Sound transport by electrons under conditions of resonant interaction

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It is shown experimentally that in resonant interaction of electrons with sound the transported sound field is comparable with the main signal.

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The transport of sound by conduction electrons, which was observed by us earlier[1], is evidence that the electron subsystem, drawing energy from the sound field, returns the energy to the lattice not only in the form of thermal phonons, but also in the form of a coherent wave that has, under certain conditions, a noticeable amplitude. From reciprocity considerations it follows that the stronger the interaction of any group of electrons with the sound wave, the greater the fraction of the absorbed energy returned to the lattice in coherent fashion, until the scattering by the impurities and phonons upsets this process.

Under conditions of nonresonant interaction of electrons with sound, which takes place when sound is transported over a chain of orbits and which corresponds to the experiment of Ref. 1, the amplitude of the transported sound was relatively low and amounted, when averaged over the different propagation directions and over the polarization of the crystal, about 10^{-2} of the amplitude of the main sound. In the case of resonant interaction, when the coefficient of the absorption of the sound by the resonant electrons greatly exceeds its value far from resonance and becomes predominant against the background of the remaining electrons, one should expect the amplitude of the transported sound to be quite appreciable and comparable with the amplitude of the main sound even if the number of resonant electrons is relatively small.

1. We observed in our study the transport of a sound field under conditions of acoustic Doppler-shifted cyclotron resonance (DSCR) on the electrons of the open orbits in gallium of high purity. The resonance condition takes in this case the form[2]

$$q\bar{v} \pm \omega = \frac{2\pi n}{T}; \quad n = 1, 2, \ldots, \tag{1}$$

where **q** and ω are the wave vector and the cyclic frequency of the sound, $\bar{v}$ is the average velocity of the electrons along **q**, T is the period of the open orbit, the " $-$ " sign corresponds to the electrons traveling along **q**, and the " $+$ " sign corresponds to the opposite motion.

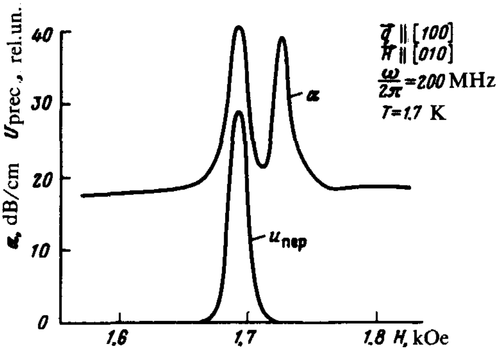

FIG. 1.

Figure 1 shows plots of the amplitude of the transported sound of the "precursor"[1)] U_{prec} and of the sound absorption coefficient α on the magnetic field under DSCR conditions near $n = 3$. As expected, the "precursor" is due to electrons traveling along the sound. The change of the phase of the "precursor" within the limits of the DSCR line width turned out to be appreciable (approximately 4π), and was approximately the same for the first four values of n.

Figure 2 shows the ratio of the amplitudes of the "precursor" transported by the electrons over a distance x and registered at the end of a sample of length $L = 4$ mm, to the main signal under conditions when resonance takes place also at the exit from the sample, as a function of x (curve 1). As seen , under DSCR conditions the amplitude of the "precursor" even exceeds somewhat the amplitude of the main pulse after the latter passes through the sample.

The dependence of the amplitude of the "precursor" on x, if (1) is satisfied, can be represented in the form

$$U_{\text{prec}} = A U_0 e^{-\alpha_{\text{res}} x} e^{-x/l} e^{-(\alpha_m + \alpha_{\text{res}})(L-x)} (L - x), \tag{2}$$

where A is of the order of the sound absorption coefficient, U_0 is the amplitude of the main signal at the entrance to the sample, α_m is the monotonic part of the absorption coefficient near the resonant value of the magnetic field, α_{res} is the resonant increment to the sound absorption coefficient, and l is the electron mean free path along **q**.

The third factor in (2) allows for the fact that the electrons moving along the path x give up energy continuously in the form of a coherent sound wave, and reciprocity considerations dictate that the argument of the exponential must be set equal to α_{res};

the fourth factor represents the number of such electrons; the fifth factor accounts for the fact that the signal is carried by the sound over a distance $(L-x)$.

The factor $(L-x)$ describes the energy pumping into the "precursor" from the main pulse, a pumping that takes place continuously over the entire sound path.[3]

Recognizing that $U_0 \exp[-(\alpha_m+\alpha_{\rm res})L]$ is the amplitude $U_{\rm out}$ of the main signal at the exit from the sample, we get from (2)

$$\frac{U_{\rm prec}}{U_{\rm out}} = A(L-x)e^{-x/l}e^{a_M x}. \tag{3}$$

It follows from (3) that the fuction $y = U_{\rm prec}/U_{\rm out}(L-x)$ must be an exponential with an exponent $(\alpha_m - 1/l)$. The function $y(x)$ obtained from the experimental results and shown in Fig. 2 (curve 2) does indeed have an exponential form. Using the measured value $\alpha_m = 2.05\ {\rm cm}^{-1}$ we get $l = 1.2 \pm 0.1$ mm. On the other hand, l can be determined from the half-width of the DSCR line by the formula $\Delta H/H \approx 1/gl$.[2] This estimate yields $l = 1.3 \pm 0.3$ mm, which again confirms that the representation of the transported sound in the form (3) is reasonable.

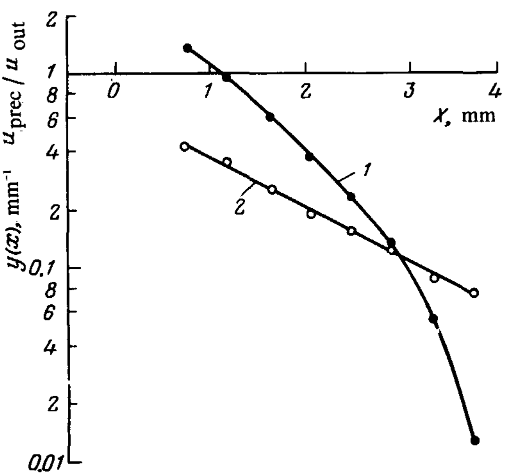

FIG. 2.

Measurements of the amplitude of the "precursor" have shown that l^{-1}, as defined by (3), has a cubic dependence on the temperature.

Conceptually, the transport in question is close to anomalous penetration of the field by "ineffective" electrons, which was observed in Ref. 4, except that there, owing to the presence of the skin layer, the electromagnetic wave vector did not have a definite value and the anomalous field penetration manifested itself in the form of weak oscillations of the surface impedance of a plane-parallel plate.

2. The case $n = 0$ in (1) corresponds to the "inclination effect."[5] To observe it, the magnetic field must make an angle $\phi \sim s/v_F$ with the normal to $\mathbf{q}$ (s is the speed of sound and v_F is the Fermi velocity). In this case the interaction also has a resonant

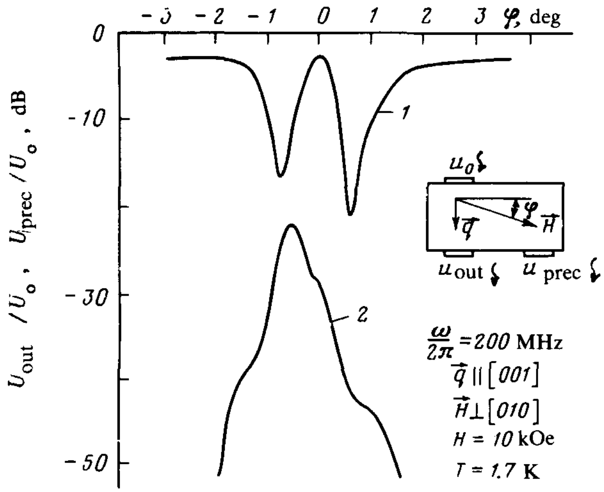

FIG. 3.

character and an intensive outflow of the sound field along H is observed. The amplitude of the main signal (curve 1) and of the transported signal (curve 2) at the exit from a sample 2.5 mm long, as a function of ϕ, are shown in Fig. 3; the figure explains also the experimental setup. At optimal ϕ, the difference between the two signals is $\sim$ 8 dB. The asymmetry of the transport curve is due to the asymmetric arrangement of the pickups.

The amplitude of the transported signal should be described by an expression similar to (2), except that the outflow of the sound and its further propagation proceed along different coordinates. The quantity l, determined from the data on the "inclination effect" (Ref. 6) is $\sim$3 mm, and the minimal distance between pickups is $\sim$2 mm, so that in this case the field extracted from a length small compared with l is of the same order as the main signal.

[1)]The term "precursor" must be taken to mean somewhat arbitrarily, since the transported sound field propagates in this case with Fermi velocity over the entire sample, in contrast to Ref. 1, where the transported sound pulse at a given instant of time is localized in a limited region of space.

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