ON THE THEORY OF ELECTROACOUSTIC PHENOMENA IN SOLIDS

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Abstract

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ON THE THEORY OF ELECTROACOUSTIC PHENOMENA IN SOLIDS

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1. When an ultrasonic wave propagates in a crystal, it will carry along the conduction electrons. As a result, in an open-circuited specimen an acoustoelectric field arises, and in a short-circuited specimen—an acoustoelectric current. Weinreich ([1]) established the following relation between the coefficient of sound absorption by electrons α and the strength of the acoustoelectric field E_a:

$$E_a = \alpha W/ens, \tag{1}$$

where n is the electron concentration, s is the speed of sound, and W is the density of the sound-energy flux.

Relation (1) may be violated in the case of a complicated electron spectrum ([2,3]) and in the case of bipolar conduction ([4]). In the present work we shall assume that the specimen contains charge carriers of only one sign and that the electron spectrum has the simplest form $\varepsilon = p^2/2m$ (m is the effective mass). We shall show that even in this simplest case, at high ultrasonic frequencies, relation (1) is satisfied only to within a certain correction factor that depends on the sound frequency, the temperature of the crystal, and the mechanism of electron scattering (by high frequencies we shall mean those for which $ql \gg 1$, $\hbar q \gg \sqrt{mT}$; here q is the wave vector of the sound wave, l is the electron mean free path, and T is the temperature of the specimen in energy units). It will then be shown that this correction factor also plays an important role in another electroacoustic phenomenon—the amplification of ultrasound by electron drift in an electric field.

2. We shall consider the acoustoelectric effect in a weak high-frequency sound field, when the sound-absorption coefficient and the electron mobility may be regarded as independent of the density of the sound flux W. In this case the electron distribution function will have the form $f(\mathbf{p}) = f_0(\varepsilon) + \mathbf{p}f_1(\varepsilon)$, where $f_0(\varepsilon)$ is the equilibrium distribution function. From the kinetic equation for electrons in a constant electric field and interacting

with a monochromatic flux of phonons ([5,6]), it is not difficult to obtain the following expression for the antisymmetric part of the distribution function:

$$\mathbf{f}_1(\varepsilon) = -\frac{\tau(\varepsilon)}{m} f_0'(\varepsilon) \left\{ e\mathbf{E} + \frac{3\pi\Xi^2 m^{1/2} qW}{4\sqrt{2}\,\rho s^2 \varepsilon^{3/2}}\, \vartheta(\varepsilon - \varepsilon_0) \right\}, \tag{2}$$

where ρ is the density of the crystal, Ξ is the deformation-potential constant, $\varepsilon_0 = \hbar^2 q^2/8m$, and $\tau(\varepsilon)$ is the electron relaxation time due to their interaction with thermal phonons, impurities, etc.,

$$\vartheta(x) = \begin{cases} 1, & x > 0, \\ 0, & x < 0. \end{cases}$$

The corresponding current density is

$$\mathbf{j} = \frac{2}{(2\pi)^3} \frac{e}{m} \int \mathbf{p} f(\mathbf{p})\, d^3p = \sigma \left\{ \mathbf{E} + \frac{\alpha W}{ens} \frac{\langle\langle \tau \rangle\rangle}{\langle \tau \rangle} \right\}, \tag{3}$$

where $\sigma = e^2 n \langle \tau \rangle / m$ is the electrical conductivity of the crystal,

$$\langle \cdots \rangle = -\frac{(2m)^{3/2}}{3\pi^2 \hbar^3 n} \int_0^\infty (\cdots) f_0'(\varepsilon)\, \varepsilon^{3/2}\, d\varepsilon,$$

$$\langle\langle \cdots \rangle\rangle = -\frac{1}{f_0(\varepsilon_0)} \int_{\varepsilon_0}^\infty (\cdots) f_0'(\varepsilon)\, d\varepsilon.$$

In the case of an open-circuit specimen $\mathbf{j} = 0$, whence

$$\mathbf{E}_a = -\frac{\alpha W}{ens} \frac{\langle\langle \tau \rangle\rangle}{\langle \tau \rangle}. \tag{4}$$

Formula (4) differs from Weinreich's relation (1) by the correction factor $\langle\langle \tau \rangle\rangle / \langle \tau \rangle$. It is easy to see that this factor is equal to unity when the relaxation time is independent of energy, and also in the case of a completely degenerate electron gas.

It is not difficult to understand the deviation obtained from Weinreich' s phenomenological relation. The latter is based on the assumption that the action of the phonon flux on the electrons is equivalent to the action of a certain electric field. In fact, as is seen from (2), the antisymmetric part of the distribution function caused by the phonon flux has an entirely different energy dependence than the part caused by the presence of an electric field. This is due to the fact that the force with which the electric field acts on the electrons does not

depend on their energy, whereas the phonon flux affects electrons of different energies differently (in particular, it does not act at all on electrons with energies smaller than ε_0). As a result, the acoustoelectric current will be expressed not in terms of the usual drift mobility $\mu = e\langle\tau\rangle/m$, as a "true" electric current is, but in terms of the "acoustoelectric mobility" $\mu_a = e\langle\langle\tau\rangle\rangle/m$ (the acoustoelectric current in a short-circuited specimen will be equal to $\mathbf{j}_a = \frac{1}{s}\mu_a\alpha W$).

If τ does not depend on energy, then the method of averaging the relaxation time no longer plays a role, and $\mu_a = \mu$. Similarly, $\mu_a = \mu$ for a completely degenerate electron gas, since in this case only electrons at the Fermi surface participate in the transport processes, and instead of the function $\tau(\varepsilon)$ the constant $\tau(\zeta)$ appears everywhere, where ζ is the Fermi energy.

In summary, one may say that the deviation from Weinreich' s relation is due to the following causes:

1) the dependence of the electron relaxation time (with respect to momentum) on their energy;

2) the spread of electrons over energies;

3) the fact that the electric field and the phonon flux perturb the electron distribution function differently.

If the electron gas is nondegenerate, and $\tau(\varepsilon) \sim \varepsilon^{\nu}$, then

$$\frac{\mu_a}{\mu} \equiv \frac{\langle\langle\tau\rangle\rangle}{\langle\tau\rangle} = \frac{\Gamma(5/2)\Gamma(1+\nu, x)}{\Gamma(5/2+\nu)}e^x, \tag{5}$$

where $x = \varepsilon_0/T$, $\Gamma(\nu, x)$ is the incomplete gamma function. In the case $x \ll 1$, formula (5) coincides with the result of work (7).

3. The ratio $\langle\langle\tau\rangle\rangle/\langle\tau\rangle$ will also appear in the theory of another electroacoustic phenomenon—the amplification of ultrasound by electron drift.

trons in an electric field. From the phenomenological theory[8–10] it follows that absorption of sound by an electron gas in a constant electric field is replaced by amplification when the drift velocity of the electrons $V = \mu E$ reaches a critical value equal to the phase velocity of sound. Meanwhile, calculation on the basis of the kinetic equation shows[11] that, for $ql \gg 1$, the critical drift velocity differs from the velocity of sound by a certain factor depending on the sound frequency and the crystal temperature.

Indeed, in[11] the following expression was obtained for the electronic coefficient of sound absorption in an electric field (for $ql \gg 1$):

$$\alpha_E = \alpha\left\{1 - \frac{1}{sqf_0(\varepsilon_0)}\int_{\varepsilon_0}^{\infty} qf_1^e(\varepsilon)\,d\varepsilon\right\}. \tag{6}$$

Here $f_1^e(\varepsilon)$ is the antisymmetric part of the electron distribution function in an electric field, equal to

$$f_1^e(\varepsilon) = -\frac{eE\tau(\varepsilon)}{m} f_0'(\varepsilon). \tag{7}$$

Substituting (7) into (6), we obtain

$$\alpha_E = \alpha \left\{ 1 - \frac{\mu(Eq)}{sq} \frac{\langle\langle \tau \rangle\rangle}{\langle \tau \rangle} \right\}, \tag{8}$$

whence it follows that the critical value of the electric-field strength is determined by the equality $\mu_a E = s$, i.e., once again, in the phenomenological result the ordinary drift mobility μ must be replaced by the "acoustoelectric mobility" μ_a.

Let us note that in the works of Spector[12] and Paranjape[13], devoted to the case $ql \gg 1$, the critical value of the drift velocity was found to be $V_{\text{cr}} = s$. This, however, is connected with the fact that in[12] all calculations were carried out for a degenerate electron gas, while in[13] it was implicitly assumed that $\tau(\varepsilon) = \text{const}$.

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Note: Figure translations are in progress. See original paper for figures.