Frequency and temperature dependences of avalanche ionization in solids under the influence of an electromagnetic field

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Formulas for the critical field are obtained on the basis of a solution of the kinetic equation. It is shown that its dependence on the temperature is determined essentially by the ratio of the frequencies of the field and of the electron-phonon collisions. This makes it possible to evaluate experimentally the role of the electron avalanche as a laser-damage mechanism.

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The question of which mechanism predominates in laser damage of transparent dielectrics has been extensively discussed of late. In a number of papers[1–3] it is stated that this mechanism is an electron avalanche. This statement, however, is insufficiently well founded, since it is based only on a phenomenological explanation[3] of the absence of a frequency dependence of the breakdown threshold, and results in electron-phonon collision frequencies $\nu > 10^{16}\ \text{sec}^{-1}$, which are rather unlikely. At the same time, the available solutions of the problem, based on the kinetic equation,[4,5] are confined to high electromagnetic-field frequencies $\Omega \gg \nu$, and lead to a frequency dependence of the critical field in the form

$$E_{\text{cr}} \sim \Omega . \tag{1}$$

It is therefore of particular interest to carry out a consistent theoretical investigation of the frequency dependence of the critical field, from laser frequencies down to a static field. Such an investigation is reported for the first time in the present paper. Its results show that a fundamental factor in the explanation of the role of the electron avalanche in laser damage is also the highly characteristic temperature dependence of the breakdown threshold. The results in our opinion, uncover a possibility of a purposeful organization of experiments aimed at determining the dominant laser-damaged mechanism for transparent dielectrics.

To solve the problem of avalanche ionization in a transparent dielectric in the field of an electromagnetic wave, we start from the quantum kinetic equation derived earlier[6] under the assumption $\Omega \gg \nu$. When averaging over the time in the region $\Omega \lesssim \nu$ it is necessary to take into account also the factor $(1+\Omega^2\tau^2)^{-1/2}$, where τ is the relaxation time of the longitudinal component of the electron momentum. The coefficients obtained in this case contain, as usual, squares of Bessel functions $J_n^2(x)$, the arguments of which takes the following form (cf. (3)[5]):

$$x = e\mathbf{E}\Delta\mathbf{p}(\epsilon)\,\tau(\epsilon)\Big/\hbar m\Omega\sqrt{1+\Omega^2\tau^2} . \tag{2}$$

Here e and m are the charge and mass of the electron, $\mathbf{E}$ is the maximum value of the field, and $\Delta\mathbf{p}(\epsilon)$ is the change in the momentum, of an electron having an energy ϵ.

Allowance for all the multiphoton processes in the conduction band leads to the following expression for the diffusion coefficient $D(\epsilon)$ and for the factor $Q(\epsilon)$ of the spontaneous energy loss

$$D(\epsilon) = D_0(\epsilon) + D_E(\epsilon); \qquad Q(\epsilon) = Q_0(\epsilon);$$
$$D_E(\epsilon) = \frac{2e^2E^2\epsilon^{3/2}}{3m\Omega^2 l(\epsilon)(1+\eta\epsilon/I)} . \tag{3}$$

Here $l(\epsilon)$ is the electron mean free path, I is the effective ionization potential,[5] $D_0(\epsilon)$ and $Q_0(\epsilon)$ are the corresponding coefficients in the absence of a field,[7] and

$$\eta = 2I/\Omega^2 m l^2(I) . \tag{4}$$

In the derivation of (3) we have used the summation formula

$$\sum_{-\infty}^{\infty} n^2 J_n^2(x) = \frac{x^2}{2}; \qquad \sum_{-\infty}^{\infty} J_n^2(x) = 1. \tag{5}$$

The obtained diffusion equation goes over in the limit as $\Omega \to 0$ into the known equation for the case of constant electric fields (see, e.g.,[8]). It can thus be used to analyze the process of avalanche ionization in the entire range of field frequencies, provided that the following conditions are satisfied:

$$eEl\big/\sqrt{1+\Omega^2\tau^2} \gg \hbar\omega_0; \qquad \hbar\Omega \ll I \tag{6}$$

($\hbar\omega_0$ is the average phonon energy). These conditions, as shown by estimates, are well satisfied for dielectrics up to visible frequencies. Using the method of obtaining the avalanche growth rate γ and the breakdown criterion $\gamma t_0 \sim 15$[5] (t_0 is the radiation-pulse duration) we obtain

$$E_{\text{cr}}^2 = \Lambda I m^2 v_s^2\left(\Omega^2 + \frac{I}{ml^2}\right)\Big/2kTe^2 \tag{7}$$

in the case of high-temperature scattering by acoustic phonons and

$$E_{\text{cr}}^2 = \Lambda_0 m v_s\sqrt{2mI}\left(\Omega^2 + \frac{2I}{5ml_0^2}\right)\Big/2e^2 \tag{8}$$

for scattering by the zero-point lattice vibrations. Here v_s is the speed of sound and $l_0 = l_0(I)$. The coefficients Λ and Λ_0 are approximately equal to unity at $t_0 \sim 10^{-7}$–10^{-9} sec, and depend little on Ω and on the parameters of the medium. For example, for Λ we have the expression

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$$\Lambda^{-1} = \frac{1}{12} \ln (t_0 / 15\Theta), \tag{9}$$

where

$$\Theta = Q^{-1}(I)I^{-1}(q/\eta)^{3/4}\Gamma(3/2)\exp(1/4\eta q) D_{-3/2}(1/\sqrt{nq})$$

$$6q = e^2E^2kT / m^2 v_s^2 \Omega^2 l$$

$D_\nu(x)$ is the parabolic-cylinder function.

A direct comparison of (7) and (8) shows the following:

1. Up to a certain temperature T_{thr}, Eq. (8) is valid and the critical fields remain practically unchanged. Then

$$kT_{thr} \approx \frac{1}{2} v_s \sqrt{2mI} . \tag{10}$$

For typical values of the parameters corresponding, say, to NaCl, we have $T_{thr} \approx 230\,°K$ ($v_s = 4 \times 10^3$ m/sec, $I = 9$ eV).

2. At $T \gtrsim T_{thr}$ the damage threshold begins to change noticeably with increasing temperature, and since the mean free path l is inversely proportional to the temperature, it follows that the critical field increases if $\Omega\tau < 1$, and there exists a temperature region in which it decreases if $\Omega t > 1$.

Thus, if the damage mechanism is an electron avalanche, then one of the following situations should be realized in experiment: either the critical field is independent of the frequency, meaning $\Omega\tau \ll 1$, and a characteristic region should exist where the critical field increases with increasing initial temperature, or else the damage threshold remains approximately the same up to the temperature T_{thr}, and begins to decrease above this value, but then a frequency dependence of the type (1) should be observed. A comparison of experimental data with the results of the present study will permit, as we see, an estimate of the frequency of the electron-phonon solutions for "hot" electrons. This is of great interest, since direct experiments have so far been unsuccessful in determining this frequency.

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