Direct Observation of Electron-Phonon Interaction

J. P. Maneval, A. Zylbersztejn, and D. Huet
Groupe de Physique des Solides de l'Ecole Normale Supérieure, Paris 5e, France
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In a heat-pulse experiment performed at liquid helium temperatures in InSb samples containing a few times 10^{17} electrons per cm^3, we have observed a strong attenuation of the longitudinal phonon pulse and no attenuation of the transverse pulses. Both these observations are related to basic properties of the electron-phonon interaction.

In a metal or a semiconductor with a spherical Fermi surface, theory predicts that the deformation potential couples the free electrons to longitudinal modes only, since transverse modes result in no dilatation.[1] This assertion has never been verified experimentally for thermal phonons since thermal-conductivity measurements do not distinguish between phonon polarizations. In this Letter, we report the first direct observation of the selective coupling of free electrons to longitudinal phonons. The technique employed is that of heat pulses[2] at helium temperatures. This technique has the advantage of providing thermal acoustic phonons whose polarizations are identifiable by their velocities. Experiments have been performed in strongly degenerate n-type indium antimonide, which has a spherical Fermi surface and a temperature-independent electron concentration at low temperatures.

The InSb samples, about 2 cm long, were taken from x-ray–oriented single crystals. After mechanical polishing, opposite faces were covered with an evaporated silicon oxide layer, a few thousand angstroms thick. The heat generator is a 450-Å-thick gold film, while the detector is made by flash evaporation of an Al-Sn (25% Sn) mixture. The heat pulse is generated by passing a current pulse (10^{-7} sec duration) through the gold film. The superconducting bolometric detector is operated at constant current, and the voltage changes induced by the incident phonons are wide-band amplified and then averaged using a PAR 160 boxcar integrator.

The bolometer signal corresponding to heat-pulse propagation along the ⟨111⟩ direction is shown in Fig. 1, where L and T refer respectively to longitudinal and transverse acoustic phonons. The upper trace is for a sample containing 1.9×10^{14} electrons per cm^3 (pure sample), while the lower one is for a doped sample containing a few times 10^{17} electrons per cm^3. Both traces were taken at the same heater input power.

Before studying these results in detail, let us first discuss the accuracy of heat-pulse measurements in general. Determination of *relative* amplitudes, such as the ratio L/T on one single trace, is fairly accurate; for example, L/T has been found to be the same within a few percent for several pure samples. *Absolute* amplitude measurements, on the other hand, are dependent on the reproducibility of the thin-film components, and variations in sensitivity of 50% from one evaporation to another are common. This should be kept in mind when comparing the two traces.

1. The most striking feature of Fig. 1 is the strong attenuation of the longitudinal peak in the doped sample. We attribute this to phonon absorption by the electrons since thermal-conductivity studies[3,4] show that the impurities, in concentrations up to 5×10^{17} cm^{-3}, contribute negligibly to phonon scattering in InSb.

2. The difference in the T peak amplitudes, 24 μV for the pure sample and 35 μV for the doped one, lies well within the limits of accuracy of absolute heat-pulse measurements. Several arguments tend to prove that the same energy flux

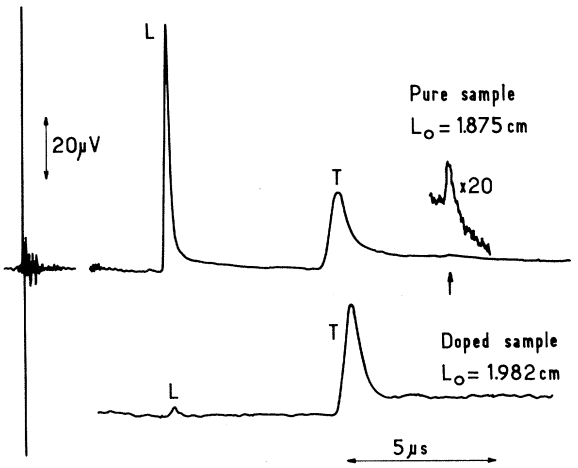

FIG. 1. Dectected heat pulses after propagation along the ⟨111⟩ direction. T_0 = 1.68 K for the pure sample and T_0 = 1.57 K for the doped sample. Input flux in both samples is 10 W/mm^2. On the upper trace, the first echo of the L peak is visible, and is also shown magnified by a factor of 20.

reaches the bolometer in both cases: (i) From a measurement of the temperature coefficient of the bolometer resistances, we deduce bolometer temperature rises of 0.32 mK for the pure sample and 0.43 mK for the doped sample. (ii) These two results, which differ by 30%, may be brought into even closer agreement ($\simeq 15\%$) if one takes into account the slight difference in resistance and operating temperature of the bolometers. Our conclusion is that the T modes are unaffected by doping, and this is further supported by the fact that it is the doped sample which exhibits the larger signal. We believe that this experiment provides the first verification of the absence of interaction between purely transverse thermal phonons and free electrons in a material having a spherical Fermi surface.

Experiments have also been performed along the ⟨110⟩ direction (Fig. 2). The modes FT (fast transverse) and ST (slow transverse) are nondegenerate in this case. The difference in amplitude of the three peaks in the upper trace results from phonon focusing.[5] We shall not study this effect here, but shall rather concentrate on a comparison of the two traces.

1. The FT/ST ratio is not altered by doping, which is consistent with the fact that the deformation potential does not couple the transverse modes to the conduction electrons. Although the FT modes are piezoelectrically active along ⟨110⟩, the phonons involved here are of too high frequency ($\gtrsim 10^{11}$ Hz) to be sensitive to this coupling.

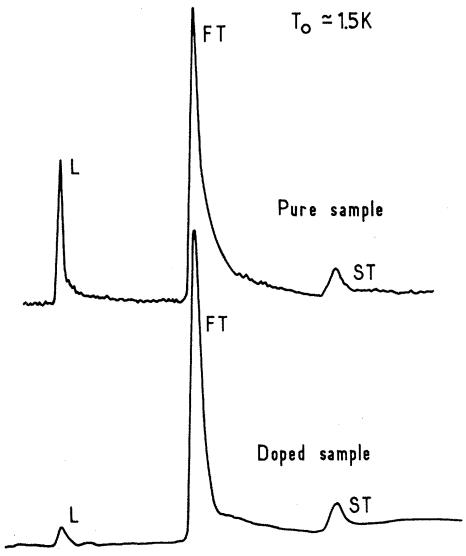

FIG. 2. Detected heat pulses after propagation along the ⟨110⟩ direction. Horizontal and vertical scales are arbitrary.

2. The L/FT ratio in the doped sample is smaller by a factor of 8 than in the pure sample. This attenuation ratio is not so large as along the ⟨111⟩ direction, even though the samples were cut from the same crystals in both cases. We believe that this difference is due to inhomogeneities of carrier concentration in the doped crystal, as discussed in the following.

We shall consider the attenuation of longitudinal acoustic phonons by a free-electron gas via deformation-potential coupling. One obtains the phonon absorption rate from time-dependent perturbation theory. Because of the smallness of the velocity of sound as compared to the electron velocities, the transition of the electron is quasielastic or, in other terms, its wave number k remains essentially unchanged. The phonon wave number q involved in the transition is largest for complete reversal of the electron motion, and then $q = 2k$. If the electron gas is degenerate,[6] there is no interaction for $q > 2k_F$ (k_F, the radius of the Fermi sphere, is about 2.5×10^6 cm^{-1} in our doped crystal), while for $q < 2k_F$, the Ziman formula[7] for semiconductors yields

$$\text{Phonon mean free path} = 2\pi\hbar\rho s/C^2m^2q, \qquad (1)$$

where ρ is the crystal density, s the velocity of sound, m the electronic effective mass, and C the deformation potential constant. From this equation,[8] the free path of phonons with $q < 2k_F$ is shorter than 1 mm ($\ll L_0$, the sample length). Thus, all phonons such that $q < 2k_F$ are completely absorbed, and only high-frequency phonons reach the detector. For the doped crystal, $2k_F$ falls in the range of the phonon wave numbers excited in the heat pulse, and the free electrons cut off part of the emitted longitudinal phonon spectrum.

Formally, the detected L peak is proportional to the energy flux dQ/dt incident on the bolometer, which is related to the emitted flux $P(q)$ by

$$\frac{dQ}{dt} \sim \int_{2k_F}^{\infty} [P(q) - P_0(q)] \exp\left(-\frac{L_0}{l(q)}\right) dq, \qquad (2)$$

where P_0 is the flux from the crystal (at temperature T_0) to the heater. The lower limit of the integral accounts for the free-electron absorption discussed above, while the exponential factor allows for all other scattering mechanisms. Among these, both electromagnetic coupling and umklapp processes are negligible because of the relatively small wave numbers involved here.[1] Isotope scattering, on the other hand, cannot be ignored.

For this process

$$l(q) = (q_0/q)^4 \text{ cm}, \quad (3)$$

where a value of $q_0 \simeq 6 \times 10^6$ cm^{-1} can be deduced from Ref. 4.

The detailed calculation of the phonon flux $P(q)$ emitted by the metallic film is out of the scope of this Letter. The most common *Ansatz*[2] is to assume for $P(q)$ a Planck distribution. For a power input of 10 W/mm^2 (Figs. 1 and 2) the characteristic temperature of the pulse would be about 7 K. With this value one needs electron concentrations of at least 2×10^{18} cm^{-3} to account for the observed L peak attenuations. This is roughly an order of magnitude larger than the concentrations measured in extra chips taken from the doped crystal: $(1.75, 2.40, 6.25, \text{ and } 6.70) \times 10^{17}$ per cm^3, a scatter unfortunately typical of doped indium antimonide. Although the blackbody-radiation model has been proved experimentally[9] to be valid in the case of a metallic film directly in contact with an insulating crystal, we feel that it is not adequate for the composite structure: metallic film–silicon oxide–doped InSb. A qualitative agreement with experiment is obtained with a pulse temperature only slightly higher than T_0, whatever the power input; this assumption is consistent with the fact that the attenuation ratios were almost power independent[10] (in the range 1 to 100 W/mm^2), and moreover, for the lowest and the highest concentrations quoted above, it yields attenuation ratios of 6 and 80, respectively. The measured values fall into this range.

In conclusion, we have observed the main features of the deformation-potential coupling by propagating heat pulses in degenerate InSb. This type of experiment is clearly of interest for the study of electron-phonon interactions. We emphasize that such a doped semiconductor is a high-pass filter for longitudinal phonons, whose cutoff can be varied by varying the Fermi level.

We are indebted to H. F. Budd for valuable discussions.

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[10]A comparable observation has been reported by T. Ishiguro *et al.*, Phys. Rev. Lett. 27, 667 (1971), in a heat-pulse experiment on p-type germanium.

Excitonic Structure of Alkali Halides

Y. Petroff,* R. Pinchaux, C. Chekroun, and M. Balkanski
Laboratoire de Physique des Solides,† Université de Paris, Paris VI, France

and

Hiroshi Kamimura
Department of Physics, University of Tokyo, Bunkyo-ku, Tokyo, Japan
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A new technique was used for the study of the reflectivity on KI, NaI, and KBr in vacuum ultraviolet; the cleavage of the samples was done in liquid helium at 1.8°K, avoiding any pollution of the surface. With this method we observed new structures and, in particular, for the first time the pure triplet exciton state predicted a few years ago by Onodera and Toyozawa.

Recently, fine-structure excitons have been observed in several alkali halides.[1-3] For KI, Baldini[2] has shown that the first exciton $n = 1$ [corresponding to $\Gamma(\frac{3}{2}, \frac{1}{2})$] is followed by a shoulder on the high-energy side. The samples were cleaved in vacuum at 6°K. The exciton $n = 2$ shows a structure of four or five peaks, with separation of 16.5 ± 1 meV. In the present Letter, we report