OPTICAL CHARACTERISTICS OF A SEMICONDUCTOR LAYER WHOSE CONDUCTIVITY STRONGLY DEPENDS ON THE INTENSITY OF THE WAVE FIELD ELECTRICAL COMPONENT

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An original and simple model is proposed which describes the optical properties of materials at whose surface a dielectric breakdown is induced by the incident electromagnetic wave. Numerical calculations have shown that a process of self-inducing of the incident wave can occur. Comparison with experimental data on self-inducing for a constant electric field is given.

It is well known that an increase in field intensity in a dielectric above a certain critical level may lead to an abrupt growth of charge carrier concentration and, consequently, of the conductivity therein. This effect in the form of a dielectric breakdown can arise at the surface of laser resonator mirrors, in semiconductor devices exposed to a powerful field. A dielectric breakdown can be caused either by a constant electric field, or by electromagnetic waves. In the present paper we studied the effect of quasistatic waves, as well as the influence exerted by the interference effects in a sample. The most probable place for a dielectric breakdown is the sample surface, since there the breakdown threshold is lower than in the bulk. The reason for this in most cases are adsorbed particle impurities on the surface, the presence of inhomogeneities there, and violation of the crystal lattice regularity [1, 2]. The breakdown at the sample surface is determined by the field intensity at the frontal surface, which arises in the presence of interference of the incident and reflected waves.

Transition to the metallic phase is brought about by the abrupt, avalanche-like, growth of the number of charge carriers. When under the effect of an electric field the "hot" electrons acquire energy sufficient for an electron-hole pair excitation and their generation rate prevails over the rate of recombination, the breakdown stage sets in. Such a breakdown mechanism is of an ionization type: excitation of electrons by an external field and their transfer to higher energy levels. A breakdown arises when the field strength exceeds the critical value, which for the case of a static field we denote as $E_{br}$. The breakdown by ionization is the principal mechanism in the case of a quasistatic field when the condition

$$\omega^2 \tau_{rel}^2 \ll 1$$

is satisfied, where $\omega$ is the cyclic frequency of the signal and $\tau_{rel}$ is the electron relaxation time. In particular, for the case considered in the present paper $\omega \approx 10^{13}$ Hz and $\tau_{rel} \approx 10^{-13}$ for semiconductors at $E \approx 10^5$ V/m [1]. Thus, the above condition is well satisfied. When this condition is not satisfied or the energy of a field quantum is close to the energy band gap, an important role is played by the multiphoton absorption. It is worth noting that when the excess of the field intensity over the critical value is small and subsequently disappears, the breakdown is a reversible process.

In the bulk of the sample two competitive processes take place: generation of free carriers in the region where $E > E_{br}$ and recombination of carriers throughout the sample. Absorption in the near-surface layer
decreases the field intensity to a level below the critical one. Besides, the breakdown threshold value at the surface is lower than in the bulk of the sample. This justifies the assumption that generation of electron-hole pairs takes place only at the sample surface and that nonequilibrium carriers appear in the sample bulk only as a consequence of diffusion. Therefore, in the sample bulk, only recombination of charge carriers occurs. Within the recombination time they diffuse into the sample bulk for a distance equal to the diffusion length $L$, on the average. Since the wave field has practically no longitudinal electric component, the drift will proceed in a “weak” external field. The final distribution of conductivity along the sample length ($x$ axis) will be exponential:

$$\sigma = eN\mu_e = \sigma_0 \exp\left(-x/L\right),$$

where $L = \sqrt{D_e\tau_{\text{rec}}}$ is the diffusion length for electrons; $D_e = (kT/e)\mu_e$ is the diffusion coefficient for electrons; $\tau_{\text{rec}}$ is the recombination time for electrons; $k$ is the Boltzmann constant; $T$ is the temperature; $e$ is the electron charge; $\mu_e$ is the drift mobility of electrons; $\sigma_0 = \sigma(x = 0) = \sigma(E(x = 0))$ is the conductivity at the frontal surface; $E = E(x = 0)$ is the electric field strength at the frontal surface;

$$N(E) = N_0\left[\exp\left((q - g)\tau_{\text{rec}}\right) + 1\right]$$

is the concentration of excited electrons in the region of their generation [2]; $N_0$ is the electron concentration in the equilibrium state ($N_0 \approx 10^{12} \text{ m}^{-3}$);

$$q = \left[\frac{e^2E^2\tau_{\text{rel}}}{M_e \cdot 1.5\Delta E}\right]$$

is the electron generation rate; $M_e$ is the effective electron mass ($M_e \approx 0.2 m_e$, $m_e = 9.1 \cdot 10^{-31} \text{ kg}$), $\Delta E$ is the energy band gap of the substance ($\Delta E \approx 1-2 \text{ eV}$), $g = 1/\tau_{\text{rec}}$ is the recombination rate of electrons in the generation region.

The life time of excited electrons in a semiconductor may be $\tau_{\text{rec}} \approx 10^{-4}$–$10^{-8} \text{ s}$, which varies according to the recombination type and depends on the carrier concentration [1].

In turn, the optical characteristics of the sample, in particular the reflection coefficient, depend on the conductivity of the reflecting layer:

$$E(x = 0) = E_0[1 + R] = E_0[1 + R(\sigma(x = 0))]$$

here $E_0$ is the strength of the incident wave field.

An exact solution of this problem would require self-consistency of spatial distributions of the conductivity and the field, which would lead to difficulties in calculations. Substantial simplification of the problem posing can be attained if the conductivity distribution over the $x$ axis is assumed to be fixed. Consider in this posing the problem of wave propagation through a material with known distribution of electric parameters. To solve it we will replace the layer with continuous distribution of complex permittivity by a set of thinner layers (justification of this replacement is given in [3]) and consider the problem of wave propagation through a multilayer structure. In the analysis we will use the method of impedance characteristics described in [4]. The field strength distribution over the $x$ axis obtained in the course of solving this problem should be coordinated with the conductivity distribution over the same axis. In this case the multilayer structure can justifiably be replaced by a two-layer one, since this leads to a simpler model of a metallic
overlayer on the dielectric substrate with the permittivity $\varepsilon$ (Fig. 1). Indeed, at the chosen wave frequency and substance parameters the wavelength is much larger than the thickness of the metal layer, which makes the model usable. In such a model of a thin metallic overlayer on a substrate, if we assume that the layer was quarter-wave one before the breakdown and that after the breakdown the condition $d_1 \gg d_2$ holds, we obtain for the reflection and transmission factors [3]:

$$
R = \frac{Z_2 - 1}{Z_2 + 1},
$$

$$
T = 2\frac{\varepsilon}{\varepsilon + \varepsilon_2} \frac{1 + Z_2\sqrt{\varepsilon_2}}{1 + Z_2} \exp(-i\varphi_2),
$$

where $Z_2$ is the input impedance of the second layer; $Z_2 = \frac{1}{\sqrt{\varepsilon_2 + \varepsilon \tanh(i\varphi_2)}}$; $\varepsilon_2 = \varepsilon - i\frac{\sigma_0}{\omega\varepsilon_0}$; $\varepsilon_0$ is the constant of the system of units; $\sigma_0$ is the conductivity averaged over the length of the second conductivity layer; $\varphi_2 = k_2d_2$ is the phase change in the layer; $k_2 = k_0\sqrt{\varepsilon_2}$; $k_0 = 2\pi/\lambda$; $\lambda$ is the wavelength in vacuum.

The metallic overlayer is assumed to be homogeneous, having the thickness $d_2$ and the conductivity determined by the conductivity in the region of charge carrier generation. A breakdown arises at a certain critical value $N_{br}$ of the electron concentration. Inside the metallic overlayer the electron concentration must not be lower than the critical value. The layer thickness $d_2$ is found from this condition. Assuming $N_{br} = 10^3 N_0$ for the substance in question, we obtain from expressions (1) and (2)

$$
d_2 = \begin{cases} 0 & \text{for } E(x = 0) < E_{br}, \\ L((q - g)\tau_{rec} - 7) & \text{for } E(x = 0) > E_{br}. \end{cases}
$$

When the sample length is known, one can find the conductivity averaged over the length of the second layer, which was used in formula (4). After averaging we find from Eq. (2)

$$
\bar{\sigma} = \frac{\sigma_0}{(q - g)\tau_{rec} - 7}.
$$

Based on physical concepts of the breakdown phenomenon, one can also assume that for a concentration of excited electrons one thousand times that of the equilibrium state, the following formula for the critical field is valid:

$$
E_{br} = \left[\frac{10.5M_e\Delta E}{e^2}\tau_{rel}\tau_{rec}\right]^{1/2}
$$

For the parameters considered in the paper we have $E_{br} \approx 4.9 \times 10^4$ V/m.

![Fig. 2](image)

Coefficients of transmission, reflection, and absorption as functions of the strength of the incident wave electric component in the case when the field maximum is at the frontal surface of the overlayer: (a) phase 1; (b) phase 2; $\Delta E = 1$ eV, $\tau_{rel} = 10^6$ s.
First we consider the case when the field strength is maximal at the sample surface. Such a system is unstable and can pass from one state to another. Figure 2 shows calculated curves of the coefficients of reflection ($R$), transmission ($T$) and absorption ($A$) versus the strength of the incident wave field. Indeed, when the critical field strength is exceeded, quasifree electrons are generated at the frontal surface. As a result the layer conductivity increases together with the coefficient of reflection from it, which leads to a decrease of the field strength at the surface and even to its dropping below the critical level. The process of electron generation stops and, after a time interval equal to the recombination time $\tau_{\text{rec}}$, the system returns to its equilibrium state. The conductivity of the layer and the coefficient of reflection decrease, the field strength at the surface increases, and the cycle repeats itself. These “switchings” do not depend on the particular shape of the concentration vs. field strength curve; the essential thing is that the electron concentration could grow considerably as the critical level of field strength is exceeded and that there was a possibility of system relaxation.

Now consider the case, when the field strength is minimal at the frontal surface of the sample. In this situation the system is also unstable and has two characteristic states. The results of calculations of the coefficients of reflection, transmission and absorption for the reflecting coating are given in Fig. 3. When the field is switched on, the leading edge of the wave produces a breakdown at the frontal surface of the sample, and the unstable situation described earlier arises. The wave, that has passed through the “metallic” layer, is reflected by the back surface of the sample, returns and interacts with the incident wave, which changes the field strength at the frontal surface. If the resulting field strength is lower than the critical value, the system comes to its equilibrium state. Thus, the critical threshold of the breakdown is increased as compared to the case of a static field.

![Fig. 3](image_url)

Coefficients of transmission, reflection, and absorption as functions of the strength of the incident wave electric component in the case when the field minimum is at the frontal surface of the overlayer: (a) phase 1; (b) phase 2; (c) phase 3; $\Delta E = 1$ eV, $\tau_{\text{rel}} = 10^6$ s.

Evidently, the critical field strengths are different for breakdowns caused by electromagnetic waves and those caused by exposure to a constant electric field, and this difference depends on the wave properties of samples.
It is interesting that the charge carrier generation is induced by the wave itself. In the optical range, this self-inducing provides a possibility for creating optical limiters. The light radiation, whose energy is somewhat lower than the semiconductor energy band gap, passes freely through the substances at low field intensity. As the intensity grows and reaches a certain critical value, the mechanism of nonlinear absorption (reflection) of the signal is switched on, and this leads to a restriction of the power of the wave that has passed through the structure [5]. Experimental data and theoretical explanation of instabilities in semiconductors exposed to a constant electric field is given in [6]. Generation of pulses at intervals of the order of the charge carrier lifetime has been observed, as a result of a breakdown and its instability.

REFERENCES

1. R. Smith, Semiconductors (Russian translation), ch. 2, Moscow, 1982.

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