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Abstract

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ACOUSTO-MAGNETIC EFFECT IN PIEZOELECTRIC SEMICONDUCTORS

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PHYSICS

Recently it has become clear that some semiconductors possess piezoelectric properties. It has been established theoretically ([1]), and partly also experimentally, for example, that all semiconductors of the group $A^{III}B^{V}$ have a piezoelectric constant different from zero. A number of phenomena associated with the passage or generation of ultrasound in piezoelectric semiconductors with monopolar conductivity have been studied both experimentally and theoretically ([2–]). However, there are no works in the literature on the study of piezoelectric semiconductors with bipolar conductivity; meanwhile the new group of piezoelectrics mentioned above makes it possible to carry out studies under conditions of bipolar conductivity.

In the present work an effect inherent only in piezoelectric semiconductors with bipolar conductivity is investigated theoretically. This effect, which we shall call the acousto-magnetic (a.m.) effect, consists in the following: if ultrasound is passed through a piezoelectric placed in a magnetic field **H**, in a direction perpendicular to **H**, then in a third direction (see Fig. 1) an electric field $E^{\text{a.m}}$ (or current $I^{\text{a.m}}$) will arise.

Fig. 1

Fig. 1

Indeed, when ultrasound passes through a piezoelectric, electrons and holes are carried along by the ultrasonic wave in one direction. If the circuit in the direction of propagation of the ultrasound is open, then the electron and hole fluxes will be equal in magnitude, so that the total electric current in this direction is zero. In a magnetic field the electrons and holes will be deflected in opposite directions and thereby create a potential difference $V^{\text{a.m}}$.

An analogous effect also takes place in semiconductors that do not possess piezoelectric properties. In such semiconductors the interaction of the acoustic wave with electrons and holes is effected by means of the deformation potential. As a rule, this interaction is considerably weaker than the piezoelectric one, and therefore in certain cases the a.m. effect in piezoelectrics will be considerably larger.

For simplicity let us consider a one-dimensional model of a piezoelectric with equilibrium concentrations of electrons and holes n_0 and p_0. We shall assume that the ultrasonic wave, propagating in the direction of the y-axis, is transverse, and represent it in complex form as $U = U_0 e^{i(ky-\omega t)}$, where k, ω are respectively the wave number and frequency of the ultrasound, and U_0 is the initial amplitude of the wave at the surface of the specimen. The electric induction $\mathbf{D}$, field $\mathbf{E}$, and displacement U are related by the equations

$$\mathbf{D} = \eta \frac{\partial U}{\partial y}\mathbf{j} + \varepsilon \mathbf{E}; \qquad \frac{\partial D}{\partial y} = 4\pi e(p-n); \qquad \frac{1}{S^2}\frac{\partial^2 U}{\partial t^2} - \frac{\partial^2 U}{\partial y^2} = -\frac{\eta}{\rho S^2}\frac{\partial E_y}{\partial y}, \quad (1)$$

where η, ε are respectively the piezoelectric and dielectric constants; S is the sound velocity for $\eta = 0$, $p_0 = n_0 = 0$; ρ is the density of the substance; $\mathbf{j}$ is the unit vector in the direction of the y-axis.

We write the equation for the electron and hole currents in the presence of a magnetic field in the form [11]

$$\begin{aligned} \mathbf{j}_n &= \varphi_n\{\mathbf{j}_n^* + \operatorname{tg}\theta_n[\mathbf{j}_n^*\vec{\chi}]\} + (1-\varphi_n)(\mathbf{j}_n^*\vec{\chi})\vec{\chi}, \\ \mathbf{j}_p &= \varphi_p\{\mathbf{j}_p^* + \operatorname{tg}\theta_p[\mathbf{j}_p^*\vec{\chi}]\} + (1-\varphi_p)(\mathbf{j}_n^*\vec{\chi})\vec{\chi}, \end{aligned} \quad (2)$$

where $\mathbf{j}_n^* = e\mu_n n\mathbf{E} + eD_n \operatorname{grad} n$, $\mathbf{j}_p^* = e\mu_p p\mathbf{E} - eD_p \operatorname{grad} p$; θ_n, θ_p are the Hall angles of the electrons and holes; φ_n and φ_p are kinetic integrals, in particular, for an energy-independent relaxation time, they are equal to $\{1+(\mu_{n,p}H/c)^2\}^{-1}$; c is the speed of light; $\vec{\chi}$ is a unit vector in the direction of the magnetic field.

The continuity equations for electrons and holes have the form

$$\frac{\partial n}{\partial t} = \frac{1}{e}\frac{\partial j_{ny}}{\partial y} - \frac{n-n'}{\tau}, \qquad \frac{\partial p}{\partial t} = -\frac{1}{e}\frac{\partial j_{py}}{\partial y} - \frac{p-p'}{\tau}, \quad (3)$$

where τ is the lifetime of nonequilibrium current carriers; n' and p' are the concentrations of electrons and holes that would be established in the semiconductor if the deformation produced by the ultrasonic wave were static. These concentrations, determined from the conditions $j_{ny}(\omega = 0) = 0$, $j_{py}(\omega = 0) = 0$ (we assume the specimen to be sufficiently thick, so that the variation of the concentrations n and p at $U = 0$ may be neglected; see, for example, [13]), are equal to $n' = n_0 e^{e\tilde{\varphi}/kT}$, $p' = p_0 e^{-e\tilde{\varphi}/kT}$, where $\tilde{\varphi} = -\int_0^y \tilde{E}_y\, dy$, $\tilde{E}_y$ is the variable part of the electric field. Taking the electric field to be potential, imposing the condition of homogeneity in the direction of the x-axis ($L \gg d$), and also taking into account that the velocity S differs little from the true speed of sound, i.e., $kS = \omega$, we obtain the following formula for the coefficient of absorption (amplification) of ultrasound α:

$$\alpha = \frac{\eta^2\omega}{2\varepsilon CS}\,\frac{\nu_n\nu_p N_1}{N_1^2+N_2^2}, \tag{4}$$

where the following notation has been introduced

$$N_1 = \nu_n\frac{\omega_p}{\omega}\left(1+\frac{\omega_\tau\omega_{Dp}}{\omega^2}\right)\left(1-\frac{v_p}{S}\right)+\nu_p\frac{\omega_n}{\omega}\left(1+\frac{\omega_\tau\omega_{Dn}}{\omega^2}\right)\left(1-\frac{v_n}{S}\right);$$

$$N_2 = \nu_n\nu_p+\nu_p\frac{\omega_n}{\omega_{Dn}}\left(1+\frac{\omega_\tau\omega_{Dn}}{\omega^2}\right)^2+\nu_n\frac{\omega_p}{\omega_{Dp}}\left(1+\frac{\omega_\tau\omega_{Dp}}{\omega^2}\right)^2;$$

$$\nu_n = \left(\frac{\omega_\tau}{\omega}+\frac{\omega}{\omega_{Dn}}\right)^2+\left(1-\frac{v_n}{S}\right)^2; \qquad \nu_p = \left(\frac{\omega_\tau}{\omega}+\frac{\omega}{\omega_{Dp}}\right)^2+\left(1-\frac{v_p}{S}\right)^2;$$

$$\omega_\tau = \frac{1}{\tau}; \qquad \omega_n = \frac{4\pi e\varphi_n\mu_n n_0}{\varepsilon}; \qquad \omega_p = \frac{4\pi e\varphi_p\mu_p p_0}{\varepsilon};$$

$$\omega_{Dn} = \frac{S^2}{D_n\varphi_n}; \qquad \omega_{Dp} = \frac{S^2}{D_p\varphi_p};$$

$v_n = \varphi_n\mu_n E_x\,\mathrm{tg}\,\theta_n$; $v_p = -\varphi_p\mu_p E_x\,\mathrm{tg}\,\theta_p$; E_x is the external electric field, C is the elastic constant.

For $p_0 = 0$ ($\omega_p = 0$) we obtain from (4) the expression

$$\alpha = \frac{\eta^2\omega}{2\varepsilon CS}\,\frac{\frac{\omega_n}{\omega}\left(1+\frac{\omega_\tau\omega_{Dn}}{\omega^2}\right)\left(1-\frac{v_n}{S}\right)}{\left\{\left(1+\frac{\omega_n\omega_{Dn}}{\omega^2}\right)^2\left(\frac{\omega_\tau}{\omega}+\frac{\omega}{\omega_{Dn}}\right)^2+\left(1-\frac{v_n}{S}\right)^2\right\}}, \tag{5}$$

which, in practically interesting cases, when the inequality $\omega_\tau\omega_{Dn} \ll \omega^2$ is satisfied, goes over into the formula obtained in [12].

Figure 2 shows the dependence of α on the position of the Fermi level for GaSb at $T = 300°\mathrm{K}$, $\eta^2/\varepsilon C = 10^{-3}$, and $\omega = 2\cdot 10^8\ \mathrm{s}^{-1}$. The minimum at the center is located at the point where $n_0 \approx p_0$; its origin is due, vo-

first, because at $n_0 \approx p_0$ the best neutralization of the electric field is achieved, and, second, because the conductivity of the specimen turns out to be the smallest. When the Fermi level is shifted toward one of the edges of the forbidden band, the absorption coefficient increases owing to the increase in the concentration of electrons or holes (as long as $\omega < \sqrt{\omega_\tau\omega_{Dn}}$ or $\omega < \sqrt{\omega_p\omega_{Dp}}$), and then decreases when the concentration of one type of carrier reaches such a value that these carriers alone screen the electric field associated with the ultrasonic wave.

Fig. 2. Dependence of the acousto-magnetic field $E^{\text{a.m}}$ (1) and of the absorption coefficient α (2) in GaSb on the Fermi level, measured from the middle of the forbidden band, at $T = 300^\circ$ K, $\omega = 2 \cdot 10^8$ s^{-1}, $w_0 = 10^7$ erg/cm$^2 \cdot$ s; $\eta^2/\varepsilon C = 10^{-3}$, $H = 10^4$ oersted. The width of the forbidden band is taken to be 0.785 eV, and the effective masses of electrons and holes $m_n^* = m_p^* = 0.15\, m_e$.

Fig. 3. Dependence of $E^{\text{a.m}}$ $(1a, ,)$ and α $(2a, ,)$ on the ultrasonic frequency ω for GaSb under the same conditions as in Fig. 2, for three concentration values: a–$n_0 = 10^{12}$ cm^{-3}, $-n_0 = 5 \cdot 10^{12}$ cm^{-3}, $-n_0 = 10^{13}$ cm^{-3}.

From equations (2), to within terms quadratic in the wave amplitude, there follows an expression for j_x. After averaging over the wavelength, taking account of the acoustoelectric field $E_y^{\text{a.e}}$, we obtain the following expression for the density of the acousto-magnetic current:

$$j^{\text{a.m}} = \sigma_\perp E^{\text{a.m}} + \frac{e\varphi_n\varphi_p\mu_n\mu_p(\operatorname{tg}\theta_p - \operatorname{tg}\theta_n)}{(\varphi_n\mu_n n_0 + \varphi_p\mu_p p_0)} \frac{1}{2} \operatorname{Re}\left[\widetilde{E}_y^*(\tilde{p}n_0 - \tilde{n}p_0)\right]; \qquad (6)$$

where

$$\sigma_\perp = e\left\{ n_0\mu_n\varphi_n + \mu_p\varphi_p p_0 + \frac{(\varphi_p\mu_p p_0 \operatorname{tg}\theta_p + \varphi_n\mu_n n_0 \operatorname{tg}\theta_n)^2}{(\varphi_n\mu_n n_0 + \varphi_p\mu_p p_0)} \right\};$$

$\tilde{n}, \tilde{p}$ are the variable components of the electron and hole concentrations; the asterisk denotes complex conjugation.

Substituting into (6) the quantities $\tilde{p}, \tilde{n}$, and $\widetilde{E}$ found from the system (1)–(3), and integrating it over the cross section of the specimen $x = \text{const}$, we obtain, in the case of an open circuit,

$$E^{\text{a.m}} = \omega_0 e\varphi_n\varphi_p\mu_n\mu_p p_0 n_0(\operatorname{tg}\theta_p - \operatorname{tg}\theta_n)\left\{\varphi_p\mu_p\nu_n\left(1 + \frac{\omega_\tau\omega_{Dp}}{\omega^2}\right)\left(1 - \frac{v_p}{S}\right) + \right.$$
$$\left. + \varphi_n\mu_n\nu_p\left(1 + \frac{\omega_\tau\omega_{Dn}}{\omega^2}\right)\left(1 - \frac{v_n}{S}\right)\right\}\left\{\varepsilon S\omega(\mu_n\varphi_n n_0 + \mu_p\varphi_p p_0)^2\sigma_\perp dN_1\right\}^{-1}(1 - e^{-2\alpha d}), \qquad (7)$$

and with a closed circuit

$$I^{\text{a.m}} = dl\sigma_\perp E^{\text{a.m}}, \qquad \text{where } w_0 = \frac{1}{2}\rho S\omega^2 U_0^2. \qquad (8)$$

In Fig. 2, for illustration, the dependence of $E^{\text{a.m}}$ on the position of the Fermi level is plotted, and in Fig. 3 the values of $E^{\text{a.m}}$ and α, calculated from formulas (4) and (7), are given as functions of the ultrasound frequency for three positions of the Fermi level in GaSb. It is clear from the figures that, as the Fermi level approaches the middle of the forbidden band, the absorption coefficient

decreases, whereas $E^{\text{a.m}}$ increases sharply. If one starts from the estimated value of the piezomechanical constant $\eta^2/\varepsilon C = 10^{-3}$, then, as is seen from the figure, the acousto-magnetic field turns out to be very considerable. It can be shown that in the case when the piezoelectric constant $\eta = 0$ and the effect is completely determined by the deformation potential,

$$E^{\text{a.m}} = \frac{2\omega\mu\left(\operatorname{tg}\theta_p - \operatorname{tg}\theta_n\right)}{S\mu_\perp n_0 e d}\left(1 - e^{-2\alpha d}\right); \tag{9}$$

$$\alpha = \frac{\mu e (E_n - E_p)^2 n_0 \omega^2 \left(1 + \frac{\omega_\tau \omega_D}{\omega^2}\right)\left(1 - \frac{v}{S}\right)}{2\rho S^5 \left\{\left(\frac{\omega_\tau}{\omega} + \frac{\omega}{\omega_D}\right)^2 + \left(1 - \frac{v}{S}\right)^2\right\}}; \tag{10}$$

$$\omega_D = \frac{S^2}{D}; \qquad \mu = \frac{\varphi_n\varphi_p\mu_n\mu_p}{\varphi_n\mu_n + \varphi_p\mu_p}; \qquad D = \frac{D_n\mu_p + D_p\mu_n}{\varphi_n\mu_n + \varphi_p\mu_p}\varphi_n\varphi_p,$$

where

$$\mu_\perp = \left[\varphi_n\mu_n + \varphi_p\mu_p + \frac{\left(\varphi_n\mu_n \operatorname{tg}\theta_n + \varphi_p\mu_p \operatorname{tg}\theta_p\right)^2}{\varphi_n\mu_n + \varphi_p\mu_p}\right]; \qquad v = -\mu E_x\left(\operatorname{tg}\theta_p - \operatorname{tg}\theta_n\right);$$

E_n, E_p are the deformation-potential constants of electrons and holes.

Formula (9), in addition to the general assumptions made in deriving (7), is obtained when the following inequalities are satisfied:

$$\frac{(E_n - E_p)^2\mu_n^2\mu_p^2\omega^2}{(\mu_n + \mu_p)^2 S^4}\left(1 + \frac{\omega_\tau\omega_D}{\omega^2}\right) \gg 1; \qquad \left|\frac{(E_n - E_p)\mu_n\mu_p\omega_D}{(\mu_n + \mu_p)S^2}\left(1 - \frac{v}{S}\right)\right| \gg 1;$$
$$\frac{\frac{4\pi e n_0}{\varepsilon}(\mu_n\varphi_n + \mu_p\varphi_p)\left|\omega_\tau + \frac{\omega^2}{\omega_D} - i\omega\right|}{\left|\left(\omega_\tau + \frac{\omega^2}{\omega_{D_n}} - i\omega\right)\left(\omega_\tau + \frac{\omega^2}{\omega_{D_p}} - i\omega\right)\right|} \gg 1. \tag{11}$$

The first two inequalities correspond to neglecting the entrainment of current carriers by the lattice, and the third to the condition of quasineutrality.

It is not difficult to see from (4), (5), and (10) that, in the case of piezoelectric interaction, the absorption coefficient at a fixed frequency ω ($\omega < \omega_n, \omega_p$) decreases with increasing concentration of current carriers, whereas the absorption coefficient due to the deformation potential increases. Therefore, for example, in

InSb at room temperatures (in the intrinsic-conductivity region) the a.m. effect in the range of ultrasound frequencies presently accessible is entirely determined by the deformation potential.

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Note: Figure translations are in progress. See original paper for figures.