ELECTRIC DISCHARGE IN NITROGEN AT HIGH ELECTRIC FIELDS

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The potentiality of theoretical calculations of the energy input into a gas, such as an electric discharge in nitrogen at large values of E/p, is indicated.

The mechanism of the development and dynamics and of streamer processes in gas gaps with large overvoltages have not been studied sufficiently. In [1, 2] theoretical investigations were carried out and experimental data were presented which indicated that under conditions of the applied voltage exceeding the static breakdown by a considerable factor, the discharge mechanism changes qualitatively and differs significantly from the well-known Townsend and streamer mechanisms. In the range of E/p = 100-500 V/cm · torr (E is the electric field intensity and p is the gas pressure), two characteristic [3] stages may be distinguished: the nonstationary discharge phase in which a rapid increase of the current occurs and, consequently, a decrease of the voltage during a time of $\sim 10^{-9}$ sec. The growth of the current in this stage is basically due to avalanche multiplication of electrons. In the second stage of quasistationary glowing, the discharge corresponds to a glow discharge according to a number of indications. At the same time, the current increase slows down substantially. The quasiglow discharge continues for several tens of nanoseconds and then transforms to a spark channel.

Such a discharge finds important practical applications in fast-acting switches [4] to obtain high-voltage pulses with small fronts of current increase and also for excitation of lasers such as the nitrogen laser [5].

For the creation of an inverted population between the $C_3\pi_u$ and $B_3\pi_g$ levels in nitrogen, first, a large rate of current increase is required, and, second, a high electron temperature ~ 10 eV is required; that is, a value of E/p must be sufficiently larger than $2\text{-}3 \cdot 10^2$ V/cm · torr during one period of pumping $\sim 10^{-8}$ sec.

The quantum efficiency in nitrogen at a wavelength of 3371 Å is sufficiently high, ~16%; however, in well-known designs the practical efficiency is 0.01-0.1%. The fundamental origin appears to be an ineffective transfer of energy from the storage element.

In the present paper, the potentiality of theoretical calculations of the energy input into a gas, such as the electric discharge into nitrogen at large values of E/p, is indicated.

Such theoretical calculations for well-known designs of nitrogen lasers are not carried out in view of the uncertainty of the physical processes. On the basis of the results of investigations [1], we shall assume that the discharge proceeds according to the avalanche mechanism of current increase. We shall assume that in the high-current, discharge stage the electric field is distributed equally along the gap except for the precathode region. The distortion of the field by the spatial discharge in the precathode region does not influence the energy contribution significantly.

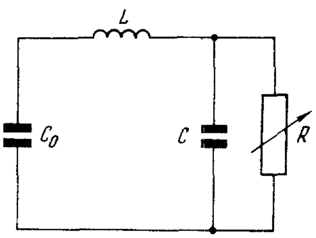

Fig. 1

The current across the gap is determined by [2]

$$i = eN_0vd^{-1}\exp\left(\int_0^t \alpha v dt\right) \tag{1}$$

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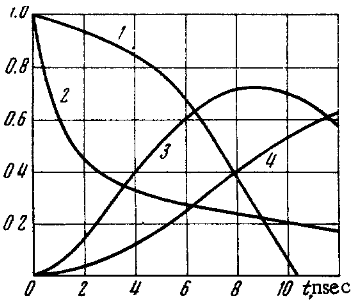

Fig. 2

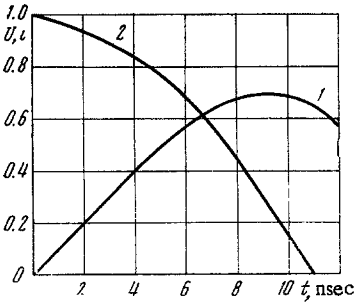

Fig. 3

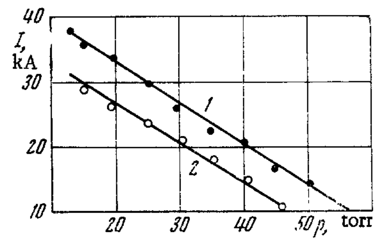

Fig. 4

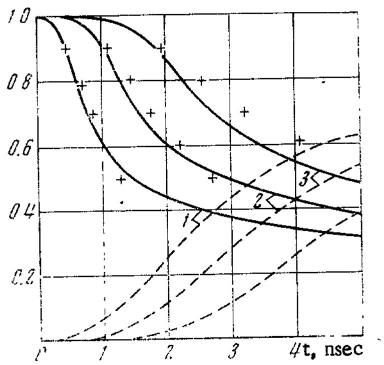

Fig. 5

where e is the electronic charge, N_0 is the initial number of electrons, d is the interelectrode spacing, α and v are the coefficient of impact ionization and the electron drift velocity, respectively. The latter are determined from [6, 7] to be

$$\alpha = Ap \exp(-Bp/E), \quad v = k_0 E/p$$

where $k_0 \approx 3 \cdot 10^5$ cm² torr/V · sec, A = 10 cm · torr, B = 300 V/cm · torr for the range $30 < E/p < 300$ V/cm · torr for nitrogen, p is the gas pressure in torrs, and t is the time. Let us adduce the calculations for the circuit (Fig. 1) in which the capacitance C_0, charged to a voltage U_0, is discharged across the inductance L into the gas gap R. Because of its small value, we may neglect the influence of the interelectrode capacitance C.

The system of equations used in the calculation is

$$z - \frac{dy}{d\tau} = x, \qquad y = Nx \exp\left[\int_0^\tau \Pi \exp(-M/x)\, x\, d\tau\right]$$
$$z = 1 - \int_0^\tau y\, d\tau, \qquad w = 2\int_0^\tau xy\, d\tau = \int_0^t Ui\, dt \,/\, {}^1\!/_2 C_0 U_0^2$$
$$z = \frac{U_*}{U_0}, \quad y = i \Big/ \frac{U_0 \sqrt{C}}{\sqrt{L}}, \quad x = \frac{U}{U_0}, \quad \tau = \frac{t}{\sqrt{LC_0}}, \quad M = \frac{Bpd}{U_0} \qquad (2)$$
$$\Pi = \frac{Ak_0U_0}{d}\sqrt{LC_0}, \qquad N = \frac{eN_0k_0}{pd^2}\sqrt{\frac{L}{C}}$$

where U is the voltage at the gap, U_0 and U_* are the voltages at the capacitance during charging and discharging, respectively, and w is the input energy. As the initial conditions, such a maximum value N_0 for the electrons was used which did not yet influence the voltage change at the circuit elements. We assume that the voltage at the capacitance does not decrease and it is equal to the initial value U_0, and the potential at the gap is determined by Eqs. (2) for the given initial voltage at the capacitance.

An iterative numerical solution using a difference version of Eqs. (2) is performed on the EVM-222 computer according to a standard program for finding the roots of transcendental equations. The choice of very small values of $\Delta\tau = \tau_{i+1} - \tau_i$ of the order of 10^{-3}–10^{-5}, which was varied to obtain a steady solution, was required in the procedure of the voltage decrease at the gap. The functional change with time of the voltage at the capacitance E_*/E_0 (1), the voltage at the gas space E/E_0 (2), the current i/i_0 (3), and the input energy w (4) are shown in Fig. 2 for specific values of $C_0 = 6300$ pF, $E_c/p = 300$ V/cm · torr, L = 3.3 nH, and p = 30 torr.

Because of the avalanche multiplication a rapid voltage decrease occurs at the gas gap, and when E/p is maintained at 90 V/cm · torr, only 17% of the stored energy in the capacitance C_0 is put into the gap.

An experimental check was carried out on an apparatus with a circuit shown in Fig. 1, where the capacitance $C_0 = 6 \cdot 10^{-9}$ F was pulse-charged to a voltage of $U_0 = 20$–30 kV during the breakdown delay of the gap being studied. The nitrogen pressure was varied from 10 to 100 torr. The circuit inductance was $L = 3.3 \cdot 10^{-9}$ H, the cross section of the discharge region was 9 cm², and interelectrode distance was 2.4 cm. The discharge in the gap was initiated by a preliminary irradiation from a discharge at the surface of the supporting insulator of the primary gap. Oscillograms of the current (curve 1) and the voltage (curve 2) for $E_0/p = 300$ V/cm · torr and p = 30 torr are shown in Fig. 3 in relative units. The voltage was recorded by means of a capacitance divider.

A comparison of experiment and theory (Figs. 2 and 3) shows good agreement of the oscillograms of the current growth across the gas gap and the change in the voltage at the capacitance C_0, that confirms the use of the calculation model described above for the given conditions. It is difficult to record the process of the voltage decrease in the plasma of the gas discharge for a discharge of the capacitance in a circuit with a small wave resistance ρ (in the present case $\rho = 0.74\ \Omega$), because the circuit inductance appears to be commensurate with the inductances of the supply and of the discharging plasma.

With a pressure increase and at constant voltage U_0, a linear amplification of the amplitude of the maximum current across the gas gap is observed [Fig. 4: 1) $U_0 = 31$ kV; 2) $U_0 = 25$ kV].

In order to analyze the influence of various factors on the voltage decrease at the gas gap, an approximate solution of the integral in the exponent in Eqs. (2) was found by a trapezoid method for x near unity. Let us take $0.6 < x < 1$. Neglecting the voltage decrease at the capacitance and neglecting the derivative dx/dt, we obtain

$$\tau = 2\{\Pi[\exp(-M) + x\exp(-M/x)]\}^{-1}\ln(1-x)[Nx^2\exp(-M/x)]^{-1} \quad (3)$$

The function $\tau(x)$ is shown by the crosses in Fig. 5 together with the calculated solution for $E_c/p = 200$ V/cm·torr, $L = 1.1$ nH, and $p = 30$ torr, 50 torr, and 100 torr for the curves 1, 2, and 3, respectively. The solid curves are the voltages at the gas gap E/E_0; the dashed curves are the currents i/i_0. As Fig. 5 shows, the approximate method for the determination of $\Delta x = 1 - x$ differs from the exact method by about 20–30%, and Eq. (3) may therefore be used for the determination of the influence of various factors on the switching time in the region of large E/p. Hence, it follows from Eq. (3) that with a decrease of N, that is, with a decrease of L and a corresponding increase of C_0 (so that the product LC_0 remains constant), the time of the voltage decrease increases. This is associated with the fact that a smaller inductance allows a larger current to be passed with a significant voltage decrease at the gap. On the other hand, with an increase in Π, that is with an increase of the pressure for a constant value of E/p, the switching time decreases, because the term in the logarithm grows more slowly than the factor in front of the logarithm decreases.

With an increase of E_0/p for fixed p, the parameter Π increases and M decreases; that is, the logarithmic term decreases, and the factor before the logarithm also decreases the switching time.

It must be noted that Eq. (3) is derived in approximation with the discharge of the capacitance during the switching time. Consequently, the conclusions obtained on the basis of Eq. (3) are valid only when $t \ll {}^1/_2\pi\sqrt{LC_0}$.

The calculation method discussed may be used for the selection of optimal parameters of a gas discharge circuit of lasers in which the excitation takes place by electron impact at high values of the electron temperature.

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