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Abstract

Full Text

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The Acoustoelectric Effect in CdSe in the Regime of Continuous Amplification of Ultrasound by an Electron Stream

(Presented by Academician S. A. Khristianovich, July 14, 1966)

The acoustoelectric (a.e.) effect consists in the fact that an ultrasonic wave passing through a semiconductor crystal leads to the formation of a constant potential difference at the ends of an open crystal, or, if the ends of the crystal are connected by a conductor, a current arises in the circuit ([1]). The purpose of the present work is to investigate the a.e. effect under conditions of continuous amplification of sound waves and to compare the experimental results with theory.

An expression for the a.e. emf in a piezosemiconductor can be obtained by calculating the average force acting on the electrons due to the sound wave. In doing so it is not at all necessary to specify the state of the electron-hole plasma of carriers itself; it is sufficient to assume that the medium (lattice + current carriers) is described by a known tensor of dielectric permeability $\varepsilon_{ij}(\omega, \mathbf{q})$. This approach has the advantage that it makes it possible to describe at once phenomena in many cases (for which the form of the tensor $\varepsilon_{ij}(\omega, \mathbf{q})$ is known), including in the presence of a constant drift field.

If a sound wave propagates through the crystal, the displacement vector in which is $\mathbf{u}(\mathbf{x}, t) = \mathbf{u}_0 \cos(\omega t - \mathbf{q}\mathbf{x})$, then, owing to the piezoeffect, an electric field $\mathbf{E}(\mathbf{x}, t)$ arises, and the force acting on an electron will be

$$f_i = -eE_i(\mathbf{x}, t) = -(4\pi e/\varepsilon_0)\beta_{i,kl}u_{kl}. \tag{1}$$

Here $\beta_{i,kl}$ is the piezotensor with respect to deformation; ε_0 is the static dielectric permeability of the lattice; u_{ik} is the deformation tensor. Under the action of the variable force $\mathbf{f}(\mathbf{x}, t)$, the concentration of electrons in the conduction band will vary from point to point, and the force averaged over a period, acting on the electrons in a unit volume, will be

$$\langle \mathbf{F}(\mathbf{x}, t)\rangle = \frac{\omega}{2\pi}\int_0^{2\pi/\omega} \mathbf{F}(\mathbf{x}, t)\, dt = \langle \mathbf{f}(\mathbf{x}, t) n(\mathbf{x}, t)\rangle, \tag{2}$$

where $n(\mathbf{x}, t)$ is the electron concentration. The current induced in the medium by the sound wave is

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$$j_i(\mathbf{x},t) = \int dx'\, dt'\, \sigma_{ij}(\mathbf{x}-\mathbf{x}', t-t')(E_j(\mathbf{x}',t') + E'_j(\mathbf{x}',t')), \tag{3}$$

where $\sigma_{ij}(\mathbf{x},t)$ is the conductivity tensor of the medium, and $\mathbf{E}'(\mathbf{x},t)$ is the self-consistent electric field determined from Poisson' s equation

$$\text{div}\ \varepsilon_0 \mathbf{E}'(\mathbf{x},t) = -4\pi e(n(\mathbf{x},t) - \langle n(\mathbf{x},t)\rangle) \quad (\langle n(\mathbf{x},t)\rangle = n_0). \tag{4}$$

Using further the continuity equation for the electrons and passing to Fourier components in expressions (3), (4), for the average force (2) we find

$$\langle \mathbf{F}\rangle = -\eta^2 S(q/2v_s)\,\text{Im}(\varepsilon_0/\varepsilon_{qq}(\omega q)). \tag{5}$$

Here $S = \frac{1}{2}\rho v_s \omega^2 u_0^2$ is the density of the flux of sound energy; $\eta^2 = 4\pi\beta_{x,xy}/\rho\varepsilon v_s^2$ is the electromechanical constant; ρ is the density of the material; v_s is the velocity of the corresponding sound wave; $\varepsilon_{qq}(\omega,\mathbf{q}) = \varepsilon_0 + 4\pi\sigma_{ij}(\omega,\mathbf{q})q_{iq}j/i\omega q^2$ is the longitudinal permittivity of the medium (here a transverse sound wave with polarization vector along the y-axis is considered). Obviously, the direct electric current through a unit area of a short-circuited semiconductor will be

$$\mathbf{j}^{(\text{ac})} = \frac{e}{m}\tau\langle\mathbf{F}\rangle = -\mu S\eta^2 \frac{\mathbf{q}}{2v_s}\,\text{Im}\left(\frac{\varepsilon_0}{\varepsilon_{qq}(\omega,\mathbf{q})}\right), \tag{6}$$

where τ is the time between collisions, m is the effective mass of the carrier, $\mu = \frac{e}{m}\tau$ is the mobility. Comparing (6) with the expression for electronic attenuation (or amplification) of sound waves in piezosemiconductors ([2]), we see that, independently of the specific form of the longitudinal permittivity of the medium $\varepsilon_{qq}(\omega,\mathbf{q})$, the Weinreich relation ([1]) is satisfied*. If, for example, in (6) we substitute the values of $\varepsilon_{qq}(\omega,\mathbf{q})$ from work ([3]), we obtain the result of work ([4]). Other expressions for the acoustoelectric emf or current may be obtained in an analogous way; for this it is sufficient only to substitute the known expressions for $\varepsilon_{qq}(\omega,\mathbf{q})$ into formula (6)**. If the crystal is open-circuited, then the acoustoelectric emf will obviously be

$$\varepsilon^{(\text{ac})} = -\frac{1}{en_0}\int_0^l \langle F\rangle\, dx = -\frac{S_0}{en_0 v_s}\frac{\alpha}{\alpha+\gamma}\left(1 - e^{-(\alpha+\gamma)l}\right), \tag{7}$$

where $\alpha = \eta^2 q\ \text{Im}(\varepsilon_0/\varepsilon_{qq}(\omega,\mathbf{q}))$ is the plasma part, and γ the lattice part, of the attenuation of the sound wave; l is the length of the crystal. In deriving (7) it was used that $S(x) = S_0 e^{-(\alpha+\gamma)l}$, where S_0 is the value of the flux of sound energy at the point $x = 0$.

When there is a directed flux of carriers in the semiconductor, then, at a drift velocity exceeding the phase velocity of the sound wave, amplification of the

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latter is possible ([2,3]). If the drift velocity of the electrons is equal to the phase velocity of the sound wave, then, as is known ([2,3]), the plasma attenuation of sound becomes zero, $\alpha = 0$, and, consequently, the acoustoelectric current or emf vanish under these conditions. Upon further increase of the drift velocity of the electrons, the plasma attenuation becomes negative ($\alpha < 0$), and therefore the acoustoelectric current and emf must change direction. It is essential that such behavior of the acoustoelectric emf and current does not depend on the magnitude of the lattice attenuation γ, which makes it possible to determine more accurately the threshold for amplification of sound waves. For a known constant field on the crystal and a known sound-wave velocity, this makes it possible to measure the drift mobility of the carriers, and conversely, for a known mobility and field, to measure the velocity of the corresponding sound wave.

To clarify the regularities in the dependence of the acoustoelectric emf on the magnitude of the applied drift field, the following experiment was set up. From a CdSe single crystal, a specimen was prepared with dimensions $3.5 \times 3.5 \times 20$ mm, whose length coincided with the y-axis of the crystal. One of the end faces of the specimen was made flat to an accuracy of $1\,\mu$ and was polished. Upon placing this

* This, however, by no means means that the Weinreich relation has a universal character. It is easy to see that it is sufficient to take into account the presence of a second type of carriers for it already to be violated: for example, in an intrinsic semiconductor with equal mobilities of electrons and holes the acoustoelectric current and emf are zero, whereas the plasma attenuation is different from zero.

** Thus, in particular, one can obtain expressions for the acoustoelectric effect also in a longitudinal quantizing magnetic field; for this, in (6) one must substitute the values of $\varepsilon_{qq}(\omega, \mathbf{q})$ found in ([5]). Like the attenuation of sound waves ([5]), the acoustoelectric emf and the magnitude of the current must experience "giant" quantum oscillations as functions of the magnitude of the longitudinal magnetic field.

at the end of the crystal into the electric-field antinode of a coaxial resonator, electromagnetic oscillations were converted into acoustic ones, and a transverse acoustic wave polarized along the c_6 axis was excited in the specimen. The wave frequency was 350 MHz; for convenience in measurements the wave was modulated by a square wave at a frequency of 1 kHz. At distances of 8 and 13 mm from the front end, and on the rear end of the specimen, electrodes were deposited; these served for connecting high-voltage batteries and a selective voltmeter, which recorded the acoustoelectric signal (Fig. 1). To create the required concentration of conduction electrons, the specimen was illuminated with a projection lamp. The front part of the specimen was used only for excitation and preliminary amplification of the acoustic wave. The magnitude of the amplification was about 60 dB/cm. The amplified acoustic wave entered the end part of the specimen, on which the acoustoelectric emf was recorded.

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Fig. 1

Figure 1: Fig. 1

Fig. 2

Figure 2: Fig. 2

Fig. 1. Schematic diagram of the experiment for observing the a.e. effect. 1—350-MHz resonator, 2—CdSe crystal, 3—electrodes, b_1 and b_2—batteries for applying the drift field.

The dependence of the acoustoelectric emf on the field in this part of the specimen is shown in Fig. 2. Fig. 2 also gives the theoretical curve, calculated from formula (7), with the longitudinal permittivity of the medium $\varepsilon_{qq}(\omega, q)$ taken as the known expression including electron drift [2].

$$\varepsilon_{qq}(\omega, q) = \varepsilon_0 + \frac{4\pi\sigma_0}{i\omega} \times$$

$$\times \frac{1}{1 - \dfrac{v_d}{v_\phi} - i\omega\tau v_T^2/v_\phi^2}$$

$$\left(v_\phi = -\frac{\omega}{q} \simeq v_s, \quad v_d = \mu E_d\right). \tag{8}$$

Here $\sigma_0 = en_0\mu$ is the dc conductivity; $v_T = (\chi T_e/m)^{1/2}$ is the thermal velocity of the electrons; $T_e = T_p(1+\xi v_d^2/v_s^2)$ is the effective electron temperature, which depends on the drift field E_d; T_p is the lattice temperature. The parameter ξ is determined by the type of carrier scattering, i.e., by the dependence $\tau(\varepsilon)$, where ε is the electron energy; thus, for scattering by centers for which $\tau = \text{const}$, the parameter $\xi = 1/3$ [6].

Fig. 2. Dependence of the acoustoelectric emf on the magnitude of the drift field. 1—experimental curve, 2—theoretical.

(The value $\xi = 1/3$ was used in the numerical estimates.) Allowance for electron heating by the drift field in the region $qr_0 > 1$ $\left(r_0 = \sqrt{\chi T_e \varepsilon_0/4\pi e^2 n_0}\right.$ is the Debye radius of the electrons) is very substantial, since it mainly determines the fall of the acoustoelectric emf in the region of large fields.

values of the drift field. The values of the constants for the CdSe crystal were as follows: $\mu = 720$ cm^2/V $\cdot$ s, $\eta = 7 \cdot 10^{-3}$, the velocity of the transverse sound wave $v_s = 1.52 \cdot 10^5$ cm/s, $T_p = 300$°K. The theoretical curve in Fig. 2 is given for $n_0 = 2.5 \cdot 10^{12}$ cm^{-3}.

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As can be seen from Fig. 2, the agreement between theory and experiment is fairly good; however, in the region of large field values ($v_d > 2.5\,v_s$) the theory gives somewhat overestimated values for the acousto-emf. The agreement between theory and experiment in this range of field values can be substantially improved if the decrease in carrier concentration with increasing field is taken into account. Physically, this process, as it turns out, is due to the thermal quenching of photoconductivity (7).

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CITED LITERATURE

1. G. Weinreich, T. M. Sanders, H. G. White, Phys. Rev., **114**, 33 (1959).
2. V. I. Pustovoit, FTT, **5**, 2490 (1963).
3. A. R. Hutson, D. L. White, J. H. McFee, Phys. Rev. Lett., **7**, 237 (1961).
4. V. B. Sandomirskii, Sh. K. Kogan, FTT, **5**, 1894 (1963).
5. V. I. Pustovoit, I. A. Poluektov, ZhETF, **51**, 1265 (1966).
6. V. L. Ginzburg, *Propagation of Electromagnetic Waves in Plasma*, § 38, Moscow, 1960.
7. R. Bube, *Photoconductivity of Solids*, IL, Chap. XI, 1962.

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