MAGNETOPHONON SPECTROSCOPY OF $Zn_xCd_yHg_{1-x-y}Te$

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The phonon and electron subsystems were studied in quaternary solid solutions of $Zn_xCd_yHg_{1-x-y}Te$ (ZMCT) by means of Raman scattering and magnetophonon resonance. The Raman spectra of several compositions confirm the three-mode behaviour of phonon spectra. The cluster mode has also been observed. Four kinds of LO-phonons (of HgTe-like, CdTe-like and ZnTe-like sublattices and ZnTe-clusters) participate in the electron-phonon interaction. Four types of one-phonon magnetophonon resonances and two types of magnetophonon resonances on the difference of phonon frequencies have been observed.

Random homogenous substitution of matrix cations by another metal atoms in the solid solution lattices with common anion (as is the case in GaAs-AlAs or HgTe-CdTe) is known to cause a continuous reconstruction of electronic structure and phonon spectra with composition. It may be assumed that the introduction of a third cation will enable us to obtain a supplementary degree of freedom in the control of material parameters. It has an additional advantage in the case of HgTe-CdTe (MCT), because the introduction of Zn-atoms stabilises the weak Hg-Te bonds in crystal lattice of this solid solution, whereas the presence of Cd-atoms destabilises them [1-3]. The introduction of the fourth component Zn causes not only a simple extension of the physical properties of MCT, but also new phenomena, related to multimodeness of the crystal lattice. 'Multimodeness' is an issue of primary significance in the study of four-component solid solutions. ZMCT has three sublattices (ZnTe-like, CdTe-like and HgTe-like). Therefore, a three-mode behaviour of the phonon spectrum in this solid solution may be predicted. Other possibilities also exist [4].

The present article discusses ZMCT structures investigated by means of magnetophonon resonance (MPR) experiments, a powerful tool for the investigation of electron and hole spectra [5].

A series of films of ZMCT obtained by liquid-phase epitaxy on CdTe substrates have been studied. The thickness of homogeneous layers is $d = 4\mu m$. The temperature dependences of electric conductivity and Hall coefficient measured in those structures have shown an activated behaviour. The quality of epitaxial layers investigated by MPR is comparable with the corresponding high-quality MCT alloys with the same energy gap (near 180–300 meV). The mobility of electrons in those layers is sufficiently high to observe the MPR. It is important to note that the parameters of these samples have not changed over the period of three years, whereas MCT samples are characterised by the temporal degradation of parameters.

MPR was observed on three samples: IV,V and VI. The measurements were performed in pulsed magnetic fields. The second derivation of transverse magnetoresistance $d^2\rho_{xx}(B)/dB^2$ as a function of a magnetic field B was registered up to 6.5 T at different temperatures within the range of 77–200 K. The most detailed investigations were performed for sample IV. The experimental records obtained for this specimen at different temperatures are shown in Fig. 1.

When the temperature was increased above 124 K, a group of strong peaks (a wide maximum) appeared in the range from 2.0 to 3.8 T; the corresponding harmonics were at

1.0–1.9 T and 0.6–0.9 T. The peak $a1^+$ is the strongest and the most distinguishable for the range 124 K≤ T ≤ 158 K, whereas peak $a1^-$ is most distinguishable at T > 158 K.

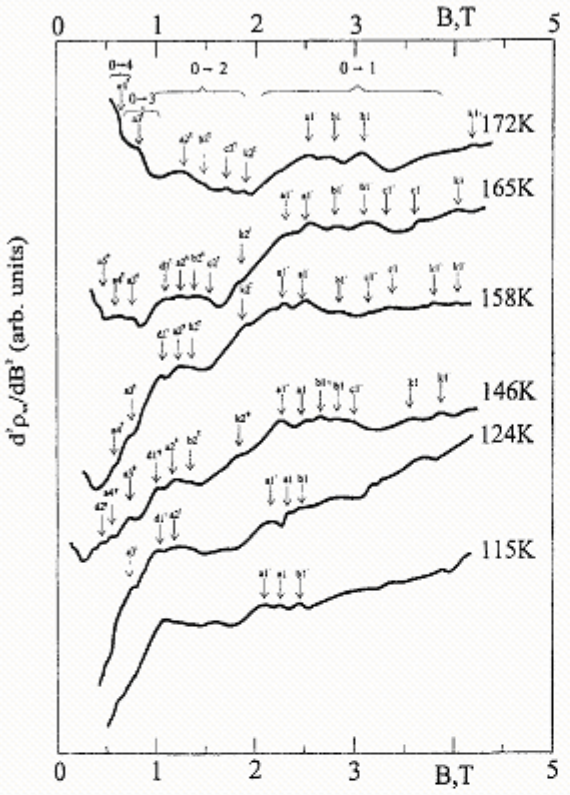

Fig. 1. Experimental records of $d^2\rho_{xx}(B)/dB^2$ obtained for sample IV at different temperatures.

These peaks are correspondent to their harmonics $a2$, $a3$ and $a4$, are observed in the fields approximately equal to $1/2B_0$, $1/3B_0$ and $1/4B_0$, respectively (B_0 is theresonance magnetic field for peak $a1^+$).

In this manner three other series of peaks can be determined – b, c and k. Therefore, the structure of wide maximums – which are clearly visible on experimental curves in Fig.1 at temperatures above 124 K – corresponds to four series of peaks. These series are related to four kinds of phonons.

A similar investigation has been performed for specimens V and VI, for which $x+y$ is significantly larger and, correspondingly, the effective mass of electrons is also greater. Consequently, the whole system of resonances is shifted to higher magnetic fields.

From these general considerations it follows that the series a is caused by the absorption of LO-phonons of HgTe-like sublattice, since these phonons have the lowest energy and they are present in the greatest number in the lattice of ZMCT. However, the energy of LO-phonons which can participate in electron-phonon interaction in this lattice has to be determined for the correct treatment of MPR-data.

LO-phonon frequencies for HgTe-like, CdTe-like, ZnTe-like sublattices as well as for ZnTe-binary clusters were determined from Raman Spectra and far-infrared reflection spectra in our previous paper [6]. The frequencies and energies of LO-phonon for the measured samples are given in Table 1.

Table 1. Values of LO(Γ)-phonons frequencies and energies for compositions IV, V and VI.

composition	HgTe -like mode	CdTe-like mode	ZnTe-like mode	ZnTe - cluster
IV ω_{LO},cm^{-1}	137	156.0	171.5	198.0
$\hbar\omega_{LO}$, meV	17.0	19.3	21.3	24.6
V ω_{LO}, cm^{-1}	136.0	156.0	174.0	198.0
$\hbar\omega_{LO}$, meV	16.8	19.3	21.7	24.6
VI ω_{LO}, cm^{-1}	136.0	156.0	175.0	198.0
$\hbar\omega_{LO}$, meV	16.8	19.3	21.9	24.6

It follows from the considerations above that peaks $a1^+$ and $a1^-$ – the strongest and the most distinguishable at T > 124 K on experimental curves in Figs. 2–4 and characterised by harmonics at corresponding magnetic fields – are caused by electron transitions $0^+ - 1^+$ and $0^- - 1^-$ accompanied by absorption of LO-phonons of HgTe-like sublattice. Our further interpretation of MPR-spectra is based on this assumption which enables us to estimate to the first approximation the parameters of the band structure using the energy value of LO-phonon of HgTe-like sublattice from Table 1 and experimental positions of $a1^+$ and $a1$ peaks in magnetic field.

The band structure parameters have been calculated according to R.Aggrawal's version [7] of the Pidgeon-Brown model [8]. This method is based on the three-level Kane's model [9].

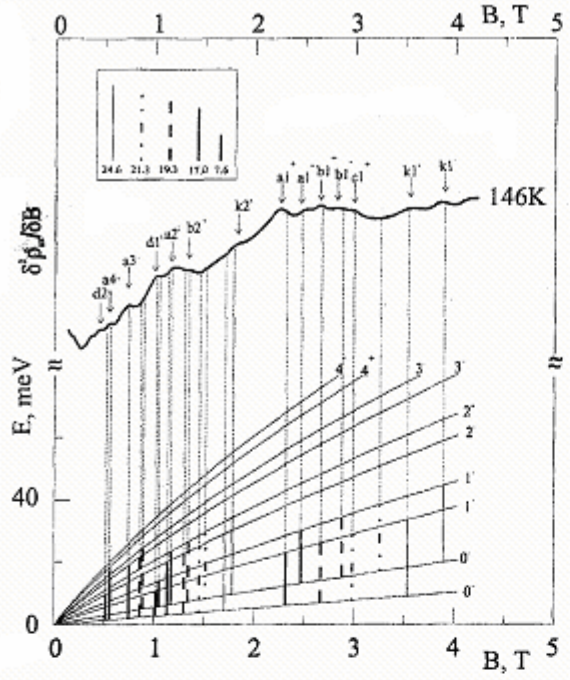

Fig 2.Experimental record of $d^2\rho_{xx}(B)/dB^2$ obtained for sample IV at temperature 146 K. The electron transitions between Landau levels corresponding to the observed MPR's are shown lower. The inset shows the appropriated phonon energies or difference of phonon energies (the values are given in meV).

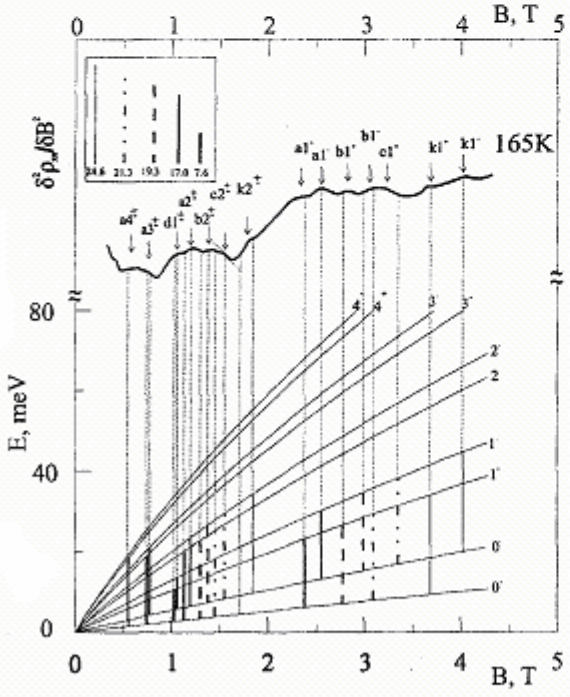

Fig. 3 Experimental record of $d^2\rho_{xx}(B)/dB^2$ obtained for sample IV at temperature 165 K. The electron transitions between Landau levels corresponding to the observed MPRs are shown lower. The inset shows the appropriated phonon energies or difference of phonon energies (the values are given in meV).

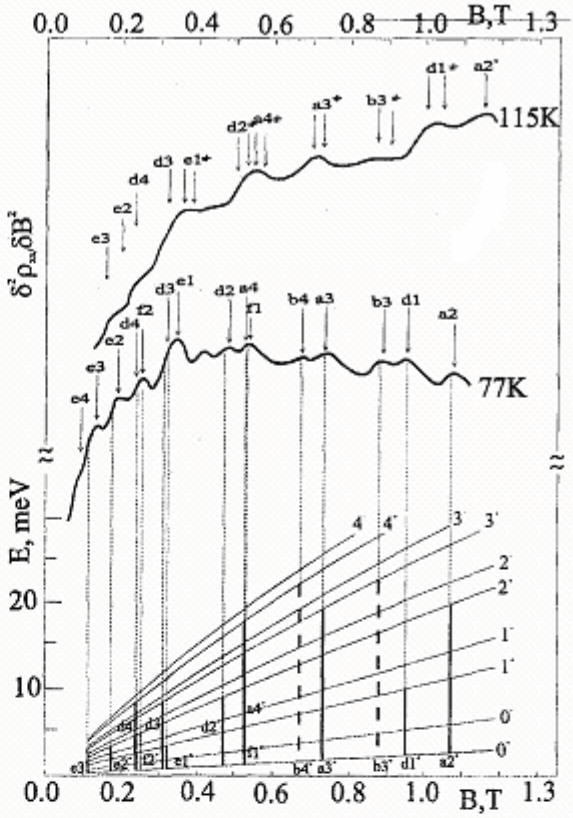

Fig. 4. Experimental records of $d^2\rho_{xx}(B)/dB^2$ obtained for sample IV at temperatures 77 K and 115 K at a smaller magnetic field scale than in Figs. 2 and 3. The electron transitions between Landau levels corresponding to the observed MPRs are shown lower

The experience has shown that the choice of the values of the Luttinger valence-band parameters γ_1^L, γ_2^L, γ_3^L and K^L is crucial to the determination of the band structure parameters for MCT [10–12] using the relations between them given below:

$$\gamma_1^L = \frac{E_P}{3E_g} + 2.5\ ,\quad \gamma_2^L = \gamma_3^L = \frac{E_P}{6E_g}\ .$$

It has been assumed that E_P = 18.0 eV and Δ = 1.0 eV [10] and they do not depend on the temperature and composition. According to [13], the next parameter K^L should be represented as follows:

$$K^L = \gamma_3^L - \frac{1}{3}\gamma_1^L + \frac{2}{3}\gamma_2^L - \frac{2}{3} - \frac{5}{4}\delta_{exch}\ ,$$

where $\delta_{exch.}$ stands for the correction for the nonlocality of the potential and is equal to 0.4 for MCT [13]. As for the parameter F, representing the interaction of the conduction band with the upper bands, we have

used the value F = -0.5 determined by Weiler et al. [10]. We have assumed this parameter to be also independent of temperature and composition.

In order to calculate theoretical positions of MPR peaks, we applied the best fit procedure to the experimental positions of peaks $a1^+$ and $a1^-$ and thus obtained the value of energy E_g = 190 meV at the obtained temperature: T = =146 K. The next step of the calculation procedure is to fit the theoretical positions of all the observed peaks of a-series to the experimental ones at the given temperature. The best fittings are shown in Fig. 2 for T = 146 K and in Fig. 3 for T = 165 K, where electron transitions corresponding to resonance peaks of series a are shown by solid lines. We can state a good agreement between the experimental and theoretical positions of resonances (the average discrepancy for eight peaks of series a^+ and a^- on the curve at 146 K is equal to approximately 1.5%). The parameters of thus obtained band for T = 146 K and 165 K are shown in Table 2.

Table 2. The band-structure parameter values for samples IV - VI

Parameters	sample IV 146 K	sample IV 165 K	sample V 106 K	sample VI 99 K
E_g, meV	192	205	320	350
E_P, meV	18000	18000	18000	18000
γ_1^L	33.75	31.7	21.25	19.64
$\gamma_2^L = \gamma_3^L$	15.62	14.6	9.38	8.57
K^L	13.62	12.6	7.38	6.57
F	-0.5	-0.5	-0.5	-0.5
Δ, meV	1000	1000	1000	1000

Now it is possible to interpret the other series of peaks, namely: b, c and k. Since the positions of peaks $b1^+$, $c1^+$and $k1^+$ are characterised by an increase in magnetic field, these peaks may be expected to be caused by electron transitions $0^+ - 1^+$ with the assisted absorption of LO-phonons of, consequently, increasing frequencies. This sequence of increasing frequencies corresponds to the LO-phonons in CdTe-like, ZnTe-like sublattices and ZnTe-clusters. The theoretical positions of MPR for all the series were calculated using the aforementioned band-structure parameters and phonon energies (Table 1). The overall representation of the electron transitions which correspond to the observed MPR peaks may be found in Figs.2,3. It shows that the suggested interpretation of MPR peaks based on the application of four kinds of LO-phonons is in good agreement with the experimentally observed structures of the resonance curves. Simultaneously, the quantitative agreement between the calculated positions of corresponding electron transitions in the magnetic field and observed peaks of four series is within the range of about 1.5% (the measurement accuracy of resonance fields is ~3%). The comparison of the two curves (the first one at 146 K and the second at 165 K) reveals that the increase in the temperature is accompanied by the increase of amplitudes of peaks $a1^-$ and $a2^-$. This observation is also made for the peaks of another series caused by electron transitions between 0^- and N^- Landau levels. It is obvious enough that the increase of temperature causes the increase of the electron occupation of 0^- Landau level and the increase in the amplitude of the aforementioned peaks. Nevertheless, the peaks of series d in the small magnetic fields are hardly visible at temperatures higher than 124 K (for sample IV).

The same method of the band-structure parameters calculation and the interpretation of MPR peaks using phonon energies as represented in Table 1 is applied to the samples V and VI. The values of the band structure parameters determined for these samples from MPR data are represented in Table 2.

The complicated structure of the peaks in a weak magnetic field is of special interest, because it cannot be interpreted as higher harmonics of the four types of MPRs described above. The transition energy for d-series is about 8 meV which equals to the energy differences of the LO phonons in binary-ZnTe and LO phonons of the HgTe-like sublattice in composition IV. It was difficult to comprehend why LO-phonons of binary ZnTe arise in the solid solution of ZMCT. The calculated phonon frequencies enable us to interpret correctly these d- and e-series of resonances for composition IV as well as for compositions V and VI.

Figure 4 represents experimental records for sample IV at smaller magnetic field scale than in Figs.2 and 3. It is obvious that d-series

begins from 0.95 T for 77 K for *d*1 peak and continues to 1/2×0.95 T and 1/3×0.95 T for *d*2- and *d*3-peaks respectively. In addition to the series of peak *d*, there is another series of peaks marked as *e*, which behave similarly to *d*-peaks with the increase of temperature within this range of magnetic field. The *e*1 peak appears at 0.33 T at the curve for 77 K, which cannot be interpreted as a harmonic of the resonances described above. The MPR curve for 77 K in Fig.4 shows that the peaks marked as *e*2 and *e*3 respectively are observable for the fractions 1/2 and 1/3 of the magnetic field at which peak *e*1 appears. Therefore, two new series of peaks have been observed in this region of the magnetic field. The same series appears at the curve obtained at 115 K, but shifted towards higher magnetic fields.

The interpretation of these series is performed by using the values of phonon energies (Table 1) and band-structure parameters based on values of E_g equal to 175 meV and 183 meV at T=77 K and 115 K, respectively. The theoretical positions of three kinds of magnetophonon resonance on the difference of phonon frequencies (MPR DPF) (on $\hbar\omega_{LO}$ (ZnTe-cluster) – $\hbar\omega_{LO}$ (HgTe-like), $\hbar\omega_{LO}$(CdTe-like) – $\hbar\omega_{LO}$(HgTe-like) and $\hbar\omega_{LO}$(ZnTe-like) – $\hbar\omega_{LO}$(HgTe-like)) are represented in Fig.4 as electron transitions.

A conclusion can be drawn that there is a good agreement between the experimental positions of peaks of series *d* and *e* and MPR DPF attributed to them. Thus, it can be stated that the resonance series *d* is caused by the transitions of electrons between the Landau levels with LO-phonon absorption in ZnTe-clusters and emission of LO-phonons in HgTe-like sublattice. The electron transitions accompanied by absorption of phonons in the CdTe-like sublattice and emission of phonons in HgTe-like sublattice correspond to *e*-series.

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МАГНІТОФОНОННА СПЕКТРОСКОПІЯ $Zn_xCd_yHg_{1-x-y}Te$

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Методами комбінаційного розсіювання (КР) та магітофононного резонансу досліджено електронну та фононну підсистеми четвірних твердих розчинів $Zn_xCd_yHg_{1-x-y}Te$ (ЦКРТ). Спектри КР для кількох складів підтверджують тримодову поведінку фононного спектру. Чотири типи LO-фононів (для HgTe-, CdTe- і ZnTe-підграток і кластерів ZnTe) беруть участь у електрон-фононній взаємодії. Спостерігаються чотири типи однофононних магнітофононних резонансів і два типи магнітофононних резонансів на різниці фононних частот.