Magnetophonon resonance in multimode lattices and two-dimensional structures (DQW)

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Abstract. The experimental results obtained for the magneto-transport in the InGaAs/InAlAs double quantum wells (DQW) structures of two different shapes of wells are reported. The Magnetophonon Resonance (MPR) o was observed for both types of the structures at 77–125K temperatures in the pulsed magnetic field. Four kinds of LO-phonons are taken into account to interpret the MPR oscillations in DQW. The particularity of MPR in DQW is the great number Landau levels caused by SAS-splitting all electron states.

1. Introduction.
Presence of numerous different phonon modes is common feature of lattices in ternary and quaternary solid solutions (TSS) and in structures with double (DQW) or multi quantum wells (MQW). This peculiarity rearranges the electron transport in such systems according the electron-phonon interaction with different modes and appears in Magnetophonon Resonance (MPR) as additional series of peaks which were observed in CdHgTe [1,2], ZnCdHgTe [3] and MnCdHgTe [4]. In case of MPR in MQW and super-lattices, exceptional additional series were observed with a subtle structure of peaks too [5]. In recent years, a great number of publications appeared, where experimental electron transport in Double Quantum Well (DQW) structures was reported. The reason for this is the constant progress in the structure fabrication technology which allows to modify the shape and width of QW or barriers, as well as the progress in measurement techniques enables to measure separately the conductivity and Hall response of each layer. These experiments have demonstrated a number of new and interesting phenomena occurring in such structures which cannot be observed in a structure with a single two-dimensional-gas (2DEG) layer. In this work are presented and analyzed new data of MPR obtained in strong pulse magnetic fields (up to 40 T) for DQWs based on the InGaAs/InAlAs hetero-structures. The analysis is based on correct calculation of the Landau level energies in QWs and on the conception of deformed tetrahedral basic cells of phonon spectra in TSS[6]. The subtle structure of the MPR peaks is explained without participation of the interface phonons or confined phonons but including the 8 canonical phonon modes which exist in the QWs and barriers.

2. Description of the structures
The DQW based on InGaAs/InAlAs/InP structures were produced by means of the low pressure metal organic vapor phase epitaxy (LP-MOVPE) on semi-insulating (100) InP: Fe substrates at the Institute of Electronic Materials Technology, Warsaw. The method for producing the structures with a single QW, which was reported earlier, was used also for producing DQW structure with rectangular, as well as triangular QWs [7]. The structure of the first type (#2506) consists of two In_{0.65}Ga_{0.35}As QW with a
thickness of about 20 nm each, and three $\text{In}_{0.52}\text{Al}_{0.48}\text{As}$ barriers (the barrier in middle have the 20 nm thickness too). In each barrier there was a donor $\delta$-doping layer (see Figure 1).

![Figure 1](#). The conduction band edge profile of the #2506 and #3183 structures.

The second DQW structure (#3181) also consists of two $\text{In}_{0.65}\text{Ga}_{0.35}\text{As}$ QWs with a thickness of about 5 nm and three $\text{In}_{0.52}\text{Al}_{0.48}\text{As}$ barriers. In this case however, the barrier between QWs was not doped. The corresponding conduction band shape is shown in Figure 2.

![Figure 2](#). The conduction band edge profile of the #3181 structures.

3. The experimental method
The transverse magnetoresistance $\rho_{xx}(B)$ as a function of the magnetic field was registered up to 35 T at different temperatures within the range of 77 – 200 K for the three types of samples. The background was deduced to keep only the oscillatory part $\Delta \rho_{xx}(B)$ of the magnetoresistance. The low temperature measurements of the Shubnikov-de Haas (SdH) and Quantum Hall Effects (QHE) were performed in stationary magnetic fields using magnetic fields up to 10 T generated by a superconducting coil.

4. Experimental curves
In Figure 3 are shown the experimental curves of $R_{xx}(B)$ and $R_{xy}(B)$ for structure #3183 obtained at temperature 4.2K in stationary magnetic fields. The pronounced SdH oscillations, on the $R_{xx}(B)$ curve, as well as the Integer Quantum (IQHE) Hall Effect, on the $R_{xy}(B)$ curve, are clearly seen. The SdH oscillations show also the beating effect which was observed earlier [8] in our experiments for both types of the structures, namely for #2506 and #3181.

![Figure 3](#). SdH and QHE for structure #3183

![Figure 4](#). MPR for structure #3183
The Figure 4 presents curves of $\Delta \rho_x(B)$ up to 37 T, where the MPR-oscillations were observed at temperatures 86 K, 118 K and 125 K for structure #3183. At temperature 86 K strong peaks appear, the amplitudes of which decrease with a temperature increase. Similar curves were obtained for the structures #2506 and #3181.

5. Discussion

5.1. The Landau levels energy.

To interpret the MPR oscillations, the Landau level energy calculation is necessary. We are using the model proposed in [9] for the rectangular and triangular DQWs. In this model the spin-splitting and tunneling gap $\Delta_{SAS}$ variable in magnetic field was taken into account. The band structures parameters, used for the Landau level energy calculation, are presented in Table 1.

Table 1. Energy band parameters for QW in structures #2506, #3181 and #3183 at 77K

| $x$ | $E_g, eV$ | $m^*/m_0$ | $g_e^*$ | $\Delta, eV$ |
|-----|-----------|-----------|--------|------------|
| 0.65| 0.723     | 0.0229    | -9.9   | 0.355      |

In Figures 5a and 5b are shown the calculated Landau levels for structures #2506 and #3183. Three subbands as well as symmetric and anti-symmetric states are seen here. Both structures have the same QWs band shape but the different electron densities which means that the Fermi energy levels are different, namely: 190 meV for #2506 and 100 meV for #3183.

5.2. Phonons.

Interpretation of the observed peaks requires the knowledge of the LO-phonon frequencies in the QWs and barriers for researched structures. There are ternary solid solutions in the $\text{In}_{0.65}\text{Ga}_{0.35}\text{As}$ QW and in the $\text{In}_{0.52}\text{Al}_{0.48}\text{As}$ barriers. The phonon spectra of these solid solutions were studied in works [10-12] and the phonon frequencies are presented in [13] too. We used these data to determine the LO-phonon frequencies of the InAs-like and GaAs-like modes in the QW of the DQW structures as well as the InAs-like and AlAs-like modes in the barriers. These frequencies and the phonon energies are displayed in Table 2.

Table 2. The LO-phonon frequencies and energies in QWs and barriers of researched structures

| Material | $v$ [cm$^{-1}$] | $E$ [meV] |
|----------|----------------|-----------|
| 1 GaAs-like in $\text{In}_{0.65}\text{Ga}_{0.35}\text{As}$ | 268 | 33.23 |
| 2 InAs-like in $\text{In}_{0.65}\text{Ga}_{0.35}\text{As}$ | 231 | 28.64 |
| 3 InAs-like in $\text{In}_{0.52}\text{Al}_{0.48}\text{As}$ | 233 | 28.90 |
| 4 AlAs-like in $\text{In}_{0.52}\text{Al}_{0.48}\text{As}$ | 323.2 | 40.06 |

The LO-phonon energies for both QW and barriers are very close and a single 28.80 meV averaged LO-phonon energy will be used for the interpretation of the experimental peaks

5.3. Interpretation.

In Figures 5a and 5b are shown the electron transitions among Landau levels with absorption of corresponding phonons. We take into account the transitions across the Fermi level because the electron transitions should start from an occupied electron level and ended on an empty Landau level. It is seen that to each MPR peaks corresponds a group of electron transitions with absorption of one of the LO-phonons mentioned in Table 2. The main series of MPR peaks are caused by electronic
transitions with absorption of the InAs-like LO-phonons which occur at 26 T and 26.5 T (transitions \(1_{\text{sym.}}-2_{\text{sym.}}\) and \(1_{\text{antisym.}}-2_{\text{antisym.}}\), respectively), 13.0 T and 13.3 T (transitions \(1_{\text{sym.}}-3_{\text{sym.}}\) and \(1_{\text{antisym.}}-3_{\text{antisym.}}\), respectively) and 10.0 T and 10.2 T (transitions \(2_{\text{sym.}}-4_{\text{sym.}}\) and \(2_{\text{antisym.}}-4_{\text{antisym.}}\), respectively) for sample #3183. In case of sample #2506 the situation is more complicated because the levels of two subbands are overlapped at energies near the Fermi level.

6. Conclusion

Four kinds of LO-phonons are taken into account to interpret the MPR oscillations in DQW. The particularity of MPR in DQW is the great number of Landau levels caused by SAS-splitting of all electron states. That means the possibility of a great number of electron transitions between these levels. This number is multiplied by four kinds of phonons. Therefore, to each peak correspond a group of electron transitions.

References

[1] Sheregii E M, Ugrin Yu O, Shuptar D D and Leshko O M 1988 JETP Letters 47 711
[2] Sheregii E M and Ugrin Yu 1990 Sov. Phys. Solid State 32 27
[3] Cebulski J, Gębicki W, Ivanov-Omskii V I, Polit J and Sheregii E M 1998 J. Phys. Condensed Matter 10 8587
[4] Cebulski J, Kąkol T, Polit J, Sheregii E M, Ploch D, Gorbatiuik I M and Rarenko I M 2004 Journal of Alloys and Compounds, 371 103
[5] Tomaka G, Cebulski J, Sheregii E M, Ściuk W, Strupiński W and Dobrzanski L 1998 Acta Phys. Pol. A 94 597
[6] Robouch B V, Kisiel A and Sheregii E M 2001 Phys. Rev. B 64 073204
[7] Tomaka G, Sheregii E M, Kąkol T, Strupiński W, Jasik A and Jakiela R 2003 Physica Status Solidi (a), 195 127
[8] Marchewka M, Sheregii E M, Tralle I, Tomaka G and Ploch D 2007 Inter. J. of Modern Physics B 21 1518
[9] Sheregii E M, Ploch D, Marchewka M, Tomaka G, Kolek A, Stadler A, Mleczko K, Strupiński W, Jasik A and Jakiela R 2004 Journ. of Low Temperature Physics 30, 1146
[10] Brodsky M and Lucovsky G 1968 Phys. Rev. Lett. 21 990
[11] Pearsall T P, Carles R and Portal J C 1983 Appl. Phys. Lett. 42 436
[12] Pinčzuk A, Worlock J M, Nahory R E and Pollack M A 1978 Appl. Phys. Lett. 40 826
[13] Madelung O 1996 Semiconductor - Basic Data (Springer-Verlag, Berlin)