Quantum induced acoustic transparency of conductors

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A method is proposed for the investigation of the acoustic band in conductors (i.e., the band produced in the periodic field of a sound wave). The method is based on observation of an abrupt decrease of absorption of a weak sound signal when a strong signal that produces the acoustic band is turned on.

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An intense sound wave propagating in a conductor can alter substantially the state of the free electrons. As shown by Keldysh,[1] in a coordinate system L_w rotating together with a traveling sound wave with velocity W, the electron spectrum has band-type character. Under conditions of weak acoustoelectric coupling, when the parameter

$$a \equiv U_0/(\hbar^2 Q^2/8m) \tag{1}$$

is small, the width of the first forbidden band is equal to $U_0=\lambda_{ik}u_{ik}$, and that of the allowed band is $\hbar^2Q^2/8m$. Here m is the effective mass of the free electrons of the conductor, Q is the wave vector of the sound, λ_{ik} is the tensor of the strain potential (with allowance for the screening by the free electrons), and u_{ik} is the amplitude of the strain tensor in the acoustic wave. The forbidden band can appear only if the uncertainty in the electron energy $\hbar/\tau$ (τ is the free path time) is smaller than U_0. We assume that the uncertainty is larger than the width of the next forbidden band aU_0, and therefore will disregard the higher forbidden bands.

The purpose of the present article is to suggest a method of directly observing and investigating the acoustic band in metals or semimetals. Assume that a weak wave with a wave vector q and velocity w propagates in parallel (or

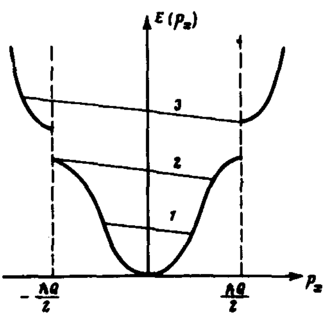

FIG. 1.

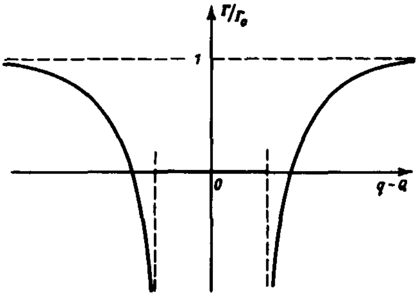

FIG. 2.

antiparallel) with an intense sound wave. At $ql \gg 1$ (where l is the electron mean free path), the absorption of the weak wave can be regarded as the process of direct absorption of ultrasonic quanta by conduction electrons. Let us ascertain how the distortion of the electron spectrum by the strong sound wave should influence the absorption of the weak wave.

We consider normal electronic transitions of the type $p_x \to p_x + \hbar q$ under the influence of the weak acoustic wave (p_x is the projection of the quasimomentum of the electron on the sound propagation direction). In the case of parallel propagation of the waves, owing to the transition, the electron energy changes by an amount $\hbar(\omega - qW)$ ($\omega - qW$ is the frequency of the weak wave in the L_w frame). Figure 1 shows the transitions for the case $w < W$. If this transition couples states that are far from the forbidden band (transition 1), then the absorption coefficient Γ has the same value Γ_0 as in the absence of the strong wave, since its field produces little distortion of the wave functions and of the occupation numbers of these states. With increasing frequency ω, when q approaches Q, the initial or final electron state may turn out to be situated in a region of width on the order of U_0 near the forbidden band, where the spectrum differs substantially from quadratic. We consider henceforth for simplicity the case $\hbar q|W - w| \leq U_0$. Transitions through the forbidden band are then impossible.

In this region, the wave functions and the distribution function of the electrons are substantially distorted by the intense sound wave, and the coefficient Γ differs substantially from Γ_0. With further increase of ω, after p_x reaches $-\hbar Q/2$ (transition 2), the energy conservation law forbids transitions $p_x \to p_x + \hbar q$ until ω increases enough to make the transition 3 possible.

We conclude from the foregoing that a transparency interval appears for the weak sound waves, i.e., a frequency interval in which the weak wave is not absorbed. The reason for this is that the corresponding electronic transitions are forbidden, since the presence of an acoustic band does not make it possible to satisfy the conservation law:

$$E(\mathbf{p} + \hbar\mathbf{q}) = E(\mathbf{p}) + \hbar(\omega - qW); \tag{2}$$

where

$$E(\mathbf{p}) = \frac{1}{2m}\left\{p_\perp^2 + \frac{\hbar^2 Q^2}{4} - \mathrm{sign}\left(\frac{\hbar^2 Q^2}{4} - p_x^2\right)\left[\left(\frac{\hbar^2 Q^2}{4} - p_x^2\right)^2 + (mU_0)^2\right]^{1/2}\right\}$$

is the energy of the electron in the moving reference frame and $p_\perp$ is the transverse component of its quasimomentum. It follows from relation (2) that the transitions $p_x \to p_x + \hbar q$ are forbidden in the region

$$|q - Q| \leqslant 2[m|W - w|\hbar^{-1}(mU_0/\hbar^2 Q + m|W - w|\hbar^{-1})]^{1/2} \equiv A. \quad (3)$$

Incidentally, there is one inaccuracy in the preceding argument. The point is that umklapp processes are possible in part of the region (3) in accordance with the scheme $p_x \to p_x + \hbar q \pm \hbar Q$ (in view of the condition $a \ll 1$, umklapp to $n\hbar Q$ at $|n| > 1$ have low probability and will be neglected). Transitions with $|n| = 1$ turn out to be possible if

$$2m|W - w|\hbar^{-1} < |Q - q| \leqslant A. \quad (4)$$

At $|Q - q| \leqslant 2m|W - w|\hbar^{-1}$, both normal transitions and umklapp processes are forbidden. Thus, the transparency interval in which there is no absorption in our approximation is

$$-2mW|W - w|\hbar^{-1} + Qw \leqslant \omega \leqslant 2mw|W - w|\hbar^{-1} + Qw. \quad (5)$$

The dependence of the ratio Γ/Γ_0 on q is shown in Fig. 2 for the case of a Fermi momentum $p_F \gg \hbar Q$, $w = W/2$, $\hbar q|W - w| = U_0$, and $U_0 \ll kT$, where T is the temperature. We see that at $W > w$ the absorption in region (4) can give way to amplification.

If $W < w$ or if the sound waves move opposite to each other, then the plot of Γ/Γ_0 is similar to that shown in Fig. 2, the only difference being that there is no amplification of the sound. We note that in the case of antiparallel propagation of the sound waves (in contrast to the case of parallel propagation), the two waves can have equal propagation speeds.

The abrupt increase of the amplification (absorption) of the sound near the transparency should generally speaking become smeared out by scattering of the electrons from the impurities or by the anisotropy of the electron spectrum, which is in fact always present in metals.

[1]L.V. Keldysh, Fiz. Tverd. Tela 4, 2265 (1962) [Sov. Phys. Solid State 4, 1658 (1963)].