Magnetophonon resonance in mixed optical modes of cadmium and mercury tellurides in $Cd_xHg_{1-x}Te$

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(Submitted 28 March 1988)
Pis'ma Zh. Eksp. Teor. Fiz. **47**, No. 12, 615–617 (25 June 1988)

A magnetophonon two-phonon resonance produced by a pair of longitudinal optical phonons from two sublattices of the crystal—HgTe and CdTe in their solid solutions—was observed in the semiconductors for the first time. Two transitions are possible: One transition occurs when the transition energy is equal to the sum of the energies of the CdTe and HgTe phonons and the other transition occurs when the transition energy is equal to the difference in their energies.

The presence in the vibration spectra of Cd_xHg_{1-x} solid solutions of two optical modes[1] in the magnetophonon resonance may manifest itself not only as a parallel observation of two extrema because of the difference in the frequencies ω_{LO} (HgTe) and ω_{LO} (CdTe).[2] Transitions in which phonons from both sublattices participate simultaneously can occur in the resonances produced by two-phonon processes if the following conditions are satisfied:

$$|E_{N^{\pm}} - E_{O^{\pm}}| = \hbar\omega_{LO}(\mathrm{HgTe}) + \hbar\omega_{LO}(\mathrm{CdTe}) \tag{1}$$

or

$$|E_{N^{\pm}} - E_{0^{\pm}}| = \hbar\omega_{LO}(\mathrm{CdTe}) - \hbar\omega_{LO}(\mathrm{CdTe}). \tag{2}$$

Of particular interest is the detection of a transition of the type in (2) which has heretofore not been observed in semiconductors, i.e., a transition in which an electron upon interacting with two phonons makes use of the difference in their energies.

It is difficult to analyze magnetophonon resonances (especially the two-phonon magnetophonon resonances) in $\mathrm{Cd}_x\mathrm{Hg}_{1-x}\mathrm{Te}$ because of the presence of technologically unavoidable gradient of the composition, which smears the oscillation peaks. We used a scanning x-ray microprobe (COMEBAX) to monitor the composition of the grown crystals and their homogeneity with respect to the composition.

We selected two essentially homogeneous samples with a high carrier mobility: the first sample with $x = 0.196$ measured $3\times0.5\times0.3$ mm and the second sample with $x = 0.295$ measured $4\times0.83\times0.5$ mm. According to the data on galvanomagnetic measurements at 77 K, the first sample had a carrier density of 6.3×10^{13} cm^{-3} and a carrier mobility of 2.3×10^{5} cm^2/(V·s) and the second sample had a carrier density of 2.9×10^{15} cm^{-3} and a carrier mobility of 1.4×10^{5} cm^2/(V·s). We measured the transverse magnetoresistance ρ_{xx} in a magnetic field up to 170 kOe at temperatures 65–200 K, using an experimental approach[3] in which weak, many-phonon resonances are isolated in n-InSb. The experimental plots of $\partial^2\rho_{xx}/\partial H^2$ for the first sample, measured at three temperatures, are shown in Fig. 1. We see that in a magnetic field of 4–20 kOe there are several, a1, a2, and a3, magnetophonon oscillation peaks which are caused by the transitions $0^+ \rightarrow N^+$ ($N = 1,2,3$) with an absorption of a longitudinal optical phonon in HgTe [$\hbar\omega_{LO}$ (HgTe) = 17 meV for $x = 0.196$ (Ref. 1)]. We have calculated by a method[4] used for n-InSb the following band-structure parameters from the

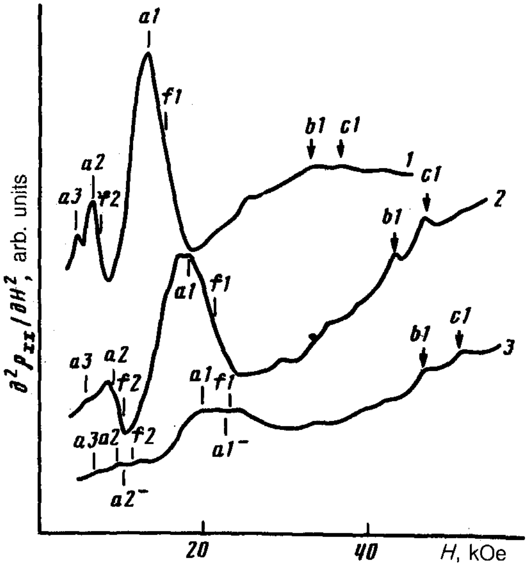

FIG. 1. Experimental traces of $\partial^2\rho_{xx}/\partial H^2$ for n-$\mathrm{Cd}_{0.196}\mathrm{Hg}_{0.804}\mathrm{Te}$. 1—77 K; 2—154 K; 3—193 K. Set a—Magnetophonon resonance involving a single LO(HgTe) phonon; c—transitions involving LO(HgTe) + LO(CdTe); b—transitions involving $2LO$(HgTe); f—magnetophonon resonance involving LO(CdTe) (calculated position).

position of the a1, a2, and a3 oscillation peaks in the magnetic field: the effective mass at the bottom of the conduction band, m_c^*, and the width of the band gap, E_g. At $T = 77$ K these parameters were found to be 0.0071 m_0 and 87.5 meV, respectively.

Knowing the parameters of the band structure has enabled us to interpret the fairly weak extrema which were observed in $H > 25$ kOe. An increase of their intensity with the temperature compared with the ordinary magnetophonon resonances suggests that these resonances have a multiple-phonon nature. As in the case with *n*-InSb,[4] the complex structure of the two-phonon magnetophonon resonances is attributable to the involvement of many combinations of phonons with a small common momentum. The edge of the two-phonon processes in the case of large magnetic fields is determined by the magnetophonon resonances in which a maximum energy combination is involved: $2\,LO(\Gamma)$ in the case of crystals of the zinc-blende type. The arrow b in Fig. 1 indicates the calculated position in the magnetic field of a resonance with the assistance of $2\,LO(\Gamma)$ (HgTe) phonons, which corresponds to one of the observed peaks. This resonance, however, is not the edge of the two-phonon processes, because in large magnetic fields there is a peak whose amplitude is comparable with the amplitude of the two-phonon magnetophonon resonances. Since this resonance cannot be caused by electronic transitions involving two phonons of the HgTe sublattice, we must take into account the interaction of electrons with the longitudinal optical phonon of CdTe [$\hbar\omega_{LO} \times (\mathrm{CdTe}) = 19.3$ meV for $x = 0.196$; Ref. 1]. The arrow c1 in Fig. 1 indicates the calculated position in a magnetic field of the magnetophonon resonance involving a mixed pair of longitudinal optical phonons, i.e., a resonance which satisfies condition (1), with $N = 1$. The calculated value of the resonant field is found to be in good agreement with the experimental value. Similar results were also obtained for the second sample in magnetic fields up to 150 kOe.

The resonances which satisfy condition (2) are situated in weak magnetic fields, since $\hbar[\omega_{LO}(\mathrm{CdTe}) - \omega_{LO}(\mathrm{HgTe})] = 2.3$ meV for $x = 0.196$ (sample 1) and 2.6 meV for $x = 0.295$ (sample 2); here $\hbar\omega_{LO}(\mathrm{HgTe}) = 16.9$ meV and $\hbar\omega_{LO}$ $(\mathrm{CdTe}) = 19.5$ meV. Figure 2 shows the experimental curves of $\partial^2\rho_{xx}/\partial H^2$ for the two samples, which were obtained on a much larger magnetic-field scale than that in Fig. 1. The extrema a4, a5, and a6 are the usual magnetophonon oscillations caused by the transitions $O^+ \to N^+$ (where $N = 4,5,6$) involving the LO phonon of HgTe. We see that the oscillations are interrupted at $H = 1.5$ kOe in the case of sample 1 and at $H = 4.6$ kOe in the case of sample 2. This pause is followed by the appearance of a new series of peaks denoted by *e*1, *e*2, and *e*3. The arrows indicate the calculated positions in a magnetic field of resonances which satisfy condition (2), with $N = 1,2,3$.

A shift up the magnetic field scale of the experimental peaks with respect to the calculated values of the resonance fields can be explained by the fact that the contribution to the resonances in this case, with $kT > 2.6$ meV, i.e., larger than the transition energy, comes from the transitions not only from the O^+ level, as predicted by the calculations, but also from higher levels.

Condition (2) corresponds to the following model: An electron absorbs an *LO* phonon of the CdTe sublattice, causing it to undergo a transition to a higher Landau level, emitting a phonon of the HgTe sublattice (transition I, shown schematically in Fig. 2). A reverse process can also occur: An electron absorbs a phonon of a lower

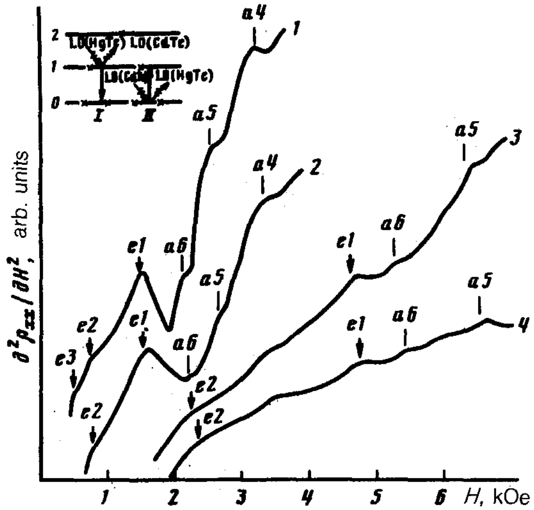

FIG. 2. Experimental traces of $\partial^2\rho_{xx}/\partial H^2$ and the scheme of the transitions corresponding to the resonances *e*. 1—77 K, $x = 0.196$; 2—82 K, $x = 0.196$; 3—77 K, $x = 0.295$; 4—90 K, $x = 0.295$.

energy, LO(HgTe), causing it to undergo a transition to a lower level, releasing a phonon of a higher energy, LO(CdTe) (transition II in Fig. 2). The probability of both transitions is the same. It is proportional to $\exp - [\hbar\omega_{LO}(\mathrm{CdTe})/kT]$ in the first case and to $\exp - [(\hbar\omega_{LO}(\mathrm{HgTe}) + \hbar\omega_c)/kT]$ in the second case, i.e., for this type of two-phonon resonance the temperature dependence of the transition probability is the same as that for one-phonon processes.

It can thus be concluded from the results presented above that a resonant scattering of electrons in a quantizing magnetic field, resulting from the interaction of these electrons with a mixed pair of phonons from two crystal sublattices, has been observed in $\mathrm{Cd}_x\mathrm{Hg}_{1-x}\mathrm{Te}$ solid solutions for the first time. A resonance whose transition energy is equal to the difference in the phonon energies has also been observed in semiconductors for the first time.

We wish to thank I. B. Levinson for valuable suggestions concerning the interpretation of the experimental results.

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Translated by S. J. Amoretty