Acoustic effects of an asymmetric electrical conductivity

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The asymmetry of electrical conductivity which has recently been discovered in crystals lacking an inversion center should give rise to some new acoustic effects.

Kazlauskas and Levinson[1] introduced the fundamental assertion that a current component which is even in the electric field is permissible [i.e., that there would be an asymmetry of the current and of the electrical conductivity, since in this case we would have $\mathbf{j}(\mathbf{E}) \neq -\mathbf{j}(-\mathbf{E})$]. The studies that followed revealed two mechanisms: an asymmetry of the carrier scattering[2,3] and the presence of microscopic and macroscopic barriers.[4,5] A sound wave in a piezoelectric crystal is accompanied by an electric field, so we would expect an asymmetry of the conductivity to also lead to new acoustic effects. These effects, in addition to being of interest in their own right, would be very convenient for studying the electrical asymmetry because of the simplification or complete absence of contacts. Corresponding experiments could provide a reliable confirmation of the experimental results of Refs. 2 and 4.

We first assume that the asymmetry of the conductivity is due to an asymmetry of the scattering of carriers. We consider a p-type InSb crystal, since this is the only case for which an experimental study has been carried out.[2] In this crystal, an electric field E parallel to the [110] direction (which we take as the ξ axis) gives rise to a transverse current $j_\perp = \chi E^2$ along the crystallographic Z axis.[2] The electric field of a piezoelectrically active sound wave propagating along the ξ axis, with displacement along the Z axis, will naturally give rise to a nonstandard effect: a transverse current which is even in the wave vector. The mechanism is fundamentally different from a concentration nonlinearity, which gives rise to an ordinary longitudinal acoustoelectromotive force.[6] Substituting in the expression for the electric field of a sound wave in a conductor,[7] and taking an average over the time, we find

$$j_\perp = \frac{\chi e_{14}^2}{2\epsilon^2}\left[1+\left(\frac{\omega}{\omega_D}\right)^2\right]\left[1+\left(\frac{\omega_c}{\omega}+\frac{\omega}{\omega_D}\right)^2\right]^{-1}|A|^2 . \tag{1}$$

Here e_{ij} is the piezoelectric modulus, ϵ is the dielectric constant, $\omega_c = \sigma/\epsilon$, σ is the conductivity, $\omega_D = s^2/D_n$, D_n is the diffusion coefficient, s is the sound velocity, ω is the angular frequency of the sound, and A is the strain amplitude. We have used the condition $kl \ll 1$, where l is the hole mean free path, and k is the wave number. For InSb at 77 K, we then find the limitation $\omega \ll 10^{11}$ s^{-1}. We make the natural assumption that σ and χ do not depend on ω, while χ/σ depends weakly on the carrier density. In InSb at a hole concentration of 10^{15} cm^{-3} (an order of magnitude lower than in Ref. 2), at $\omega = 10^{10}$ s^{-1}, at an electrode length of 0.3 mm along ξ (the attenuation of the sound must be taken into account), and at a strain amplitude of 10^{-5} at the input, an acoustoelectromotive force of about 20 mV/cm would then be induced in the electrodes. An important point is that this electromotive force is of essentially the same magnitude as the ordinary longitudinal acoustoelectromotive force for given parameter values. It may be that this effect has already been observed, in Ref. 8 and several subsequent studies, where a large transverse acoustoelectromotive force was found (and attributed to a nonuniformity of the illumination or several other secondary factors).

We wish to stress the Shmelev *et al.*[9] have mentioned the possibility in principle of the appearance of a transverse acoustoelectromotive force for certain definite asymmetry mechanisms in the opposite limit, $kl \gg 1$. The effect which they were dealing with, however, would be difficult to observe (it is four orders of magnitude weaker than the longitudinal acoustoelectromotive force).

A slightly different version seems more promising. Let us assume that two sound waves of identical frequency ω are propagating in the direction opposite each other along the ξ axis. The product of the electric fields of the oppositely directed waves in the expression for the current contains a term which is uniform along ξ and which varies at a frequency 2ω. The signal representing the acoustoelectromotive force that is received will be an unusual case of a transverse convolution in the interior of a single crystal, rather than at its boundary.[6] The expression for the current oscillation amplitude differs from (1) only in that $|A|^2$ is replaced by $2|A_1A_2|$, where A_1 and A_2 are the strain amplitudes for the oppositely directed waves.

Another very interesting topic is an asymmetry of the conductivity which results from microscopic and macroscopic barriers. At fields of hundreds of volts per centimeter, a difference in the conductivity values in opposite directions ranging up to an order of magnitude has been observed experimentally.[4] This situation could lead to an interesting effect in the field of a standing sound wave. When this wave is turned on, a "rectified" current, periodic in space, will arise because of the alternating piezoelectric field. In the steady state, in which there is no rectified current, there should be a charge and an electric field which are periodic in space. An electrooptic effect would make it possible to observe this structure, by virtue of the change in the refractive index (cf. the photorefractive effect[10]). In contrast with the case of an asymmetry due to scattering, however, the frequency dependence of the current is not clear here. Consequently, the suggested experiment could confirm, but could not refute, the results of Ref. 4. It would also be convenient for determining the nature of the barriers used, from the frequency dependence. Let us find an estimate for the case in which there is no frequency dependence in the megahertz group (it is a simple matter to suggest some simple models of such barriers). We consider a crystal of the $3m$ type. We assume that a sound wave with a strain amplitude $A \cos kz \cos \omega t$ has a displacement along the crystallographic Z axis and that a probing light beam is polarized along the Z axis. The perturbation in the refractive index for a pronounced asymmetry of the current can thus be estimated roughly, in order of magnitude, from

$$\Delta n \sim \frac{n^3 \Gamma_{33} e_{33}}{2\epsilon_{33}} A \cos(kz + \alpha). \qquad (2)$$

Here n is the unperturbed refractive index of the probing beam, ϵ_{ij} is the low-frequency dielectric constant, e_{ij} is the piezoelectric modulus, and Γ is the linear electrooptic tensor. For $LiNbO_3$ with $A = 10^{-4}$ we find $\Delta n \sim 10^{-4}$.

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