Acoustovoltaic effect in semiconductors

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A new effect in semiconductors—an acoustovoltaic current associated with the ejection asymmetry of electrons from a trapping level—is described below. In a linear approximation it leads to the previously unconsidered fundamental asymmetry for sound propagation in two, mutually opposite directions, which is not associated with the presence of an external field.

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The ejection asymmetry of electrons from traps was observed in an investigation of the anomalous photovoltaic effect (see review in Ref. 1). As a result of uniform illumination of a homogeneous, pyroelectric crystal specimen, a short-circuit current or photovoltage of tens of kV/cm, which is associated with the holographic memory mechanism in a number of ferroelectric crystals, is produced. The cause is seen in the fact that, because of the asymmetry of the potential field of the impurity, the ejection of an electron from an impurity level into the conduction band by the action of light occurs, on the average, in some preferential direction along a particular polar axis (trapping is also asymmetrical). It was pointed out that such asymmetry is also characteristic of type A_2B_6 crystals that belong to the 6 mm symmetry class. However, observation of the anomalous photovoltaic effect in them is complicated by the large photoconductivity.[1] For simplicity, we shall restrict our discussion to acoustical effects in these crystals.

Let us assume that the charge carriers are electrons and that their mobility μ is isotropic. The problem of sound propagation in such crystals under the above-stated restrictions was solved in Ref. 2 for an arbitrary direction of sound propagation. During the passage of a piezoactive wave in a crystal, the electron density in the conduction band is perturbed, which leads to a breakdown of the equilibrium for the electron between the conduction band and trapping levels. For simplicity, let us assume that equilibrium is re-established in a shorter time than the period of the sound wave. (For CdS, for example, it was possible to observe a relaxation time of $\sim 10^{-10}$ sec.[3]) For re-establishment of equilibrium a preferential filling or emptying of the trapping levels must occur. By analogy with the photovoltaic current, it is clear that this inevitably leads to the appearance of a local current which is associated with the electron-capture (ejection) assymmetry. We call this the acoustovoltaic current. It is clear that it will appear only in the symmetry classes that allow the pyroelectric effect. In a first approximation it is natural to assume that

$$\mathbf{j}_a = q\Delta\mathbf{l}\frac{\partial n_t}{\partial t}, \tag{1}$$

where n_t is the number of electrons in the trapping levels, q is the electron charge, and $\Delta\mathbf{l}$ is the averaged displacement vector of an electron which is ejected from an impuri-

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ty level during the free transit time. In the equilibrium state, of course, the current must be absent. From symmetry considerations, $\Delta \mathbf{l}$ is parallel to the C axis. For estimates, let us assume that $\Delta l \approx pl$, where l is the electron mean free path length and p is a factor characterizing the electron ejection asymmetry.

Thus, consideration of the acoustovoltaic current reduces to that of including the additional term (1) in the expression for the total current. The remaining equations are completely identical to those given in Ref. 2. We shall not write the final expressions for the sound velocity, absorption coefficient, etc., since the only difference from the corresponding formulas of Ref. 2 is that of replacing the diffusion frequency ω_D by some effective value ω_D'

$$\omega_D' = \omega_D \left\{ 1 - \frac{(1-f)\,\Delta l s \cos\theta}{f D_n} \right\}^{-1}. \tag{2}$$

Here, f is the usual trap factor, s is the velocity of sound, $\omega_D = s^2/fD_n$, D_n is the diffusion constant, and θ is the angle between the direction of $\Delta \mathbf{l}$ and that of wave propagation. It is clear that the value of ω_D' is different for propagation in two opposite directions. For very small f (a highly compensated semiconductor) ω_D' can even go to zero in one of the directions, i.e., the diffusion current is compensated for by the acoustovoltaic current. However, it is obviously more reasonable to use simpler cases when the asymmetry of the absorption coefficient is very large.

In accordance with the crystal symmetry, $\Delta \mathbf{l}$ is parallel to the C axis. Therefore, the asymmetry is missing in the usual case of transverse waves which propagate perpendicularly to the C axis. We are interested either in longitudinal waves which propagate along the C axis, or quasi-longitudinal and quasi-transverse piezoactive waves which propagate at an angle to the C axis. Let us present estimates for a quasi-transverse, 1-GHz wave which propagates at a 30° angle to the C axis. We shall use parameters typical of CdS at a temperature of 80 K.[4] Let us assume that $f = 0.1$, $p = 0.3$, $\mu = 4 \times 10^3$ cm^2 V·sec^{-1}, $\gamma = 1 - v_d/s = -0.1$, where v_d is the electron drift velocity. Thus, for the two opposite directions in the crystal we obtain gain coefficients of 18 and 25 cm^{-1}, respectively, for a conductivity of 10^{-4} ohm^{-1} cm^{-1}. (Let us emphasize that the electric field each time is directed opposite to the sound propagation direction in order to exclude the field-produced asymmetry.) For a conductivity of 5×10^{-5} ohm^{-1} cm^{-1}, we obtain gain coefficients of 10 and 14 cm^{-1}. For $\gamma = 0.1$ the absorption coefficients are the same.

This means that a significant difference in the acoustic properties of a crystal can be observed in two opposite directions for an appropriate choice of parameters. In particular, the generation of sound by an external, dc electric-field pulse occurs in the corresponding oblique crystal cut with a different intensity when the direction of the external field is reversed.

We shall not discuss here other obvious manifestations of this asymmetry, but only mention the following special case, which can be important at low temperatures. In A_2B_6-type compounds the contribution of the asymmetrical central cell to the field of the impurity ion is so large that attempts to use the hydrogen model to describe the

shallowest traps are groundless.[4] Only for certain crystals (including CdS) does the calculation of the effective mass from the hydrogen model for one of the shallow levels not lead to a contradiction, although the applicability of the hydrogen model is dubious.[4] Simple estimates show that even when we attempt to remain within the framework of the hydrogen model, we arrive at the unavoidable conclusion of severe asymmetry of the impurity field. In fact, the electric field of the ion is oppositely directed on different sides of the ion and, accordingly, produces via the piezoeffect, deformations of opposite sign. Thus, the elastic deformations produce, via the deformation potential, an asymmetry in the value potential field which acts on the electron (justification for the "macroscopic" treatment of the deformation is the same as that for introducing the dielectric constant). In the CdS crystal such asymmetry of the potential field at a distance of the Bohr radius from the center of the ion is of the same order of magnitude as the binding energy of the electron in the impurity level; i.e., even at low temperatures, when impurity levels of the above-stated type can serve as trapping levels, the electron ejection asymmetry can be very large.

Thus, the acoustovoltaic current and the asymmetry of the sound propagation open up a new aspect of the manifestation of electron ejection asymmetry and provide an effective method for studying this recently discovered, interesting effect.

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