Even electrical conductivity in piezoelectrics with streaming; separation of the shift and ballistic contributions

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(Submitted 3 February 1984)
Pis'ma Zh. Eksp. Teor. Fiz. **39**, No. 6, 268–270 (25 March 1984)

Possible mechanisms are discussed for the current which is even in the field in crystals lacking a center of inversion. It is shown that in crystals with a degenerate band under streaming conditions this current results primarily from a shift mechanism, i.e., from a displacement in **r** space of the current carriers upon quantum transitions.

A current component of even parity in the field arises when piezoelectric crystals are illuminated; the effect is called the linear photogalvanic effect.[1,2] Even before the discovery of the effect, Kazlauskas and Levinson[3] pointed out that a current even in the field could arise in a static electric field **E**. This current is determined by the third-rank tensor $\vec{\chi}$:

$$j_\alpha = \chi_{\alpha\beta\gamma} E_\beta E_\gamma . \quad (1)$$

The contribution to current (1) from the anharmonic two-phonon scattering of current carriers, which gives the carriers a directed velocity quadratic in the field, was calculated in Ref. 4. This contribution, called the "ballistic" contribution in the theory of the linear photogalvanic effect, corresponds to the incorporation in the general expression for the current,

$$\mathbf{j} = -e \sum_{n,n',\mathbf{k}} \mathbf{v}_{nn'}(\mathbf{k}) \rho_{n'n}(\mathbf{k}) , \quad (2)$$

of components of the electron density matrix $f_{n\mathbf{k}} = \rho_{nn}(\mathbf{k})$ which are diagonal in the band index n. In addition to the ballistic contribution, there is a "shift" contribution to the linear photogalvanic effect, described in (2) by the nondiagonal components $\rho_{n'n}(\mathbf{k})$ with $n' \neq n$. As was shown in Ref. 5, the shift contribution results from the displacement of an electron in coordinate space upon a quantum transition $n, \mathbf{k} \to n', \mathbf{k}'$. This contribution arises even in the Born approximation (in single-phonon transitions, for example), and the expression for the shift current can be put in the form

$$\mathbf{j}_{sh} = -e \sum_{nn'\mathbf{k}\mathbf{k}'} \mathbf{R}_{n'\mathbf{k}', n\mathbf{k}} w_{n'\mathbf{k}'; n\mathbf{k}} , \quad (3)$$

where $w_{n'\mathbf{k}, n\mathbf{k}}$ is the probability per unit time of the quantum transition, the shift is

$$\mathbf{R}_{n'\mathbf{k}', n\mathbf{k}} = -(\nabla_\mathbf{k} + \nabla_{\mathbf{k}'}) \Phi_{n'\mathbf{k}', n\mathbf{k}} , \quad (4)$$

and $\Phi_{n'\mathbf{k}, n\mathbf{k}}$ is the phase of the transition matrix element. No method has been proposed so far for separating the shift and ballistic contributions directly in an experiment.[6] Ivanov and Tkachenko[7] have discovered a quadratic conductivity, making it important to be able to separate these contributions in experiments with a static (or slowly varying) electric field. This possibility arises at low temperature under streaming conditions, when an electron accelerated in the electric field reaches an energy sufficient for the emission of an optical phonon of frequency Ω (the active region) without undergoing scattering; as it then emits a phonon, it loses essentially all its energy.[8] Under these conditions, the two-phonon processes responsible for the ballistic contribution are strongly suppressed.

We have calculated the shift current for p-type $A^{\rm III}B^{\rm V}$ semiconductors with a degenerate Γ_8 valence band. These semiconductors simultaneously exhibit polar and deformation interactions of holes with LO phonons, described by the operator

$$\mathcal{H}_{h\text{-phon}} = iC(\mathbf{q}\cdot\mathbf{u}/q^2) + (d_0/\sqrt{3}) \sum_{\alpha \neq \beta \neq \gamma} [\mathbf{J}_\alpha \mathbf{J}_\beta] u_\gamma \,, \tag{5}$$

where $\mathbf{u}$ is the displacement of the sublattices during the optical vibrations, $\mathbf{q}$ is the phonon wave vector, J_α is the matrix of the momentum operator in the representation $D_{3/2}$, $[AB] = (AB + BA)/2$, $C = e\Omega(4\pi\rho/\epsilon^*)^{1/2}$, ρ is the density, $\epsilon^{*-1} = \epsilon_\infty^{-1} - \epsilon_0^{-1}$, and ϵ_∞ and ϵ_0 are the high-frequency and static dielectric functions. Under streaming conditions, the emission of LO phonons by holes occurs near the point $p = p_0\mathbf{e}$ in momentum space, where $p_0 = (2m^*\hbar\Omega)^{1/2}$ and $\mathbf{e} = \mathbf{E}/E$. Since the current is determined primarily by heavy holes, m^* will be understood as the mass of these holes. Using (3)–(5), we can show that under streaming conditions the shift R_z along the axis $z\|(001)$ in a single event involving the emission of an LO phonon is determined by

$$R_z(\mathbf{e}) = (2\sqrt{3}\, d_0/5C)\, e_x e_y\, (1 - 6e_z^2)\,. \tag{6}$$

This expression was derived in the spherical approximation for the energy spectrum and under the assumption $d_0k_0/C \ll 1$, where $k_0 = p_0/\hbar$. In the optimum case $d_0k_0 \cong C$, the displacement is $R_z \cong k_0^{-1}$. According to (6), when there is an electric field directed along the (110) axis, a current

$$j_\perp = j_\| R_z \frac{eE}{\hbar\Omega} \tag{7}$$

is generated along the (001) direction. Here $R_z = \sqrt{3}d/5C$, and $j_\|$ is the current in the field direction, which is independent of the magnitude of the field under streaming conditions:

$$\mathbf{j}_\| = eN(\hbar\Omega/2m^*)^{1/2}\mathbf{e}, \tag{8}$$

where N is the density of holes. For GaAs we have $d_0/C = 5\times10^{-8}$ cm, and at $E = 1$ kV/cm we have a ratio $j_\perp/j_\| = 0.5\times10^{-3}$.

Under streaming conditions the probability that the hole energy will reach a level sufficient for the emission of two LO phonons is small, on the order of the parameter $\exp(-2E_0/3E) \ll 1$, where $E = em^*\Omega/\hbar\epsilon^*$, and the ballistic current due to the absorption of a phonon in the passive region, followed by the emission of a phonon at $k_BT \ll \hbar\Omega$, is small, on the order of the parameter $n_L(E_0/E)^2$, where $n_L \cong \exp(-\hbar\Omega/k_BT)$. At low temperatures, both contributions to the ballistic current can be made quite small. We note that in the case of degenerate bands the ballistic contribution arises not only from the anharmonicity but also from two sequential single-phonon transitions through different subbands. In addition to these contributions, a ballistic current may arise from quantum corrections to the scattering cross section which are proportional to the electric field. Under streaming conditions the contribution from the quantum corrections is small, on the order of $\bar{p}/p_0 = 0.6(E/E_0)^{1/3}$, where $\bar{p}$ is the average momentum of the hole after the emission of the LO phonon. Under ordinary conditions, all these contributions are comparable in magnitude, and the current which is even in the field is

$$j_{\perp} = j_{\parallel} a_0 (eE/k_B T), \tag{9}$$

where a_0 is a characteristic length which depends on the particular scattering mechanism ($a_0 \sim d_0/C$ for scattering of holes by optical phonons; or $a_0 \epsilon_0 b/4\pi e_{14}$ for scattering by acoustic phonons, where e_{14} is the piezoelectric modulus, and b is the strain energy constant).

Consequently, measurements of the current component which is even in the field under streaming conditions appear worthwhile both for directly separating the ballistic and shift contributions and in connection with the possibility of a direct determination of the ratio d_0/C.

We thank Yu. L. Ivanov and A. Yu. Tkachenko for the opportunity to see the results of Ref. 7 before publication.

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Translated by Dave Parsons
Edited by S. J. Amoretty