerated electrons.

d) Formation of instabilities in electrode regions and propagation of spark channels

It follows from direct observations that a spark channel appears near the electrodes and that it grows in the form of an ionization wave traveling in a weakly ionized gas. This means that the formation time of a spark channel can be divided arbitrarily into two components: nucleation time of a spark-initiating center, capable of propagation to the opposite electrode, and the time taken to traverse the gap by the spreading channel. In spite of the arbitrary nature of this division, it is useful because the dominant processes in these two stages may be different. For example, in considering the propagation of an ionization wave, we can use various model representations, particularly the concept of discharge propagation developed[83] to explain the growth of a laser spark.

We shall first consider the models which deal with the nucleation stage of a spark channel. The instability of a cathode layer in a glow discharge is pointed out by Ecker *et al.*[84] They consider a system of equations describing a cathode layer and analyze the stability of this layer in the presence of fluctuations of the current density; they show that the necessary condition for an instability is an increase in the secondary emission coefficient on increase of the current. This condition is fulfilled if the secondary process on the cathode is the field-electron emission. The electric field in the cathode layer required for any significant field-electron emission is 10^6 V/cm or higher. The current is amplified directly on the cathode by surface microinhomogeneities. One of the electric-field instabilities, called the cathode instability by Mesyats,[24] develops in the cathode layer. The mechanism of this instability can be described as follows. A random increase in the current enhances the ion density in the cathode layer and this enhances the cathode field and causes the field-emission current to grow further. The final result is explosion of microinhomogeneities on the cathode surface and appearance of a cathode spot. If the field is high, surface microinhomogeneities explode after a short time interval.[65] For example, in the case of a discharge in vacuum between aluminum electrodes an average field of 0.8×10^6 V/cm produces a cathode spot in 10^{-8} sec. Enhancement of the cathode field and appearance of the cathode spot are facilitated also by insulating contaminants and films. The growth time of the cathode instability is[24]

$$t=\frac{A}{\alpha v_+},\qquad(30)$$

where the coefficient A is of the order of unity.

Explosive processes in field 10^5–10^6 V/cm have been observed in the case of pulse discharges in air.[64] After 50 nsec an examination of the cathode shows the appearance of microcraters of the same kind as those observed after nanosecond discharges in vacuum, for which the occurrence of explosions has been proved unambiguously. The presence of the cathode-material lines on transition from volume to spark discharges is reported by Baksht *et al.*[63] A cathode instability is most likely to occur at high gas pressures and high current densities, because the cathode field is then high. At high current densities in a volume discharge the decisive factor, which initiates a spark channel, is the explosion of microprojections and formation of a cathode spot.[63]

The thermal instability of the cathode layer is investigated in Refs. 85 and 86. Since the dissipated power is higher in the cathode layer than in the discharge column, it follows that the thermal energy stored in the cathode region is much higher. We then have a situation analogous to that in shock tubes, where a high gas pressure produces a shock wave. The theory of shock waves is, in fact, used in an analysis of an instability of the boundary between the cathode layer and the plasma column.[85] Nucleation of thermal instabilities is most probable near microprojections of the cathode surface and in the theoretical solutions the microprojection size always occurs as a parameter. The difficulty in solving the problem lies in the fact that we have to allow self-consistently for the changes in the parameters of the cathode layer as the instability grows. An analytic solution is obtained in the cited papers by adopting a step-like field distribution and calculating the maximum field intensity using the formulas of Basov *et al.*[10] Moreover, the conductivity of the cathode layer is assumed to be constant. The instability growth time is identified with the breakdown delay time, because the growth of a channel into the gap is much faster than the nucleation of initiating centers. In the absence of microprojections on the cathode and at low pump powers the delay time is given by the expression

$$t_d\sim\frac{2p}{(\gamma-1)Q_C},\qquad(31)$$

where γ is the adiabatic exponent and Q_C is the specific power dissipated in the cathode layer.

If the pump rate is high, the breakdown delay time is inversely proportional to $Q_C^{1/3}$. This result is analogous to that obtained for the discharge column instability,[68-69] but in the present case the instability is a function of the power evolved in the cathode layer. On the other hand, according to these authors the basic factor is that we are considering the rise of the conductivity in a current filament, whereas the conductivity has been assumed to be constant in earlier treatments. A comparison with the experimental results[35] shows good agreement. It should be pointed out that this approach could be applied also to an instability of the anode region of a discharge and then the state of the anode surface should also have a considerable influence on the anode layer stability. The electron current reaching the anode becomes localized in the various microprojections of the anode surface and, consequently, the highest evolution of energy occurs near these microprojections. The presence of insulating low-conductivity contaminants on the anode may result in their being charged by electrons and in subsequent breakdown, which creates regions of high-density plasma in the anode region.

The next stage in the growth of a conducting channel is its propagation into the gap. We can describe this stage mathematically by considering the problem of the propagation of an ionization wave because of enhancement of the field at the tip of an initiating center (microprojection) and a strong impact ionization in this region. This formulation is typical of that used to explain the motion of cathode and anode streamers. A qualitatively similar model has been applied to lightning channels.[87] However, it is difficult to apply quantitative solutions to volume discharges when allowance has to be made for the growth of a channel in a weakly ionized gas.

At present the most highly developed, in the mathematical sense, is the concept of a detonation or combustion wave.[83] This concept has been used to calculate the rates of growth of spark channels in volume discharges.[86] The equations of hydrodynamics have to be solved together with the Laplace equation for microprojections of various shapes to allow for the change in the electric field at the end of a current filament. In the case of an ellipsoidal hillock the path of a channel is given by[86]

$$v = k\left(\frac{4Qy^2}{\rho A^{1/2}\ln^2\lambda}\right)^{1/3}, \tag{32}$$

where $k=(\gamma^2-1)^{1/2}$; ρ is the gas density; A is the channel cross section; $\lambda=A^{1/2}/4yk$; y is the instantaneous length of the channel; Q is the specific power introduced into a discharge column.

We carried out an extensive comparison with our own experimental results and those reported by other workers. The best agreement is obtained for growth velocities of 10^5–10^6 cm/sec. The model in question gives poor results at high discharge-maintenance voltages and for high intensities of the field at the end of the conducting channel. It also fails to account for the strong dependence of the velocity on the field intensity in the column.

7. APPLICATIONS OF VOLUME DISCHARGES

a) Gas lasers

The investigations of discharges described above have been largely stimulated by the search for new methods of excitation of gas lasers. Discharges utilizing gas ionization by an electron beam have new properties, compared with those known earlier. These discharges can be produced in enclosures whose volumes are tens and hundreds of liters at pressures up to several tens of atmospheres. The electron temperature is easily controlled by selecting a suitable field intensity, which makes it possible to ensure optimal excitation of the vibrational states of molecules. The electron density can be set in a wide range of values: 10^{11}–10^{16} cm^{-3}. These properties are responsible for the extensive use of discharges in high-power molecular lasers, which are called electron-beam-controlled or combined-pumping lasers (for a review see a paper by Basov *et al.*[88]).

Important ideas and experiments preceded the construction of these lasers.[4-7] For example, amplification of stimulated emission from a CO_2 laser, excited by a glow discharge, was observed during the passage of a proton beam,[89] stabilization of "negative" radiation from a low-pressure glow discharge by an electron beam was demonstrated,[90] and the idea of creation of a homogeneous density of free electrons by adding vapors of easily ionizable elements to CO_2 gas was put forward[91] (cesium vapor was considered as the example).

Many CO_2 lasers excited by nanosecond, microsecond, and longer electron-beam pulses, as well as those operating continuously, are now available. The efficiency of such lasers is 10–30%, and their energy input and output radiation energy are limited by the volume discharge instability. The most powerful of the available pulsed CO_2 lasers have output energies of a few kilojoules[92] and cw lasers have output powers up to 30 kW (Ref. 93).

One of the promising applications of volume discharges is associated with the fact that ion–molecule reactions proceed rapidly and large complexes are formed if the density of neutral and charged particles is high. This provides opportunity for introducing new methods of pumping gas lasers. In some of the experiments carried out on plasmas generated by electron beams it has been shown that population inversion can be established by such nontraditional processes as recombination,[94] charge exchange,[95] transfer of excitation from the buffer to the main gas,[96,97] etc. There is considerable interest in excimer lasers which utilize molecules whose upper excited state is stable and the lower is repulsive. Compounds of rare gases with fluorine have yielded high output energies in the ultraviolet range (lasers utilizing KrF molecules can emit radiation of 108 J energy and 1.9×10^9 W peak power[50]).

Volume discharges provide effective means for stimulating reactions in chemical lasers because homogeneous ionization can be produced in large volumes and energy can be deposited uniformly in the active medium.[98]

b) Plasma reactors

Volume discharges are attracting attention as potential plasma reactor media because of the high degree of departure of the plasma from equilibrium and simplicity of controlling the electron temperature. For example, increase of the electric field from zero to the breakdown value makes it possible to regulate the electron temperature from fractions of an electron volt to a few electron volts, keeping the electron density constant.[99-101] At low electron temperatures a strongly supercooled plasma provides a suitable medium for investigating recombination, charge exchange, cluster formation, and many other processes which occur rapidly at high pressures.[102] Essentially the use of electron-beam-maintained discharges provides means for generating a plasma whose departure from equilibrium is of the same order as the plasma responsible for "negative" radiation emitted from a glow discharge,[90] but with the added advantage of practically unlimited volumes and high neutral-particle pressures so that a wider range of problems can be investigated.

c) Switching of pulse currents

Volume discharges initiated by an electron beam were initially studied with the aim of providing means of switching large pulsed currents.[3-8] Experiments established that two switching regimes are promising. In the first regime the discharge is nonself-sustaining and in the second an electron beam is used to initiate a stable spark channel.

Devices based on nonself-sustaining volume discharges are known as injection thyratrons.[103,104] This is one of the few gas-discharge devices which provides means for total control of the discharge current, i.e., not only for switching on but also for interruption of the current in a matter of tens of nanoseconds at working voltages of a few hundred kilovolts. Large currents can be passed in the nonself-sustaining regime by a suitable selection of gases with a high drifty velocity.[105] For example, at very low values of the ratio E/p (≈ 1 $V \cdot cm^{-1} \cdot Torr^{-1}$), the drift velocity in methane is $\sim 10^7$ cm/sec.

The use of these devices in systems with inductive energy storage is considered in Refs. 104 and 105. The unique combination of the ability to switch-on large currents and to interrupt them can be used in generators of pulsed voltages in which the usual exploding wires for terminating the current are replaced with an injection thyratron, i.e., a device that can be used many times. Another promising application of injection thyratrons is connected with construction of inductance-free switches operating at a high pulse repetition frequency.[103,104]

Spark gaps with an operating voltage of 10^5–10^6 V or higher utilize the properties of a beam-initiated discharge, or specifically, the property of a short and very stable delay time of the appearance of a spark channel. Experiments have been described involving initiation of a spark discharge channel by application of pulses up to 2×10^6 V, involving the rise of the voltage to its maximum value in 10^{-6} sec (Ref. 106). The discharge took place in an $N_2:SF_6$ mixture at pressures up to 11 atm. The delay time of the spark channel was 25 nsec and its stability was ± 1 nsec, which was sufficient for parallel switching-on of several channels.

8. CONCLUSIONS

We have concentrated our attention on processes that govern the electrical properties and the energy deposited in a discharge. Most of the published investigations have been concerned with these subjects because they are of primary importance in the use of discharges in high-power lasers and devices for switching large electric currents.

Attainment of maximum energy deposition while retaining the volume nature of the discharge depends on the discharge stability. In spite of the large number of papers on the subject of stability, the nature of the various phenomena is still not clear. Obviously, the mechanism of formation of a spark channel differs with the discharge conditions. Therefore, it is hardly possible to describe it within the framework of a single model. There are many experimental observations demonstrating that the development of an instability begins in the cathode or anode region. It is concluded that the high field intensity near the electrodes is often responsible for the initiation of spark channels. Under certain conditions the instability is due to the presence of an electronegative molecular component in the gas. The process of capture should affect not only the properties of the discharge column but also the field distribution in the electrode regions. Unfortunately, there have been only a few detailed investigations of the role of the capture processes.

The most remarkable application of discharges excited by electron beams is their use as active media in gas lasers, which has made it possible to increase the output power of lasers by many orders of magnitude. The role of the beam in such lasers reduces to the provision of free electrons in the gas while energy is supplied by a nonself-sustaining discharge current. The electric field in the plasma is selected to ensure the optimal electron temperature for the pumping of the vibrational molecular levels. The problem of the electron distribution function of nonself-sustaining discharges, associated with the optimal pumping conditions, has been investigated in detail[100,101] and, therefore, we shall not consider it here.

In the case of lasers utilizing electron transitions in molecules pumped by volume discharges the density of charged and neutral particles is high and the ion–molecule reactions are fast. Although these lasers are characterized by high efficiencies and high output energies in the ultraviolet part of the spectrum, the mechanism of their operation and the conditions for creating optimal pumping have not yet been investigated sufficiently thoroughly. Therefore, the problems requiring solution (especially in the case of gas mixtures) include determination of the constants of elementary processes, studies of pumping kinetics, selection of the optimal pumping conditions, etc.

There is no doubt that further investigations will make it possible to determine the properties of these discharges more fully and to find new ways of using them in practice.

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