Formation of a bubble in electron density by an external field

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(Submitted 1 October 1987; resubmitted 30 November 1987)
Pis'ma Zh. Eksp. Teor. Fiz. **47**, No. 1, 56–58 (10 January 1988)

The formation of a hole (or bubble) in the electron density in the conduction band of an insulator in a strong nonuniform rf field has been detected. An equation is derived for determining the probability for multiphoton ionization of valence-band electrons from experimental data on breakdown.

Experiments on the breakdown of transparent dielectrics by a nanosecond laser pulse focused to an ultrasmall spot ($\widetilde{D} = 0.4$–0.84 μm in diameter) have revealed anomalously high breakdown thresholds,[1] exceeding those for small spote ($3 < \widetilde{D} < 20$ μm) by a factor of 10^2.

It turns out that in the case of a highly nonuniform field the velocity at which electrons are transported away from the center of the spot, ξ_a, exceeds the avalanche ionization constant γ. In the field of the leading edge of the pulse, the "heated" electrons of donor states of the dielectric move off to the periphery of the spot. In the redistributed electron density of the conduction band, ρ, a hole (or bubble) and a halo appear. At the center of the spot, an avalanche does not have time to develop, while in the halo it cannot develop because of the negligible value of γ. The dielectric remains stable until the mechanism of multiphoton ionization of valence-band electrons "turns on." The ionized electrons change the structure of the halo from within, reducing the radius of the hole-halo boundary, R. Saturation of the halo leads to a collapse of the hole, the appearance of an avalanche, and the breakdown of the dielectric. This mechanism explains the anomalous dependence of the breakdown threshold.[1]

In a highly uniform field of an electromagnetic wave $E \cos \omega t$, the energy distribution of the conduction-band electrons reaches a steady-state distribution $\tilde{f}(\epsilon)$ with an average electron energy $\theta(E^2)$ (Ref. 2). The electron system is open: There is a transfer of energy away from the photon part of the heat reservoir to the phonon part. The electron mean free path with respect to scattering by phonons, the photon pickup length l_1 and time τ_1, the electron-diffusion coefficients in energy space (B) and coordinate space (D), and the electron relaxation time τ_S can be estimated as follows:

$$l_0^2 \approx D\tau_0; \; l_1^2 \approx l_0^2 \frac{\tau_1}{\tau_0}; \; \tau_1 \approx \frac{\omega^2}{B}; \; B \approx \gamma I^2; \; D \approx \frac{2\theta}{m} \tau_0; \; \tau_S \cong \frac{\theta^2}{B},$$

where τ_0 is the electron-phonon collision time (we would have $\tau_0 T \lesssim 1$ at a phonon temperature T above the Deybe frequency ω_D), and I is the ionization potential of the dielectric. The coefficient B is estimated in terms of the known function[2] $\gamma(E^2)$.

In the case of a unique focusing of a laser pulse,[1] the amplitude is approximated

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by the function $E = E_0 \exp(-r^2/2a^2 - t^2/2\tau^2)$ with the inhomogeneity parameter $a = 0.6\tilde{D}$ and a pulse length $\tau = 18$ ns (breakdown occurs at $E_0 = 3 \times 10^7$ V/cm). In a field of this sort, the system of electrons is in a quasisteady state ($\tau \gg \tau_S$). The sharp $E(r)$ dependence results in the appearance of two quite different regions. In the "hot" region ($r \lesssim a$) the properties of the system are determined by the local value of $E(r)$ ($l_0 \lesssim l_1 \ll a$). The nonuniform field gives rise to a flux

$$\mathrm{j} = -D\nabla\rho - \mu(\nabla U + \nabla\theta)\rho; \quad \theta(E^2) = \frac{\theta_0}{E_0^2} E^{2\ 2}, \qquad (1)$$

where U is the potential energy which arises from the redistribution of ρ, and the local values of the diffusion coefficients and the mobility are related by $D \approx \mu\theta$, $\theta_0 = \theta(E_0^2)$, in the case of quasisteady systems. It follows from (1) that the electrons leave the hot region in a time $\xi_a^{-1} \approx a^2/D$. Under the condition $\xi_a(E_0^2) > \gamma(E_0^2)$, an avalanche cannot develop in the hot region (as the field is reduced, γ falls off more rapidly than θ^2), since the electron lifetime in the region $r \lesssim \alpha$ is too short for the acquisition of the ionization energy I. Since the high-energy component disappears from the distribution function $f(\tilde{\epsilon},r)$, so the average energy of the electrons at point r is smaller than the corresponding value θ for a homogeneous system with $E = E(r)$. In the "cold" region ($r > a$), the transport processes slow down markedly with increasing r, and an avalanche breeding of electrons is not possible, ($\gamma \ll 1/\tau$). Under the condition $\xi_a > \gamma$, electrons thus collect at the periphery: A hole and a halo appear in the redistributed density.

The maximum number (z_*) of electrons that can move from the center to the periphery can be estimated at fixed values of the parameter of the reservoir, $\{E^2(r), T\}$, from the minimum of the generalized thermodynamic potential

$$\varphi(z) \approx -\theta_0 z + \frac{z^2 e^2}{a\epsilon}$$

(ϵ is the static dielectric constant). The value $z_* \approx \theta_0 a\epsilon/e^2$ corresponds to saturation of the peripheral region. A hole appears if the density of donor states in the dielectric, ρ_0, is too small for saturation ($\int_0^a \rho_0 d^3r < z_*$). The radius ($R$) of the hole-halo boundary, the nonsaturating halo charge z, and the density distribution are found by minimizing the generalized potential as a functional of the density:

$$z = \int_0^R \rho_0 d^3r = \int_R^\infty \frac{\epsilon}{4\pi e^2} \Delta\theta\, d^3r; \quad \rho(r < R) = 0; \quad \rho(r > R) = \rho_0 + \frac{\epsilon}{4\pi e^2} \Delta\theta. \qquad (2)$$

A sharp boundary of the hole corresponds to the solution of the electrostatic problem. The density in the hole region is nonzero because of diffusion processes. Setting $\mathbf{j} = 0$ in (1) ($\hat{\nabla} U < \hat{\nabla}\theta$ at $z < z_*$), we find

$$\rho(r < R) \approx \rho(R) \exp((r^2 - R^2)/a^2).$$

Under hole-formation conditions $\{a < a_* = (2\theta/m\gamma T)^{1/2};\ z < z_*\}$, the appearance of an avalanche is prevented. Expressions for γ and θ were derived for weak fields

($E < E_D$) in Ref. 2. In strong fields ($E > E_D$), the quantity γ reaches an asymptotic value, which can be estimated from the condition of a mandatory pickup (or loss) of a photon in the collision of an electron with a phonon ($l_0 = l_1$):

$$\gamma_D \approx \omega^2 T/I^2 \approx 10^{11}\ \mathrm{s}^{-1}; \quad E_D = (3m^2\omega^4/2mIe^2)^{1/2} \approx 10^7\ \mathrm{V/cm}.$$

The asymptotic value θ_D is limited by the ionization potential I. The asymptotic values of a_* and z_* are $a_D \approx (2I/m\gamma_D T)^{1/2} \approx 1\ \mu$m and $z_D \simeq Ia\epsilon/e^2 \approx 10^3$. The stability of an electron system in the case of focusing to an ultrasmall spot ($\alpha < \alpha_D$) simulates an ideal dielectric at donor-electron densities $\rho_0 < \rho_D \approx 10^{16}\ 1/\mathrm{cm}^3$.

With increasing field intensity, the probability (w_n) for multiphoton ionization of valence-band electrons, accompanied by the pickup of $n = I/\omega + 1$ photons, increases. The contribution to the ionization is important at the center of the spot at the time the pulse peaks ($w_n \sim E^{2n}$; $E < E_A = 5 \times 10^8$ V/cm; Ref. 3). An instability of the dielectric at $a < a_D$ sets in after saturation of the halo and collapse of the hole ($R \approx a$; $\rho_0 \ll \rho_D$):

$$N_A \cdot \int w_n(E) d^3 r dt = w_n(E_0) N_A \frac{2\pi^2}{n} a^3 \tau \approx \frac{Ia\epsilon}{e^2}, \tag{3}$$

where N_A is the density of valence-band electrons. Equation (3) can explain the anomalous increase in the breakdown thresholds at the observed behavior of the thresholds as functions of the spot diameter and the intensity. It has become possible to determine the probabilities for multiphoton ionization of valence electrons of a dielectric within an error no worse than the error in the measurements of the probability for the multiphoton ionization of the atoms of gas. The satisfaction of relation (3) for various values of ω and the behavior of the critical dimension, $a_D \approx \omega_D/T$ can be tested experimentally.

We wish to thank S. I. Anisimov and A. B. Migdal for a discussion of these results.

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Translated by Dave Parsons