ACOUSTOELECTRIC "AFTEREFFECT" IN PHOTOCONDUCTORS

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We shall show here that a new class of phenomena, which we shall call acoustoelectric "aftereffect," should be observed in photoconducting crystals. When elastic oscillations and an alternating electric field of the same frequency interact, a relatively slowly relaxing inhomogeneity of the electric properties of the crystal sets in. When the alternating electric field is turned on again (but the acoustic generator is not turned on again), an elastic wave is generated in the crystal. We confine ourselves, for simplicity, to the most interesting case of piezoelectric crystals, since the generalization to the case of a deformation potential is obvious and has been carried out a number of times for similar problems. We emphasize that this pheonomenon has apparently already been observed experimentally in a more complicated modification [1].

We present first a qualitative picture of the phenomenon and introduce the necessary notation. Assume that an elastic wave with relative-deformation amplitude $A_0 \exp[i(kx - \omega t) - \alpha x]$ propagates through the crystal. At the instant $t = 0$ we apply to the crystal along the X axis an alternating electric field $E_1\exp(i\omega t)$. Since the current is proportional to the product of the carrier density by the electric-field intensity, the alternating electric field and the sound-induced correction to the carrier density give rise to a nonequilibrium increment to the carrier density, of the form $\exp(ikx)$. The recombination will then be more intense in some parts of the crystal than in others, and a spatially-inhomogeneous bound space charge is produced at the recombination levels. At the instant $t = t_1$ we turn off the field, and then we turn off the sound generator. The space charge at the recombination levels and the field produced by it produce as before a nonequilibrium increment of the type $\exp(ikx)$ to the carrier density (its magnitude will of course change after the field is turned off). The system will relax to equilibrium with a characteristic carrier lifetime τ in the conduction band. If an alternating electric field $E_2\exp(i\omega t)$ is again turned on at the instant $t = t_2$, then, naturally, a field inhomogeneity of the type $\exp[i(kx + \omega t)]$ will again appear in the system with inhomogeneous carrier distribution (correction of the $\exp(ikx)$ type), and generates via the piezoeffect sound [2, 3] having the same frequency as the initial sound.

In the case of piezoelectrics, it is convenient to operate in the presence of a constant electric field in the regime of weak supracriticality, when the amplification of the sound by the carrier drift is much smaller than the absorption of the reflected signal. It is unnecessary here to take into account the reflection of the sound and generation of a sound wave propagating against the carrier drift (these phenomena are disregarded below). Since prolonged action of the electric field leads to heating of the crystal, we assume that the constant field can be changed (decreased or removed completely) when $t_1 \leq t \leq t_2$. The factor $\gamma = 1 - (v_d/s)$ introduced in [4] will be designated for this time interval by a prime (γ'). For simplicity, we assume that the constant field is the same at $t < t_1$ as at $t > t_2$.

We now discuss the initial system of equations for the quantitative solution of the problem. The changes of the number of electrons in the conduction band n_c and at the trapping levels n_t and of the space charge at the recombination levels Q_r are determined by the equations

$$\begin{cases} \dfrac{\partial (n_c + n_t)}{\partial t} = F - \dfrac{n_c}{\tau} + \dfrac{1}{q}\dfrac{\partial j}{\partial x}; \\ \dfrac{\partial Q_r}{\partial t} = -q\dfrac{n_c}{\tau} + qF . \end{cases} \tag{1}$$

Here F is the number of electrons generated by the light per unit time, -q is the electron charge, and j is the current. For simplicity we assume that the holes are rapidly captured directly at the place at which they are produced (as in the case, for example in CdS [5]). We include in our consideration only "fast" traps with a characteristic trapping time τ_t such that $\omega\tau_t \ll 1$. Then the partition of the nonequilibrium part of the electrons between the conduction band and the trapping levels is determined by the usual trap factor f (see [4]). These equations must be supplemented by the equations of state and of elasticity theory and by the Poisson equation. Since the forms of these equations are perfectly clear, we present immediately the final result. The amplitude of the relative deformation of the secondary wave is

$$A_1 = \frac{e^2}{8\varepsilon C}\,\frac{f^2\mu^2 E_1 E_2^*}{s^2}\left[\gamma + i\left(\frac{\omega_c}{\omega} + \frac{\omega}{\omega_D}\right)\right]^{-2}\left[(\gamma' - 1) + i\left(\frac{\omega_c}{\omega} + \frac{\omega}{\omega_D}\right)\right]^{-1}\times$$

$$\times \{1 - \exp[-\beta(\gamma)t_1]\}\exp\{-\beta(\gamma'))(t_2 - t_1)\}\, A_0 \exp(-\alpha x)\,\frac{x\omega_c}{s};$$

$$\beta(\gamma) = \frac{f\omega_c}{\omega\tau}\left\{\left(\frac{\omega_c}{\omega} + \frac{\omega}{\omega_D}\right) - i(\gamma - 1)\right\}^{-1}. \tag{2}$$

This formula has been written out for the time interval $\tau \gg t - t_2 > L/s$, where L is the sample length ($0 \leq x \leq L$). The generalization to the case of smaller t is obvious. All the symbols are standard and taken from [4]. The calculations were performed under the assumption that $(\mu^2 E_j E_j^*/s^2) \ll 1$ and $A_1 \ll A_0$. It is easily seen from (2) that for a reasonable choice of the time t_1 and t_2 and for not too small E_1 and E_2 we can obtain a sufficiently intense aftereffect.

The "aftereffect" was apparently already observed experimentally by Zemon [1]. The subtle difference lies only in the fact that the initial acoustic signal itself was generated by an alternating electric field (the corresponding generation mechanism calls for a special study). Since in Zemon's experiment $\mu^2 E_j E_j^*/s^2 \gg 1$, the aftereffect should be very large (our quantitative calculations do not apply, of course, to this case).

We note that the "slow" traps ($\omega\tau_t \gg 1$) can play in the aftereffect exactly the same role as the recombination levels. The aftereffect should then be observed also in the absence of photoconductivity.

In conclusion, the author is sincerely grateful to Dr. Zemon for a reprint of his article and for a private communication, in which it was noted that it is desirable to produce an alternate theory for the phenomena observed in [1]. This has stimulated the present investigation to a considerable degree.

[1] S. Zemon, J. Appl. Phys. 42, 3038 (1971)

[2] A.A. Chaban, Fiz. Tverd. Tela 12, 3305 (1970) [Sov. Phys.-Solid State 12, 2674 (1971)].
[3] B.A. Auld, D.A. Wilson, D.K. Winslow, and E. Young, Appl. Phys. Lett. 18, 339 (1971).
[4] D.L. White, J. Appl. Phys. 33, 2547 (1962).
[5] R.H. Bube, Photoconductivity of Solids, Wiley, 1960.

E R R A T A

The following corrections are to be made in the article by V. G. Baryshevskii et al., Vol. 15, No. 2: 1) On p. 79, in the first line after formula (2), read ... $r_0 = e^2/m_e c^2$ ... instead of ... $r_0 = \lambda^2/m_0 c^2$... 2) In the two lines above the table on p. 80, read ..."the direction of rotation of the polarization plane"... instead of ..."the direction of the polarization plane"... 3) In the second line below the table on p. 80, read ... $|\vec{n}| = 2/26 \approx 7.69\times10^{-2}$... instead of ... $\approx 7.85\times10^{-2}$... The numerical coefficient in (5) remains unchanged.

In the article by A. A. Chaban, Vol. 15, No. 2, p. 74, line 35 from the top, read ... exp[i(kx ± ωt)]... instead of ... exp[i(kx + ωt)]...

In the article by Ya. B. Zel'dovich et al., Vol. 15, No. 3, p. 111, frames "c" and "d" of Fig. 3 should be interchanged, and the scale in frame "c" should be 5 mrad.