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LOWERING OF THE OPTICAL BREAKDOWN THRESHOLD IN A LASER FOCUS BY SUPERIMPOSING A MICROWAVE FIELD

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It has been established that the threshold of optical breakdown in the focus of a laser beam (see, e.g., the review [1]), for inert gases and air at pressures on the order of atmospheric and lower, corresponds to an electric field intensity in the light wave on the order of 10^6 - 10^7 V/cm. We describe in this article an experiment showing that when a sufficiently strong microwave field (exceeding 10^3 V/cm) is present in the focusing volume, the threshold of the optical breakdown can be lowered (to 10^5 V/cm).

We used in the experiment a ruby laser Q-switched by a rotating prism (laser pulse duration 60 nsec, energy 0.6 J, divergence 7'). The laser beam was focused with a lens (f = 18 mm) into a low-Q microwave resonator (short-circuited section of a waveguide for the 3-cm band, with cross section 23 x 10 mm). The laser beam entered the cavity through an opening in the broader wall of the wave guide, so that the electric-field vector coincided with the direction of the laser beam for the fundamental H_{10} mode. The resonator was excited with a pulsed magnetron at 9400 MHz (pulse duration 1 μsec). The microwave pulse power reached 100 kW, corresponding to an electric field intensity at the laser focus with amplitude $\sim 7 \times 10^3$ V/cm. A special synchronization circuit was used to synchronize the laser monopulse with one of the pulses of the magnetron, which operated in the pulse-repetition mode. A light beam from a special illuminator, reflected from the front face of the Q-switching prism during a definite phase of its rotation, was incident on a photo-pickup located about 3 meters away. The signal from the pickup triggered the magnetron. The microwave pulse repetition frequency was thus governed by the number of prism revolutions (550 Hz). By shifting the photo-pickup relative to the system pickup it was possible to set the required time position (including a time lead) of the microwave pulse relative to the laser pulse.

At the investigated pressures, the microwave generator power was insufficient to cause microwave breakdown in the resonator without applying the laser pulse. The microwave breakdown field when the generator operates in the pulsed mode [6] is 2 - 3 times larger than the maximum microwave field used in the experiment, even at the minimum pressures($\sim$ 40 mm Hg in the case of argon) and increase with increasing pressure. The optical breakdown was observed visually and recorded photoelectrically by means of the appearance of the spectral lines of the investigated gas in the emission spectrum of the light spark. In addition, the spark was photographed.

Experiments in Kr, Ar, and He have shown that the presence of a microwave field greatly lowers the laser-breakdown threshold. It was observed experimentally at the same time that the reduction of the threshold is practically independent of the position of the laser pulse inside the rectangular microwave pulse. The results of the experiments are shown in Figs. 1

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and 2. Table I lists values of the ratio E_2/E_2' (E_2' and E_2 are respectively the threshold values of the electric field intensity in the light wave, averaged over the focusing volume, with and without the microwave field superimposed).

Table I

P, mm Hg	100	160	260	360	460
Ar	7	24	31	29	28
Kr	3,5	8,3	19	19	19
He	1,3	1,4	1,5	1,5	1,6

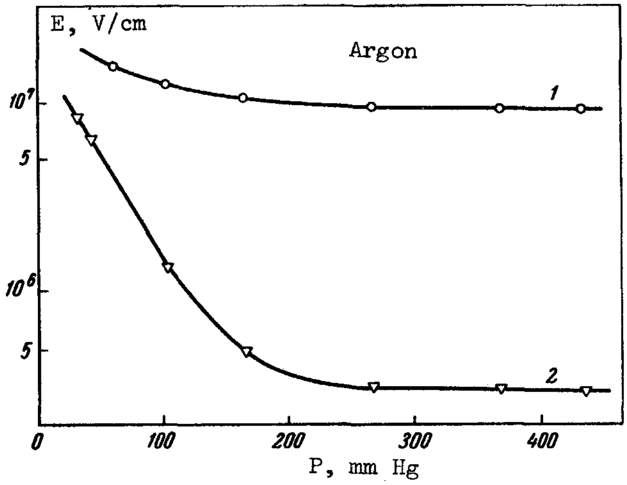

Fig. 1. Threshold laser field vs. pressure without (1) and with (1) microwave field.

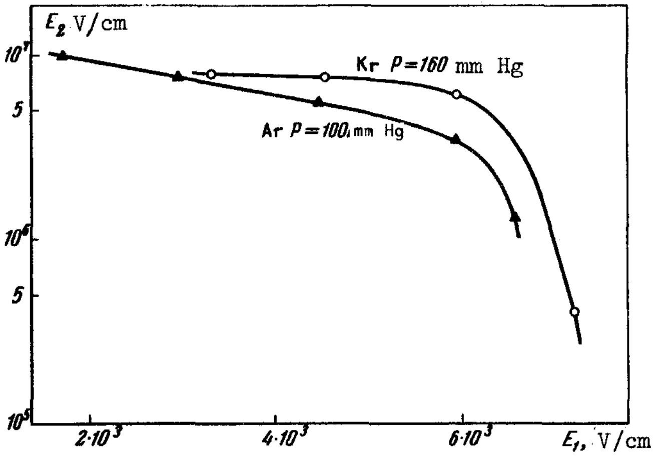

Fig. 2. Threshold laser field vs. microwave field intensity.

According to electron-avalanche notions, optical breakdown of a gas takes place when the energy acquired by the free electrons by bremsstrahlung absorption in collisions with the neutral atoms exceeds a certain critical value that depends on the type of gas, on the pressure, on various types of losses (of energy and of electrons) during the stage of the primary breakdown [1, 3, 4]. When a microwave field $E_1 \exp(i\omega_1 t)$ is superimposed and if $\vec{E}_1 \perp \vec{E}_2$ ($E_2 \exp(i\omega_2 t)$ is the field in the light wave) and $\omega_2^2 \gg \nu_{eff} \gg \omega_1^2$, the resultant rate of energy acquisition is the sum of the rates of energy acquisition in the laser and in the microwave fields, i.e.,

$$\frac{d\epsilon}{dt} = \frac{e^2 E_2^2 \nu_{eff}}{2m\omega_2^2} + \frac{e^2 E_1^2}{2m\nu_{eff}}.$$

Under the conditions of the experiment, the rate of heating in the microwave field is larger by one order of magnitude or more than the rate of heating in the laser field. However, no electron avalanche develops without the action of the laser since, according to estimates for the field values used in the experiment, the rate at which energy is lost to excitation of the neutrals exceeds the rate of heating by the microwave field. On the other hand, when the light field is applied, the probability that the electron will jump through the excitation-loss band increases greatly, primarily as a result of the "escape" of the electrons from the upper excited levels via the photoeffect with absorption of one or two laser photons.

The quantum-kinetic equation [2] for the number of electrons $n(\varepsilon, t)$ under simultaneous action of the microwave field and the laser is written in the form

$$\begin{aligned}\frac{\partial n(\epsilon,t)}{\partial t} &= G_1 N_a\{-a_1(\epsilon)n(\epsilon,t) - b_1(\epsilon)n(\epsilon,t) + a_1(\epsilon-\hbar\omega_1)n(\epsilon-\hbar\omega_1) + \\ &+ b_1(\epsilon+\hbar\omega_1)n(\epsilon+\hbar\omega_1)\} + G_2 N_a\{-a_2(\epsilon)n(\epsilon,t) - b_2(\epsilon)n(\epsilon,t) + \\ &+ a_2(\epsilon-\hbar\omega_2)n(\epsilon-\hbar\omega_2) + b_2(\epsilon+\hbar\omega_2)n(\epsilon+\hbar\omega_2)\} + Q,\end{aligned} \tag{1}$$

where a_1, b_1, a_2, and b_2 are the coefficients of stimulated bremsstrahlung absorption and emission, G_1 and G_2 are the photon fluxes for the microwave and laser fields, respectively, N_a is the neutral concentration, and Q are terms that take the losses into account. Solving this equation under the assumptions made in [2], we can obtain the following expression for the determination of the avalanche time constant θ_0:

$$\frac{I_1^* m\nu_{\text{eff}}}{e^2 E_1^2 \theta_0} = \alpha + \beta(1-\alpha) W_2 \theta_0. \tag{2}$$

I_1^* is the potential of the first excited level, α the probability of jumping through the excitation-loss band, β the ratio of the number of excited atoms with energy $I_k^* \geq I_i - 2h\omega_2$ to the total number of excited atoms, and $W_2 = CE_2^4$ is the probability of two-photon absorption [1].

Using the breakdown condition

$$\frac{1}{\theta_0} - \frac{1}{\tau_{D_e}} = \frac{1}{\theta_{\text{cr}}} \equiv \frac{\ln n_f/n_0}{\tau_p} \tag{3}$$

(n_0 and n_f are the initial and final numbers of electrons in the focusing volume, τ_p the duration of the laser pulse and τ_{D_e} is the electron diffusion lifetime), we obtain an expression for the threshold laser field

$$E_{2\text{cr}}^4 = C^{-1}\left[\frac{I_1^*\left(1+\dfrac{\theta_{\text{cr}}}{\tau_{D_e}}\right) m\nu_{\text{eff}}}{e^2 E_1^2 \theta_{\text{cr}}} - \alpha\right] \frac{1+\dfrac{\theta_{\text{cr}}}{\tau_{D_e}}}{\beta\theta_{\text{cr}}(1-\alpha)}. \tag{4}$$

Table II

P, mm Hg		100	160	260	360	460
Ar	E_{2T}	$2{,}3 \cdot 10^6$	$4{,}7 \cdot 10^5$	$2{,}9 \cdot 10^5$	$2{,}4 \cdot 10^5$	$2{,}6 \cdot 10^5$
	E_{2E}	$1{,}8 \cdot 10$	$4{,}4 \cdot 10^5$	$3 \cdot 10^5$	$3 \cdot 10^5$	$3 \cdot 10^5$
Kr	E_{2T}	$3{,}9 \cdot 10^6$	$1{,}8 \cdot 10^6$	$3{,}6 \cdot 10^5$	$2{,}9 \cdot 10^5$	$3 \cdot 10^5$
	E_{2E}	$2{,}9 \cdot 10^6$	$1{,}2 \cdot 10^6$	$4{,}2 \cdot 10^5$	$3.9 \cdot 10^5$	$3{,}8 \cdot 10^5$
He	E_{2T}	$1{,}6 \cdot 10^7$	$1{,}4 \cdot 10^7$	$7{,}9 \cdot 10^6$	$5{,}6 \cdot 10^6$	$4{,}7 \cdot 10^6$
	E_{2E}	$1{,}2 \cdot 10^7$	10^7	$7{,}2 \cdot 10^6$	$6{,}4 \cdot 10^6$	$5 \cdot 10^6$

The quantities α and β in (4) can be caluclated by taking detailed account of the excitation losses, using the procedure of [5].

Table II shows a comparison of the theoretical threshold fields (E_{2T}) calculated with formula (4) with the experimental values (E_{2E}).

As seen from Table II, the theoretically calculated threshold fields are in satisfactory agreement with the experimental results.

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[4] V. E. Mitsuk and V. A. Chernikov, ibid. 6, 627 (1967) [6, 124 (1967)].
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OBSERVATION OF THE STRUCTURE OF DIAMAGNETIC EXCITONS IN THE ELECTROABSORPTION SPECTRUM OF Ge

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It is shown in a number of theoretical [1,2] and experimental papers [3, 4] that the discrete structure of the absorption edge of semiconductors in a strong magnetic field is of exciton nature. The maxima in the magnetoabsorption spectrum should be attributed in this case to the ground exciton states connected with different Landau subbands that take part in the interband optical transitions. Naturally, there should exist besides the ground state, in general, also a number of excited states of such excitons.

The corresponding exciton series can be excited in the simplest case by the formula

$$\mathcal{E}_{ex} = \mathcal{E}_{\ell'\ell} - \frac{R^*}{(n + \delta n)^2}, \quad n = 0, 1, 2, 3, \ldots, \qquad (1)$$

where $\mathcal{E}_{\ell'\ell}$ is the energy distance between the edges of the combining Landau subbands in the valence and the electron bands, with quantum numbers ℓ' and ℓ; δ_n is the quantum defect and depends on the magnetic field and on ℓ. The Rydberg constant $R^* = \mu_n^* e^4/2h^2\kappa^2$ contains the reduced effective mass which, generally speaking, can be a function of ℓ and also of the magnetic field H; κ is the dielectric constant.

Exciton states of this kind can be called, in contradistinction to the exciton states in the absence of the field, diamagnetic states, since they are connected with the diamagnetic Landau subbands. It should be noted that the presence of a strong magnetic field distorts noticeably also the ratio of the intensities of the terms of the series, compared with the case when there is no field and when the relative intensities are given by simple relations [5].

According to the data of [1], the relative intensities of the excited states can decrease by nore than one order of magnitude, making their detection difficult. Nonetheless, Johnson [3] observed recently a structure in the magnetoabsorption spectra of InSb and Ge; this struc-