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The coupling of intersubband transitions and the quantum-well LO phonon in p-doped GaAs–GaAlAs multiple-quantum wells

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Abstract. We have applied resonant Raman spectroscopy to two p-type modulation-doped GaAs–GaAlAs multiple-quantum wells (MQW) with well widths d_W = 10 and 30 nm. In both samples one of the hole intersubband transitions observed is coupling to the quantum-well LO (longitudinal optical) phonon. The influence of an external magnetic field on this coupling phenomenon was investigated. A shift of the intersubband transition energy with excitation energy due to well width fluctuations results in an anticrossing of the two branches of the coupled modes. From the strength of the coupling as well as from the small depolarization shift of the intersubband transitions, the conclusion must be drawn that depolarization field effects are of low importance in p-doped MQW structures. The coexistence of a non-interacting quantum-well LO phonon is discussed in detail.

1. Introduction

We have investigated the inelastic scattering of light by intersubband transitions in p-type modulation-doped GaAs–GaAlAs multiple-quantum wells (MQW). Such experiments were performed before by Pinczuk *et al* [1, 2] (for a review see [3]). We are able to complete their results by new findings which allow a more detailed comparison with measurements performed on n-doped samples of similar structure. The latter have been the subject of a large number of earlier investigations (for example [4, 5]).

In backscattering geometry—as realized in the majority of experiments—two types of electronic Raman spectra are observed depending on the relative orientation of the polarizations of the incident and scattered light [6, 7]. With both polarizations orthogonal to each other ('depolarized spectrum') the spectra are interpreted as due to spin-density fluctuations with measured intersubband transition energies close to the subband spacings. The excitations in 'polarized spectra' (both polarizations are parallel) should arise from charge-density fluctuations. These transitions are of collective character and shifted to energies larger than the subband spacings by the effects of macroscopic electric

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fields (depolarization shift). A macroscopic field is simultaneously attached to the longitudinal optical (LO) phonon. Besides other (weaker) mechanisms of interaction this field may give rise to a strong coupling of the two kinds of excitation. A mutual renormalization of the coupled modes in the quantum well will result. These depolarization field effects are found to be obvious in n-doped GaAs–GaAlAs MQW. The two branches of the coupled modes (usually labelled as I_+ and I_-) are significantly shifted as compared to the energies of the quantum-well LO phonon or the pure subband spacing [4].

The observations made in p-doped samples of comparable carrier densities are in conspicuous contrast. With regard to the positions of intersubband transitions, only marginal differences were measured in the polarized and depolarized spectra. In the early experiments a phonon-like coupled mode was found to be fully absent and just an uncoupled sharp phonon line was observed [1]. Theoretical considerations of Ando [8] demand larger depolarization field effects than observed.

As in these earlier investigations we find in our samples again an uncoupled bare GaAs LO phonon (at 36.7 meV), whose resonance behaviour was already discussed in [9]. But, if the energy of our dye laser is tuned to resonant excitation of intersubband transitions with an energy close to that of the LO phonon, the two branches of coupled modes are observed in addition. As can be expected from the known weak depolarization field, the approximate coincidence in energy of both excitations is a necessary condition to observe interaction phenomena at all. In one of our two samples investigated resonant interaction was only achieved with the electronic transition energy suitably shifted by a magnetic field.

A further possibility to tune the energy difference between an intersubband transition and the LO phonon in a QW sample of given layer thickness is based on the sharp resonance behaviour of the electronic Raman scattering process. As determined by the energy of the incident photons, intersubband transitions are preferably induced in quantum wells of a defined width. Fluctuations of this width cause a shift of the intersubband transitions with laser energy [10, 11]. As a consequence interesting in our context an anticrossing of the two branches of the coupled modes is observed.

After some information about experimental details we describe the observations performed on that sample ('sample A') which is a structure similar to that investigated in [1]. This section includes remarks about the influence of an external magnetic field, polarization selection rules and effects of the sample inhomogeneity. The measurements on the second sample ('sample B') will be described in less detail. The discussion of the results refers to the strength of the coupling between hole intersubband transition and quantum-well LO phonon and to the coexistence of a coupling and a non-coupling quantum-well LO phonon.

2. Experimental details

Our resonant Raman scattering experiments were performed in conventional backscattering geometry at a sample temperature of about 2 K and with magnetic fields up to 8 T oriented normal to the heterostructure layers ($\langle 0\,0\,1\rangle$ direction). A tunable continuous-wave (CW) dye laser was used as light source operating in the range 680–770 nm. Laser powers of about 10 mW were focused to an area of about $10^{-2} \times 10^{-1}$ cm^2. The polarized and depolarized spectra were recorded in configurations $z(xx)\bar{z}$ and $z(yx)\bar{z}$, where the light polarizations x and y correspond, respectively, to the $\langle 1\,0\,0\rangle$ and $\langle 0\,1\,0\rangle$ axis. Directions x' and y' denote $\langle 1\,1\,0\rangle$ and $\langle 1\,\bar{1}\,0\rangle$. Additionally all possible

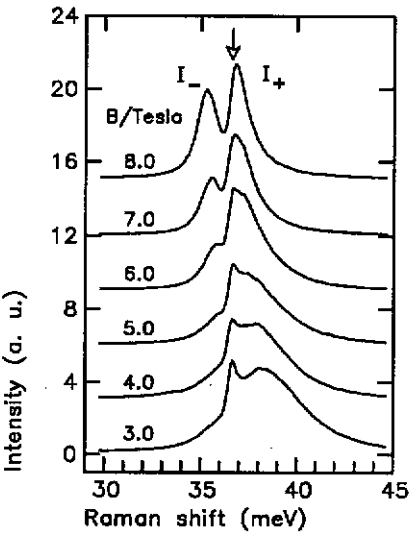

Figure 1. Raman spectra of sample A (well width $d_W = 10$ nm) for different magnetic flux densities B measured with a laser energy $E_L = 1.748$ eV in configuration $z(xx)\bar{z}$. Two branches of coupled modes (I_+ and I_-) are observed for $B \geqslant 5$ T. The arrow indicates the energy of the GaAs LO phonon.

combinations of circular polarizations were realized to probe the selection rules of hole excitations in an external magnetic field.

The most striking differences between the two investigated p-type modulation-doped GaAs–$Ga_{1-x}Al_xAs$ MQW result from their well widths d_W. The first one ('sample A', $d_W = 10$ nm) is similar to the samples studied by Pinczuk *et al* [1]; the second one ('sample B', $d_W = 30$ nm) should have a subband structure as theoretically discussed by Ekenberg [12] with two interacting two-dimensional hole gases in each well (close to the interfaces), which has the consequence of two nearly degenerate highest hole subbands. Both these subbands (h_0, h_1) are occupied with holes and can serve as initial states (h_i) of intersubband transitions, while in sample A the initial state is definitely h_0. Our MQW structures have Be-doped layers of thickness d_D with Be concentrations n_D in the centre of the barriers, which are separated from the GaAs wells by spacers of thickness d_S. Sample A: $x = 0.43$, $n_D = 1.25 \times 10^{18}$ cm^{-3}, $d_D = 3.5$ nm, $d_S = 24.5$ nm. Sample B: $x \approx 0.45$, $n_D = 1.2 \times 10^{18}$ cm^{-3}, $d_D = 30$ nm, $d_S = 10$ nm. Carrier concentrations of respectively 2.4×10^{11} cm^{-2} (sample A, measured at 77 K) and $\sim 10^{12}$ cm^{-2} (sample B, estimated) result. The mobility in sample A was measured as 3700 cm^2 V^{-1} s^{-1} at $T = 77$ K.

3. The observed Raman spectra

In both samples investigated several hole intersubband transitions to primarily heavy-hole final states h_n are observed. The highest intensity is achieved when the laser energy is tuned to resonance with the energy difference between valence and conduction subband states h_n and c_n of the same subband quantum number n. In both samples the energy of one intersubband transition $h_i \rightarrow h_n$ nearly agrees with the energy of the GaAs LO phonon (i.e. the quantum-well LO phonon), which is a necessary condition to observe marked effects of their interaction.

We could measure the Raman intensity of the coupled modes only in the case of resonant excitation of the interacting intersubband transition $h_i \rightarrow h_n$ (spectra observed with a laser energy close to resonance are shown in figure 1 for different magnetic fields,

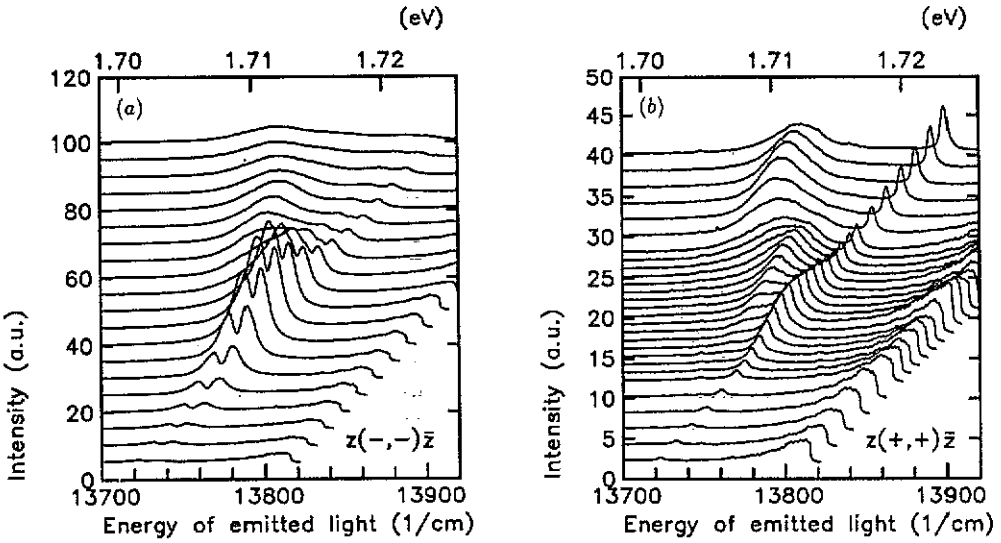

Figure 2. Spectra of sample A (B = 6.5 T) for different laser energies E_L in two configurations of circular polarizations, $z(-,-)\bar{z}$ (*a*) and $z(+,+)\bar{z}$ (*b*). The spectra are obtained with laser energies which vary between 1.736 eV and 1.761 eV in steps of about 1.2 meV or 0.6 meV, respectively.

and the resonance behaviour is displayed in figure 2). In contrast to this behaviour a second, non-coupling GaAs LO phonon shows measurable intensity as a sharp line at arbitrary laser energies with several maxima in the scattering cross section whenever the frequency of the exciting or scattered photon agrees with the energy of appropriate quantum-well excitons (resonance curves are shown in figures 3 and 4 of [9]).

Our two samples differ distinctly with respect to the average energy differences between neighbouring subband states. In sample B the valence subbands are close together, showing a flat dispersion [12]. At finite in-plane wavevectors they are strongly mixed. Intersubband excitations occur as nearly vertical transitions in the wavevector space at any wavevector smaller than the value where the highest valence subband crosses the Fermi energy. This results in broad and overlapping lines in the Raman spectrum, which are additionally superimposed by luminescence transitions from higher conduction subband states [9], and in broad resonance curves of the scattering cross section, too. In sample A the subbands are separated more clearly. This does not, however, exclude effects of their mixing. The observed intersubband transitions are sharper, especially in the case when the in-plane motion of the charge carriers (holes) is quantized by a magnetic field oriented parallel to the MQW main axis. Accordingly we prefer to discuss the coupling phenomena in detail only in the case of sample A, while the results found in sample B can only serve for comparison.

Because of the large number of close-lying intersubband transitions and their widths in sample B, no special effort was necessary to reach an energy overlap of an $h_i \rightarrow h_n$ excitation with the LO phonon. In fact the $h_{0/1} \rightarrow h_5$ transition nearly coincides (spectra showing the two branches of coupled modes are displayed in figure 7). In the case of sample A, however, the energy of the $h_0 \rightarrow h_2$ transition (i.e. the energy of one component) has to be tuned in resonance to the LO phonon by applying a magnetic field

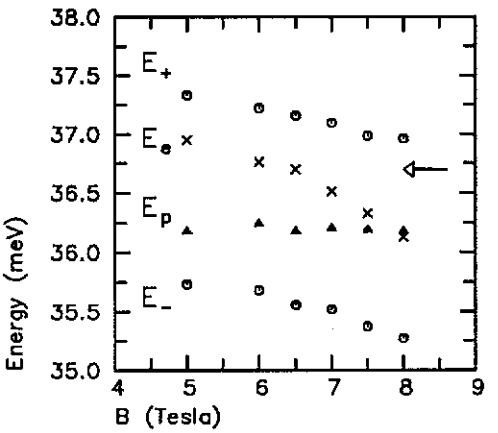

Figure 3. Raman shift of the coupled modes I_+ and I_- observed in sample A versus magnetic flux density B. $E_e(B)$ and E_p are the energies of the fictively uncoupled hole intersubband and phonon excitation as found from fitting equation (1) to spectra of the type displayed in figure 1. The arrow marks the energy of the LO phonon as measured in undoped bulk GaAs.

to observe significant effects of their coupling. As shown in figure 1 the two branches of the coupled modes I_+ and I_- emerge most clearly at high magnetic fields.

The methods used for evaluation of the coupling parameters, e.g. the energies E_e and E_p of the uncoupled electronic and phonon modes (displayed for example in figure 3) will be discussed in the following section.

4. The formalism of evaluation

For the evaluation of data from coupled excitations two different formalisms are widely used: the Fano and the Green function formalism (see for example [13]). Both methods have their special merits: the Fano technique is easily applicable in the case of an excitation with low damping coupled to a broad (quasi-) continuum of states; the Green function can be applied advantageously in the case of two or more narrow-width excitations. Because of the comparably large difference of the widths of the interacting excitations treated here the lineshapes of the coupled modes can be reasonably reproduced using both methods, but the parameters derived from the application of the Green function formalism are more easily amenable to physical interpretation. Beyond this the fitting of a Fano profile to the lineshape (as suggested earlier by us [14]) turned out to be inadequate, because of the finite linewidth of the electronic transition (the parameters used are not constant in this case, but in fact depend on the energy E).

In the Green function formalism the Raman spectrum of two coupling excitations e (electronic transition) and p (phonon) is proportional to [13]

$$I(E) = \mathrm{Im}\left(\sum_{i,j=\mathrm{e,p}} T_i \langle i|G(E)|j\rangle T_j\right) \tag{1}$$

with the Green function operator

$$G(E) = \begin{pmatrix} \tilde{E}_\mathrm{p} - E & V \\ V^* & \tilde{E}_\mathrm{e} - E \end{pmatrix}^{-1}.$$

The energies $\tilde{E}_i$ are assumed as complex to describe effects of an overlap of the interacting lines (interference effects), $\tilde{E}_i = E_i + \mathrm{i}\Gamma_i$, with the energy E_i and linewidth Γ_i of the fictively uncoupled excitations. V is the matrix element of the electron–phonon coupling.

The T_i are the scattering amplitudes of the coupling excitations. The difference in the phase of T_e and T_p and the argument of the complex quantity V add up to just one parameter of the fit.

For vanishing linewidth of the coupling excitations, the zeros of the reciprocal Green matrix $G(E)$ yield two energies E_+ and E_-:

$$E_\pm = \tfrac{1}{2}\{E_p + E_e \pm [(E_p - E_e)^2 + 4|V|^2]^{1/2}\}. \tag{2}$$

An identification of E_+ and E_- with the energies of the peaks of the I_+ and I_- modes (e.g. in figure 1) neglects effects of interference to the lineshapes of overlapping excitations.

Commonly one finds in the literature [15] the frequencies of a coupled mode system determined from the zeros of the total dielectric function. This is correct in the case of coupled excitations of collective character. To avoid any presuppositions about the coupling mechanism and about the type of the electronic transition we use our more general method for data evaluation. In the case of weak interaction as given here both formalisms should yield corresponding results.

We have applied two methods to find the parameters E_p, $|V|$ and $E_e(B)$ from the evaluation of our Raman spectra. The first one uses the information stored in the lineshapes of each individual spectrum: The I_+ and I_- modes were simulated using equation (1); luminescence background and the sharp bare LO phonon line were fitted by sums of Gauss and Lorentz functions. The quality of the results found for the parameters sought was controlled by fitting a wealth of spectra measured with different laser energies in the range of resonant excitation. Only the scattering amplitudes T_i should be found to vary as an effect of the dependence of the scattering cross sections on the energy of the incident photons, while all the other parameters should remain constant (for fixed magnetic flux density B). In fact only the energy of the coupling phonon E_p and the absolute value of the coupling strength $|V|$ are obtained as independent of laser energy (apart from acceptable and unsystematic errors of data evaluation), while E_e shifts. This could be interpreted as an effect of the inhomogeneous width of the quantum wells as discussed in [10] and [11] (intersubband transitions in quantum wells of different widths are selectively excited depending on laser energy).

The second method of evaluation used here is based just on this shift of the electronic transition energy E_e with laser energy. The energies E_+ and E_- of the coupled modes were determined by simply fitting symmetric lineshapes to a great number of spectra (figure 6). Describing all these pairs of energy values with parameters E_p and $|V|$ fixed and E_e variable (dependent on laser energy) by application of equation (2) we got mean values for E_p and $|V|$, which agree well with that found by the first method for each individual spectrum.

The energy E_p of the coupling phonon was chosen as variable in our fit. In fact we found a value for its energy which does not agree with that of the non-coupling sharp phonon line. The latter has the same energy as the LO phonon in undoped bulk GaAs (36.7 meV at $T = 2$ K). Compared to this the coupling phonon was found to be at slightly lower energy. This is discussed in more detail in section 7.2. The linewidth of the coupling phonon as derived from fitting equation (1) is nearly identical to that of the narrow non-coupling phonon ($\Gamma_p \approx 0.5$ meV, limited by spectrometer resolution).

5. Sample A

In sample A ($d_W = 10$ nm) the coupling intersubband transition is $h_0 \rightarrow h_2$ (some admixture of neighbouring light-hole subbands to h_0 and h_2 cannot be excluded), which is most

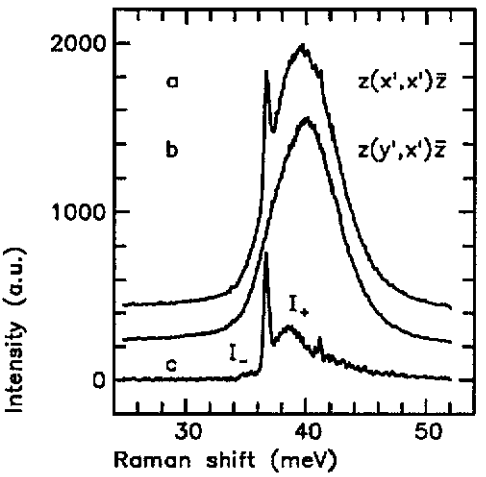

Figure 4. Spectra of sample A measured with laser energy $E_L = 1.749$ eV for $B = 0$ T. In configuration $z(y'x')\bar{z}$ (spectrum (*b*)) the observed intensity is nearly pure luminescence as tested by varying E_L. The subtraction of the spectra (*a*) and (*b*) from each other eliminates this polarization-independent luminescence and yields the Raman spectrum of configuration $z(x'x')\bar{z}$ (spectrum (*c*)) with slight indications for the existence of two branches of coupled modes I_+ and I_-.

intensively excited in the Raman spectra with the laser energy in resonance with the $h_2 \rightarrow c_2$ exciton (1.748 eV). For $B = 0$ T the $h_0 \rightarrow h_2$ transition is observed only in the polarized spectrum at about 38.5 meV. If we subtract the polarized and depolarized spectra from each other to eliminate the polarization-independent luminescence background, slight indications for the existence of two branches of coupled modes are observable for $B = 0$ T (figure 4). Two clearly separated branches, however, are obvious only with magnetic fields of flux densities $B \geqslant 5$ T applied (figure 1). Besides the Raman intensity of the coupled modes and of the non-coupling quantum-well LO phonon, a luminescence line from a transition $c_2 \rightarrow h_0$ dominates these spectra.

In the following we discuss the dependence of our observations from magnetic flux density B, from scattering configuration (polarization) and from laser energy (resonance of the scattering efficiencies). In a separate section the effects of sample inhomogeneities are presented in detail. If nothing else is indicated, all parameters which describe the coupled modes are found by fitting equation (1) to the spectra.

5.1. Magnetic field effects

Applying a magnetic field $B \| \langle 0\,0\,1 \rangle$ the most intense component of the electronic transition $h_0 \rightarrow h_2$, split by the magnetic field, shifts to lower energies with increasing B. Crossover of the uncoupled excitations is reached at about $B = 8$ T (figure 3), while E_e starts from about 2 meV ($B = 0$ T) above E_p. At $B = 8$ T two modes (I_+ and I_-) of nearly equal intensities and linewidths are observed in the Raman spectrum (figure 1).

In the range $B \geqslant 5$ T the energy E_p of the coupling phonon and the absolute value of the coupling strength $|V|$ are found to be field-independent: $E_p = 36.2 \pm 0.1$ meV, $|V| = 0.9 \pm 0.1$ meV. The value of E_p is shifted by -0.5 meV as compared to that given in undoped bulk GaAs [16].

5.2. Polarization selection rules

Raman spectra of sample A were recorded for all possible combinations of linear and circular polarizations in backscattering geometry at an external magnetic field of $B = 6.5$ T. The coupled modes were observed in both configurations of linear polarizations

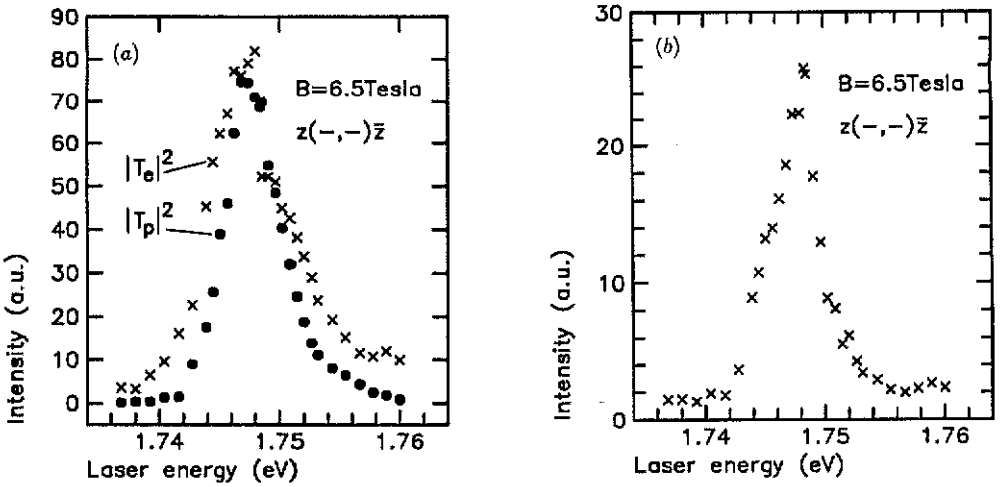

Figure 5. (*a*) Squared absolute values of the scattering amplitudes T_e (×) and T_p (●) of the intersubband transition $h_0 \rightarrow h_2$ and of the coupling quantum-well LO phonon versus laser energy as found by fitting equation (1) to the spectra. (*b*) Intensity of the non-coupling quantum-well LO phonon versus laser energy. (Sample A, $B = 6.5$ T, scattering configuration $z(-,-)\bar{z}$.)

(the 'polarized' and 'depolarized' spectrum) with no significant difference concerning the coupling strength or the positions of the coupling excitations. The most conspicuous distinctions result from the intensity of the non-coupling phonon, from differences in the amplitudes T_e and T_p and from the resonance behaviour of these parameters.

Using circular polarizations (denoted as + or −) the intensities of the Raman lines are found to dominate in spectra observed with incident and scattered light polarized in the same sense (with respect to a fixed axis and not to the direction of propagation; see figure 2). In one of these configurations ($z(-,-)\bar{z}$) nearly the whole intensity of the coupled excitations is concentrated, while in the other ($z(+,+)\bar{z}$) a second, less intense component of the $h_0 \rightarrow h_2$ transition is observed (with an energy of 40.0 meV at $B = 6.5$ T), whose energy difference to the LO phonon is obviously too large (much larger than $|V|$) to cause effects of resonant interaction.

In [2] the magnetic-field-dependent splitting of the $h_0 \rightarrow h_1$ transition in a comparable MQW structure is displayed and compared to theoretical calculations of the level splitting. An extension of these calculations to the h_2 subband was not performed by us till now, but the polarization selection rules observed in the experiment for both split transitions were compared. We found that the coupling $h_0 \rightarrow h_2$ component obeys the same polarization selection rules as the high-energy splitting component of the $h_0 \rightarrow h_1$ transition published in [2]; the other $h_0 \rightarrow h_2$ component observed the same rules as the $h_0 \rightarrow h_1$ component of lower energy. We conclude that the Landau quantum numbers of the initial and final states could be, respectively, the same.

5.3. Resonance of scattering efficiencies

In figures 5(*a*) and (*b*) we compare the resonances of scattering efficiencies in the configuration of circular polarizations $z(-,-)\bar{z}$ ($B = 6.5$ T, spectra are shown in figure

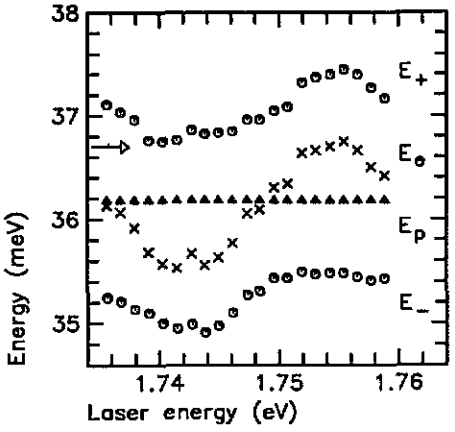

Figure 6. Variations of the energies E_+ and E_- of the two branches of coupled modes versus laser energy caused by well width fluctuations (sample A, $B = 8.0$ T, $z(xx)\bar{z}$). The energy E_p of the coupling phonon is chosen such that the full anticrossing is described by equation (2) with minimal variation of the coupling strength with laser energy. This yields the energy $E_e(E_L)$ of the fictively uncoupled hole intersubband transition $h_0 \rightarrow h_2$. The arrow marks the energy of the LO phonon as measured in undoped bulk GaAs.

2(*a*)) in which the intensity of the coupled modes exceeds that observed for Raman lines with other combinations of polarizations by one order of magnitude or more. Figure 5(*a*) shows the resonance of the Raman intensities of the interacting modes, figure 5(*b*) the corresponding intensity variation of the non-coupling LO phonon. The resonance behaviour in both diagrams evidently confirms that both the coupling and the non-coupling phonon modes have to be attributed to the quantum well. The coincidence of the resonance maxima of both excitations excludes the interpretation that these phonon modes exist in wells which differ in doping or width or both. The fact that the resonance maxima of the non-coupling phonon are shifted in other configurations of circular polarizations is not surprising, because other Landau levels should participate in the intermediate states involved in the scattering process. Nothing definite can be said about the existence of coupled modes in these configurations, because possible leakages from the most intense $z(-,-)\bar{z}$ configuration cannot be completely excluded.

The widths of the resonance curves—as well as the widths of the intersubband transitions—are mostly determined by sample inhomogeneities, by fluctuations in the thicknesses of the quantum wells [11]. An interesting consequence of these thickness fluctuations will be discussed in the following section.

5.4. Effects of well width inhomogeneities

The observation of a shift of a hole intersubband transition energy E_e versus excitation energy E_L due to fluctuations in the widths of the quantum wells was already reported by Goldberg *et al* [10]. As we could show recently, our sample seems to be of higher quality in terms of the interface roughness [11]. This results in an $E_e(E_L)$ dependence as shown in figure 6 which differs from the pure linear shift displayed in [10]. With the dye laser tuned to the energy of the maximum of the scattering amplitude T_e or far away from it (the intersubband transition should of course be just observable), the measured subband spacing corresponds to the most frequent well width, while with laser energies in between inelastic scattering takes place preferably in such wells in which the condition of resonant excitation is fulfilled.

A simple simulation of this dependence was realized with a Gaussian probability distribution for the well width fluctuations. The halfwidth of the distribution was found to be nearly just one monolayer of the crystal. The fact that our investigations were

performed with high magnetic fields excludes the possibility that subband dispersion contributes to this effect; the in-plane motion is quantized.

As a consequence of the described dependence $E_E(E_L)$ it turns out to be difficult to measure the shift of an intersubband transition with the magnetic field. The energies $E_e(B)$ displayed in figure 3 are observed with the laser energy tuned to the maximum of the scattering amplitude T_e. This can only be performed when the full resonance curve is measured for each magnetic field of interest.

The shift of the intersubband transition energy E_e with laser energy has an especially interesting consequence. By selective excitation of electronic transitions in quantum wells of slightly different width the relative position of the $h_0 \rightarrow h_2$ hole excitation changes with respect to the LO phonon. An anticrossing behaviour of the coupled I_+ and I_- modes results. While the anticrossing displayed in figure 3 is an effect of a varied magnetic flux density B, now the electronic transition energy shifts with laser energy (figure 6, $B = 8$ T fixed). If the energies E_+ and E_- of the coupled modes are known (for example from a fit of symmetric line profiles) the energies $E_e(E_L)$ and E_p of the coupling excitations and the coupling strength $|V|$ are derivable from the variation of E_+ and E_- with laser energy E_L.

Using equation (2) the full anticrossing should be well described with E_p and $|V|$ constant. The energies $E_e(E_L)$ and E_p displayed in figure 6 were derived in our data evaluation by choosing E_p as a constant which minimizes the variation of $|V|$ with E_L about its mean value $|\bar{V}|$. Residual variations of $|V|$ with E_L—especially when coincidence of E_e and E_p is realized—result from neglecting linewidth effects. The values of E_p and $|\bar{V}|$ are in full agreement with those determined by fitting equation (1) to the individual spectra. The phonon energy is again found to be shifted by -0.5 meV compared to the value measured in undoped bulk GaAs (marked by an arrow in figure 6).

6. Sample B

The second investigated sample (sample B, $d_W = 30$ nm) yields spectra in which the intensity of inelastic scattered light and that of a broad and strongly structured luminescence background is hardly separable. Therefore a detailed evaluation as performed for sample A is excluded.

With laser energies almost exactly in the same range as used for the investigation of sample A we observe again two broad Raman lines (I_+ and I_- in figure 7) close to the sharp line of an again uncoupled GaAs LO phonon. They can be well interpreted as resulting from the interaction between the $h_{0/1} \rightarrow h_5$ intersubband transition and a softened quantum-well LO phonon.

Fitting equation (1) to spectra of the type displayed in figure 7 we find the energies $E_e = 34.8 \pm 0.5$ meV and $E_p = 35.5 \pm 0.5$ meV for the coupling excitations (E_p is about 1.2 meV smaller than the phonon energy in undoped bulk GaAs) and $|V| = 3.5 \pm 0.5$ meV for the coupling strength.

In sample B (for $B = 0$ T) the excitations I_+ and I_- were only measured in the polarized spectrum, while in the depolarized spectrum no Raman intensities of coupled modes could be separated from the luminescence background.

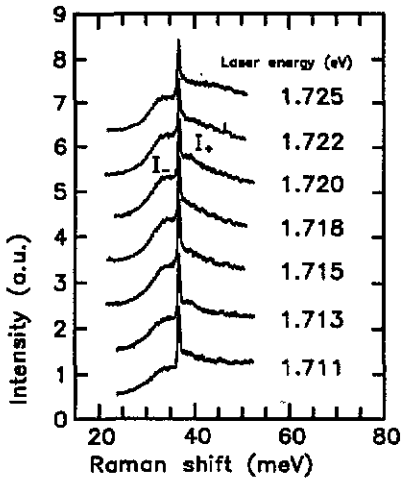

Figure 7. Raman spectra of sample B ($d_W = 30$ nm) measured with various laser energies E_L ($B = 0$ T, configuration $z(xx)\bar{z}$). For $E_L = 1.72$ eV close to a sharp GaAs LO phonon line two branches of coupled modes (I_+ and I_-) are observed. An intense luminescence background prevents a detailed evaluation.

7. Discussion

7.1. Depolarization field effects

Strong depolarization field effects should manifest themselves as a difference in the intersubband transition energies received from polarized (charge-density intersubband excitations) and depolarized spectra (spin-density intersubband excitations). A significant depolarization shift of intersubband excitations with collective character observed in the polarized spectrum would simultaneously be consistent with a strong coupling to the LO phonon (an effect of the macroscopic electric field) [6, 7]. The carrier concentration belongs to the parameters which dominate the size of the depolarization shift.

With $B = 0$ T in sample B a small depolarization shift (≤ 1 meV, depending on the transition energy) is measured for all hole transitions and the coupled modes are only observable in the polarized spectrum. For the $h_0 \rightarrow h_1$ excitation in sample A we derive a depolarization shift of about 0.7 meV, while the transition close to the LO phonon ($h_0 \rightarrow h_2$) occurs only as a charge-density intersubband excitation for $B = 0$ T showing just insignificant indications of interaction (figure 4). These observations are in qualitative agreement with results found from investigations on n-doped MQW samples [4, 5, 17]. But in spite of comparable carrier concentrations the depolarization field effects observed in our p-doped structures are much smaller than in the n-doped samples.

One observation which calls all quantitative calculations into question till now is described in [8]. In MQW structures comparable to our sample A a growth of the carrier concentration from 2×10^{11} cm^{-2} (nearly the same as in sample A) to a value of 5.8×10^{11} cm^{-2} results in a complete disappearance of any depolarization shift, while the theory predicts an increase. Many-body effects are held responsible by Ando.

With a magnetic field applied, the differences between the polarized and depolarized spectra concerning the energy of intersubband transitions or the interaction with the LO phonon disappear, at least in the case of sample A, where the sharpness of the excitations allows an investigation in detail. The small strength of the coupling—directly obvious in the anticrossings of figures 3 or 6—suggests that contributions of weak polaron-type Fröhlich [15] or deformation potential interaction can be important in this case.

7.2. The quantum-well LO phonons

In sample A as well as in sample B the simultaneous occurrence of a coupling and a non-coupling LO phonon is observed, which are both identified as excitations of the quantum well from their resonance behaviour. An important attribute, which helps to elucidate their origins, is their difference in energy. While the non-coupling narrow phonon line is found at the same energy as the LO phonon in undoped bulk GaAs, the energy E_p of the coupling mode—resulting from the application of the Green function formalism (equation (1))—is shifted to lower energy by 0.5 meV (sample A) or 1.2 meV (sample B), respectively.

Modifications of the LO phonon frequency in polar semiconductors can be caused by doping (investigations on p-doped bulk GaAs by Raman scattering are published, e.g. in [18]). The screening of the polarization field of the LO phonon, which results in a reduction of its frequency, was also discussed in the interpretation of magnetophonon resonance experiments (on n-doped GaAs–GaAlAs heterojunctions [19]). The wavevector dependence of this screening effect was shown by neutron scattering on n-type PbTe [20]. The shift of the LO phonon caused by screening decreases with wavelength. Long-wavelength LO phonons are expected to be more strongly softened. So the non-coupling phonon could be a confined LO phonon mode with a shorter wavelength than the coupling one, or a phonon with a finite in-plane wavevector, Raman active due to impurity-induced Fröhlich scattering.

The simultaneous occurrence of a non-interacting LO phonon and one branch of coupled modes in the Raman spectrum of p-type bulk HgTe was reported just recently and interpreted in an analogous manner [21].

8. Conclusions

We have investigated the interaction of hole intersubband transitions and the quantum-well LO phonon in two p-type modulation-doped MQW of quite different character due to conspicuously differing well widths. The coupled modes are observed only in the case of resonant excitation of the participating intersubband transition. At least in one of our samples the evaluation of a lot of spectra yields well determined values of the energies of the coupling excitations and of the interaction strength. We can state two facts. Depolarization field effects are surprisingly weak in our samples (this is in contrast to observations performed in n-doped MQW structures [4]) and the energy of the interacting LO phonon does not agree with the value observed for a second, non-coupling phonon, which was also identified as a quantum-well excitation. The reason for the distinct behaviour of these two types of LO phonons possibly results from different wavelengths.

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