

Anisotropic photoconductivity in ferroelectrics

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An anisotropic photoconductivity has been discovered in the ferroelectric $\text{Pb}_5\text{Ge}_3\text{O}_{11}$. In a field $E = 1.5 \text{ kV/cm}$, an electric-field-induced transverse photocurrent is comparable in magnitude to the photovoltaic current in the absence of a field. The mechanism for transverse photoconductivity under the experimental conditions is analyzed.

An anisotropic photoconductivity, i.e., an anisotropy of the electrical-conductivity tensor induced by light, has been predicted by Gal'pern and Kogan.^{1,2} They analyzed the mechanisms for the appearance of a photo-emf in the direction perpendicular to the static electric field during the photoionization of impurity centers in multivalley semiconductors and during the heating of an isotropic plasma in a light wave.^{1,2} An anisotropic photoconductivity in the case of interband absorption has been studied theoretically by Belinicher and Novikov,³ and it has been detected⁴ in the semiconductor GaSe. In the present letter we report the first observation of an anisotropic photoconductivity in a ferroelectric, specifically, $\text{Pb}_5\text{Ge}_3\text{O}_{11}$.

The $\text{Pb}_5\text{Ge}_3\text{O}_{11}$ crystals were studied at room temperature (a phase transition $C_3 \rightarrow C_{3h}$, involving a change in the point symmetry, occurs at $T_c = 177^\circ\text{C}$). The samples had dimensions of $5 \times 5 \times 4 \text{ mm}$ along the x , y , and z axes, respectively (Fig. 1). The light source was an LGM-11 helium-cadmium laser (wavelength of $0.44 \mu\text{m}$ and power of 10^{-2} W). The light propagated along the optic axis $C_3 \parallel z$. Electrodes of silver paste were applied to each of the side faces of the sample. The static electric field E was applied along the x axis, and the photoinduced current was measured along the y axis.

The measurements were carried out by a modulation method. Specifically, an

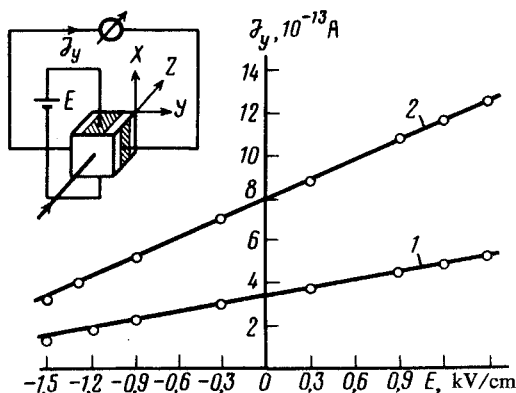


FIG. 1. Current-voltage characteristics under the conditions under which a transverse photoconductivity is observed in $\text{Pb}_5\text{Ge}_3\text{O}_{11}$, for two values of the angle β_0 : 1— $\beta_0 = 0^\circ$; 2— $\beta_0 = 45^\circ$ (room temperature, $\lambda = 0.44 \mu\text{m}$).

electro-optic modulator periodically changed the polarization state of the incident light (which was initially linearly polarized) at the frequency of a master oscillator, and the current that appeared in the crystal and that depended on the degree of linear polarization was measured with a Unipam synchronous nanovoltmeter.

In a crystal of symmetry C_3 , that component of the transverse photocurrent density which is proportional to the degree of linear polarization of the light, P_{lin} , can be written¹⁾

$$j_y = IP_{\text{lin}} [(\chi_{222} \cos 2\beta - \chi_{111} \sin 2\beta) + E_x (\tilde{\sigma} \cos 2\beta + \sigma_{2112} \sin 2\beta)] , \quad (1)$$

where $\tilde{\sigma} = (\sigma_{2122} - \sigma_{2111})/2$, χ_{klm} is the tensor of the linear photovoltaic effect, σ_{klmn} is the photoconductivity tensor, I is the light intensity, and β is the angle between the polarization plane and the y axis. Figure 1 shows I - V characteristics $j_y(E_x)$ for $\beta_0 = 0^\circ$ and 45° , where β_0 is the angle between the axes of the linear polarization of light at the entrance to the crystal and the x and y axes. In determining the components of $\tilde{\sigma}$ and σ_{2112} from the data in Fig. 1, we took into account the dependence of the light polarization and intensity in the sample on the z axis (the absorption coefficient is $\alpha \sim 5 \text{ cm}^{-1}$; the specific angle of rotation of the polarization plane due to natural optical activity is $\rho = \pm 15 \text{ deg/mm}$) and the polydomain nature of the sample (the angles ρ differ in sign in neighboring domains). As a result, we found $\sigma_{2112} = 1.3 \times 10^{-13} \text{ cm/V}^2$ and $\tilde{\sigma} = 0.5 \times 10^{-13} \text{ cm/V}^2$.

A transverse photoconduction current j_y arises during direct interband transitions when we take into account in the electron photoproduction rate g_k , in addition to the main component $g_k^{(0)} = g(k_x^2, k_y^2)$, the component $g_k^{(2)} = g_k^{(0)} a k_x k_y$, which describes the optical alignment of the momenta of the photoelectrons, with a predominant distribution along an axis making an angle of (sign a) 45° with the x axis. We also need to take into account the dependence of the momentum relaxation time τ on the electron energy ϵ . The mean free path of a photoelectron produced in a state with wave vector \mathbf{k} can be written

$$t_k = \int_0^\infty dt \exp \left[- \int_0^t dt' / \tau(\epsilon(t')) \right] , \quad (2)$$

where the function $\epsilon(t)$ describes the change in the electron energy over time caused by the electric field: $\epsilon(t) = \epsilon(k_x(t), k_y, k_z)$, $k_x(t) = k_x - (eEt/\hbar)$. Expanding τ in a series around the point ϵ_0 , and working in first order in the small parameter $eE\tau/\hbar k \ll 1$, we find the following expression for t_k as a function of the electron wave vector:

$$t_k = \tau \left(1 - \frac{\partial \tau}{\partial \epsilon} \frac{\hbar k_x}{m^*} eE_x \right) , \quad (3)$$

where m^* is the effective mass of the electrons. The transverse photocurrent is calculated from $j_y = -2e \sum_{\mathbf{k}} g_{\mathbf{k}} v_y t_k$, where $v_y = \hbar k_y / m^*$; in this approach we are assuming that the momentum distribution of the electrons becomes completely isotropic after the first scattering event. Substituting (3) into this expression, and summing over \mathbf{k} , we find, in accordance with Ref. 3,

$$j_y = \frac{2}{15} a k_0^2 \frac{e^2}{m^*} \left(\tau^2 \frac{\partial \ln \tau}{\partial \ln \epsilon} \right)_{\epsilon_0} \propto \frac{I}{\hbar \omega} E_x , \quad (4)$$

where $\epsilon_0 = \hbar^2 k_0^2 / 2m^*$, $k_0 = [2\bar{m}(\hbar\omega - E_g)/\hbar^2]^{1/2}$ is the wave vector of the electrons involved in the optical transition, E_g is the width of the energy gap, $\hbar\omega$ is the photon energy, and \bar{m} is the reduced effective mass of the electron and hole. The contribution of photo holes to j_y is described by an expression similar to (4).

Our estimates for light polarized at an angle of 45° from the vector \mathbf{E} yield

$$ak_0^2 \propto (\hbar\omega - E_g)/\bar{E}, \quad (5)$$

where \bar{E} is the energy distance between the lower conduction band or the upper valence band (these bands are assumed to be simple bands) and the nearest other band. Analysis of the optical absorption spectra shows that the wavelength $0.44 \mu\text{m}$ in $\text{Pb}_5\text{Ge}_3\text{O}_{11}$ crystals at room temperature is near the fundamental absorption edge, with an exponential ω dependence of the absorption coefficient. Under the experimental conditions we thus have $\hbar\omega < E_g$, and interband optical transitions obviously involve several optical phonons. The dimensionless parameter ak_0^2 in (4) is thus comparatively small. Assuming, for definiteness, $m^* = 0.4m_0$ (m_0 is the mass of a free electron) and $|\partial \ln \tau / \partial \ln \epsilon| = 0.5$, with $\sigma_{2112} = 1.3 \times 10^{-13} \text{ cm/V}^2$, $\alpha = 5 \text{ cm}^{-1}$, and $ak_0^2 = 10^{-2} - 10^{-3}$, we find the photocarrier mobility $\mu(\epsilon_0) = e\tau(\epsilon_0)/m^*$ to be $300 - 900 \text{ cm}^2/(\text{V} \cdot \text{s})$. The symmetry C_3 , in contrast with, say C_{3v} , D_{3h} , or D_{6h} , allows a transverse photoconduction current to be excited in the polarization $\mathbf{e} \parallel \mathbf{E}$ or $\mathbf{e} \perp \mathbf{E}$. Presumably, however, the corresponding contribution to the coefficient a will be small in comparison with that proportional to $e_x e_y$. Experimentally, we do, in fact, find that the coefficient $\tilde{\sigma}$ is roughly one-third of the coefficient σ_{2112} .

The observation of a transverse photoconductivity in the ferroelectric $\text{Pb}_5\text{Ge}_3\text{O}_{11}$ confirms the usefulness of studying this ferroelectric by the methods used in semiconductor physics.

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¹A photoconductivity $j_y \sim E_x$ can also arise during excitation by circularly polarized light that is propagating along the z axis.³

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