FORMATION OF A VOLUME DISCHARGE IN LASING MEDIA

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Novel model of the volume discharge formation in a preionized medium is proposed. The model provides an explanation for some experimental facts which can not be explained in the context of known models. There are, in particular, the presence of inhomogeneities in the form of microfilaments, improvement of the discharge homogeneity (and, as result, an increase of the laser radiation energy), increase of specific energy deposition into the medium with an increase in the number of preionization electrons, and the improvement of the discharge stability with increasing discharge volume.

Design of the pulsed gas lasers with high pressure of the active medium has essentially increased interest in investigations of volume discharge. Though the processes in such a discharge are described in several monographs,[1,2] the physics of volume discharge formation (period from voltage application to the electrodes till the cathode fall formation) is still unclear.

It is known that the necessary condition for ignition of high pressure volume discharge is preionization of the active medium. To explain the effect of the initial ionization on the development of the discharge at the first stage model of homogeneous plasma column formation was proposed. It is based on the idea of overlapping heads of the electrons avalanches after their size reaches some critical value (see Ref. 3). According to this model ignition of a homogeneous volume discharge is only possible when the electron concentration in the volume exceeds 10^4 cm^{-3}, which, as a rule, contradicts the experimental facts (see Ref. 4). Criteria of volume discharge ignition proposed in Ref. 5 closely agree with the experimental data. However, it should be noted, that these criteria were obtained under formal assumption that the electron avalanches are to overlap during the time the electron number density doubles. In fact, the physics of discharge development was beyond the frame of that paper. Besides, the models presented in Refs. 3 and 5 can not explain relationships between the maximum energy deposition into a gas (see Refs. 4 and 7), laser radiation energy (see Ref. 6,) and concentration of the initial electrons.

In this paper we present a novel physical model of the volume discharge formation providing creation of active laser media.

FORMATION OF THE DISCHARGE PLASMA COLUMN

Let we have uniform preionization of the discharge gap produced with an external source. As a result there appear in the gap electrons and ions whose concentration is n_0. Then a voltage pulse with the amplitude U_0 is applied to the gap. Since the drift velocity of electrons is much higher than their diffusion transversely to the electric field applied, the electrons in their drift along the electric field will ionize gas and form the train of avalanches which follow one after another. As a result, thin conductive filaments are formed (see Fig. 1). The radius of each filament will increase at the rate of electron diffusion:

$$R_f = \sqrt{4Dt}\ , \qquad (1)$$

D is the diffusion coefficient; t is time. Simultaneously with the radius the number of electrons in the filament N_f increases.

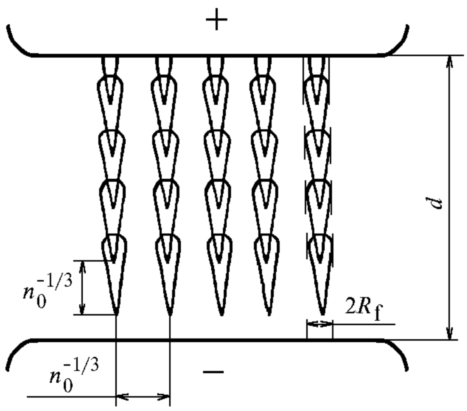

FIG. 1. The model discharge scheme.

$$N_f = N_f^0 \exp(\nu_i\, t), \qquad (2)$$

where $N_f^0 = d/r$ is the initial electron number in the filament; d is the discharge gap, $r = n_0^{-1/3}$ is the average distance between electrons at the preionization stage, ν_i is the ionization frequency. The electron concentration within a filament can be calculated in the following way:

$$n_e = \frac{N_f}{\pi R_f^2 d} = \frac{n_0^{1/3} \exp(\nu_i t)}{\pi R_f^2} . \quad (3)$$

Once the filament radius reached Debay radius

$$R_D = \sqrt{kT_e/(4\pi e^2 n_e)} , \quad (4)$$

the filament extension is dramatically inhibited since the electron diffusion is changed for the ambipolar one. That means that in the time interval ($< 10^{-7}$ s) considered the filament extension terminates.

Equating $R_D = R_f = R$ one can easily determine the filament radius at that moment in time:

$$R = \sqrt{\frac{4D}{\nu_i} \ln\left(\frac{kT_e}{4 e^2 \sqrt[3]{n_0}}\right)} . \quad (5)$$

By introducing the value $n_0^{cr} = R^{-3}$ (called the critical concentration), we can write the criterion for homogeneity of plasma discharge column as follows:

$$n_0 \geq n_0^{cr} = \left[\frac{4D}{\nu_i} \ln\left(\frac{kT_e}{4 e^2 \sqrt[3]{n_0^{cr}}}\right)\right]^{-3/2} . \quad (6)$$

Thus, if $n_0 < n_0^{cr}$, the plasma is formed of a great number of filaments. It was observed in Ref. 6 when a thin layer of volume discharge was investigated by optical methods. It should be noted that the integral glow the filaments can give an impression of the discharge homogeneity.

Moreover, if $n_0 < n_0^{cr}$ the process of nonuniform excitation could be dramatically enhanced in the medium wherein the role of step-ionization processes quadratic in the electron number is great.

As n_0 increases up to n^{cr} the filament density grows and, as consequence, the homogeneity of the discharge improves. The area occupied by the discharge (the sum area of all filaments, S_f) and its ratio to the active area of the electrodes S will also increase. As a result, the specific energy deposited into the gas volume occupied by the discharge plasma column (filaments) will decrease. It should produce a good effect on the discharge stability and increase the maximum energy deposited into the gas.

Using this model we have tried to explain some experiment with lasing media where either the maximum energy deposit into the gas,[4,7] or the laser emission power[6,8] were observed to depend on n_0. For this purpose the ratio S_f/S versus n_0 was calculated for experimental conditions of the above references. The kinetic coefficients required (D, ν_i, T_e) were found from the Boltzman equation (see Ref. 9) solved numerically. The calculated results are shown in Fig. 2. It is seen, that in all cases $S_f < S$. This is caused by the fact that the initial electron concentrations realized in the experiments were lower than the critical concentration. For this reason, according to the above model, discharge plasma column in these experiments was most likely composed of a large number of filaments. Hence, the increase in n_0 improved the discharge homogeneity due to an increase in the volume occupied by the filaments thus giving rise to an increase in the radiation energy (see Refs. 6 and 8). It should be pointed out that no consideration has been given to the reasons of channel formation inside a single micro-filament. However, it is obvious, that the less is the number of filaments formed in the gap, the higher is the current density through them and the faster is the channel formation, other conditions being the same. Then, an increase of the filaments number at a constant current density provides an increase in the maximum energy deposited into the gas as was observed in the experiments described in Refs. 4 and 7.

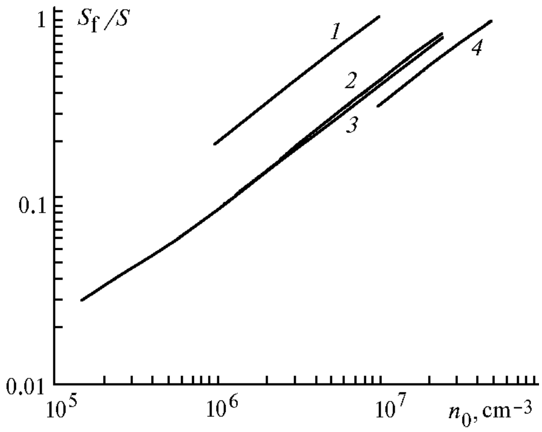

FIG. 2. Ratio of the total microfilaments area (S_f) to the active area of electrodes (S) obtained under different experimental conditions.

Besides, when analyzing Eq. (6) one can conclude that n_0 increases with increasing E/N (E is the electric field strength; N is the number density of gas molecules) which does not contradict the experimental data from Ref. 5.

EFFECT OF CATHODE PROCESSES ON THE DISCHARGE FORMATION

Processes in the cathode region connected with the cathode layer formation show strong effect on the formation of a uniform discharge. To clarify the role of the above processes a one-dimensional model of the discharge formation providing self-consistent description of the processes occurring both in the cathode region and in the main discharge volume was created. This model includes a system of equations for concentration of electrons (n_e), ions (n_i), excited molecules (n_*) and the Poisson equation

$$\frac{\partial n_e}{\partial t} + \mu_e E \frac{\partial n_e}{\partial x} = \nu_i(E)\, n_e,$$

$$\frac{\partial n_i}{\partial t} - \mu_i E \frac{\partial n_i}{\partial x} = \nu_i(E)\, n_i,$$

$$\frac{\partial n_*}{\partial t} = \nu_e(E)\, n_e - \frac{\partial n_*}{\tau_p},$$

$$\frac{\partial^2 \phi}{\partial x^2} = \frac{e}{\varepsilon_0}(n_e - n_i)$$

with the boundary conditions on the cathode:

$$\varphi = 0, \quad j_e = \gamma_i\, \mu_i\, E\, n_i + \gamma_{ph} \int_0^d \frac{\partial n_*}{\tau_p}\, dx,$$

and on the anode:

$$\varphi = U(t),$$

where φ is the potential; E is the electric field strength; μ_e and μ_i are the mobility of electrons and ions respectively; ν_i and ν_e are the frequencies of ionization and excitation, respectively; γ_i is the coefficient of the secondary ion-electron emission; γ_{ph} is the photo-emission coefficient, which is equal to the number of electrons emitted from the cathode per one photon emitted by an excited molecule. The voltage across the gap is assumed to be increased within the front duration τ_{fr} and it is approximated by the following function:

$$U(t) = \begin{cases} (U_0/\tau_{fr})\, t, & t < \tau_{fr}, \\ U_0, & t \geq \tau_{fr}. \end{cases}$$

The results of calculations indicate that the drift of electrons causes formation of positive discharge area near the cathode (ion layer) with the length:

$\sim\mu_e U_0/(2d\tau_{fr})$.

Ions partially screen the external field, reducing it in the main volume and amplifying in the cathode region, wherein the increase of the ionization rate occurs. As a result, the plasma column shifts to the cathode and the cathode layer is formed.

It is clear that for a uniform discharge formation uniform electron emission from the cathode should be provided yet before the layer formation. Otherwise, the electrons are not able to compensate for uniformly positive charge of ions what leads to a distortion of the electric field and discharge contraction.

The secondary electron-ion emission traditionally considered as the main source of electrons can not provide uniform electron flow since at the points of local electric field amplification at the cathode (for instance, on micro-pins) a local increase of current of ions and secondary electrons occurs. Thus, the rate of ionization is higher in this area and it can result in the filaments formation.

Uniform electron emission can be provided by the radiation from plasma column, even if it has a filamentary structure described in the previous paragraph since the radiation intensity is averaged over the entire column volume.

Hence, for the homogeneous discharge formation the current of photo-electrons has to exceed that of the secondary electrons to compensate for the inhomogeneities in the electron-ion emission. According to our estimation the ratio between the photocurrent j_{ph} and the emission current j_{em} in the presence of micro-pins should be about two orders of magnitude.

Calculations of the discharge formation for the experimental conditions of Ref. 4 which, in particular, has determined the lower boundary of the volume discharge existence in the mixture CO_2:N_2:He = 1:1:3 under different pressures were performed to test this estimation. The value of j_{ph}/j_{em} required for the discharge formation is relatively difficult to be estimated theoretically since it depends on the electrode surface state. Therefore we had to take this value as applied to the experiment at pressure of 1 atm. Then the lower boundary of the discharge existence based on the condition $(j_{ph}/j_{em}) > (j_{ph}/j_{em})_1$ was calculated for different pressures. Here $(j_{ph}/j_{em})_1$ is the value obtained at 1atm.

The calculated results are shown in Fig. 3. It is seen that theoretical curve (*1*) is in a good agreement with the experiment (*2*).

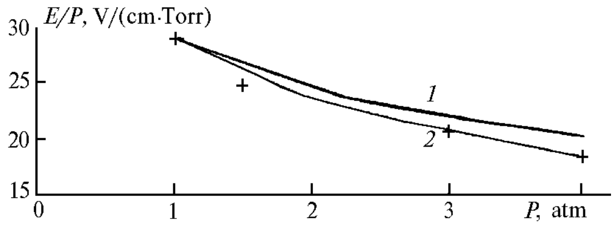

FIG. 3. Limiting E/P values (low existence boundary for the volume discharge) versus pressure. Curve 1 – calculations; curve 2 – experiment (see Ref. 4).

Besides the thickness of the ion layer was found to be approximately the same in all cases.

It is necessary to note here that photo-current is proportional to the plasma column volume, that is, to the difference between the discharge volume and that of ions layer, other conditions being the same. In our opinion, the photo-current decrease can explain the difficulties with space discharge ignition in the small discharge gaps (see Ref. 4). Besides the results of Ref. 10 where highly uniform and long-lived volume discharge was obtained due to filling the gap with electrons can also be explained by the absence of inhomogeneities associated with the electron emission from the cathode and with the cathode layer formation.

In conclusion we should like to note, that the model proposed shows clear physical picture of volume discharge plasma column formation with the preionization and enables a consistent explanation of the following experimental facts:

– the necessity of n_0 increase with increasing voltage applied;

– the increase in maximum energy deposited into gas with the n_0 increase;

– improvement of the discharge homogeneity with increasing n_0, that leads to the laser radiation energy increase;

– the effect of the discharge volume and cathode emission conditions on the formation of a uniform discharge which, in particular, manifests itself in the difficulties of discharge formation in small gaps and in a sufficient improvement of the discharge stability when plasma cathode is used or the gap is filled with electrons.

REFERENCES

1. G.A. Mesyats, V.V. Osipov, and V.F. Tarasenko, *Pulsed Gas Lasers* (Washington, 1995), 272 pp.
2. Yu.D. Korolev and G.A. Mesyats, *Physics of Pulsed Gas Breakdown* (Nauka, Moscow, 1991), 223 pp.
3. A.J. Palmer, Appl. Phys. Lett. **25**, 138–140 (1974).
4. Yu.I. Bychkov, V.V. Osipov, et. al., Izv. Vyssh. Uchebn. Zaved. SSSR, Ser. Fizika, No. 4, 89–94 (1986).
5. V.N. Karnyushin and R.I. Soloukhin, Dokl. Akad. Nauk SSSR **236**, 347–350 (1978).
6. H. Shields, A.J. Alcock, and R.S. Taylor, Appl. Phys. **B31**, 27–35 (1983).
7. Yu.A. Rubinov and Yu.T. Mazurenko. Zh. Tekh. Fiz. **49**, 389–394 (1979).
8. Sumida, et. al., J. Appl. Phys. **52**, 2682–2690 (1981).
9. J.J. Lowke, A.V. Phelps, and B.W. Irwin, *ibid*. **44**, 4664–4671 (1973).
10. O.B. Kovalchuk, B.G. Shubin, et. al., in: *Proc. of VII Conf. on Physics of Gas Discharge*. (Samara, 1994), pp. 86–87.