

## ACCEPTOR RAMAN SCATTERING IN GaAs–Al<sub>x</sub>Ga<sub>1-x</sub>As QUANTUM-WELL STRUCTURES

D. GAMMON and R. MERLIN

*Department of Physics, The University of Michigan, Ann Arbor, Michigan 48109, USA*

and

D. HUANG and H. MORKOÇ

*Coordinated Science Laboratory, University of Illinois at Urbana-Champaign, 1101 Springfield Avenue, Urbana, Illinois 61801, USA*

We report resonant Raman scattering from Be acceptors in GaAs–Al<sub>x</sub>Ga<sub>1-x</sub>As quantum well structures, grown by molecular beam epitaxy. Center- and edge-doped samples with well widths in the range 70–165 Å were investigated as a function of temperature and uniaxial stress. The data show confinement-induced shifts and splittings of the lowest-lying acceptor levels in good agreement with recent calculations, and also excitations that may involve impurity states derived from higher subbands. The stress dependence of the spectra reveals coupling of the lowest acceptor transition to transverse acoustic phonons. Confinement-split lines exhibit a not fully understood intensity exchange with increasing temperature.

### 1. Introduction

The properties of isolated impurities in semiconductors have attracted a great deal of attention for many years because of the important role impurities play in device applications, and the fact that they are the solid-state analog of atomic hydrogen. Quantum-well structures (QWS's), showing quasi-two-dimensional behavior, and having parameters that can be varied almost at will, provide an additional incentive for impurity studies [1–11]. Features of interest include the dependence of the binding energy on the well width ( $L$ ), confinement-induced splittings of degeneracies, and broadening of the impurity spectrum resulting from the inequivalence of different positions within a well [1–4]. Experimentally, these effects have been investigated in GaAs–Al<sub>x</sub>Ga<sub>1-x</sub>As QWS's by use of photoluminescence (acceptors [5–7] and donors [6,8]), infrared (donors [9]) and Raman scattering (acceptors [11] and donors [10]) techniques. In this work, we review our previous report [11] on Raman scattering from Be acceptors in QWS's, and present new results on the uniaxial-stress dependence of the spectra.

### 2. Experimental

The samples used in this work were grown by molecular beam epitaxy on (001) Si-doped GaAs substrates with a 0.2–0.5 μm buffer layer on top. They consist of 20–50 periods of ≈ 100 Å thick Al<sub>0.3</sub>Ga<sub>0.7</sub>As barriers, and GaAs layers with thicknesses in the range 70–165 Å. The overlap of wavefunctions associated with different wells is negligible for these structures. Be acceptors were incorporated during growth at the centers or edges of the GaAs slabs with dopant concentrations ranging from  $7 \times 10^{15}$  to  $3 \times 10^{16}$  cm<sup>-3</sup>. The width of the doping spike was  $\leq L/2$ . Values of  $L$  were determined from photoluminescence and absorption measurements [12]. The Al mole fraction in the barriers was determined from growth conditions and confirmed from the positions of longitudinal optical (LO) phonons in the Raman spectra [13].

Resonant Raman experiments were performed using laser energies  $\omega_L$  in the vicinity of the HH2 and LH2 excitons [14], associated with the first excited confined states of the wells. The resonances were very sharp with widths less than  $\approx 5$

meV. Spectra were recorded in the  $z(x', x')\bar{z}$ ,  $z(x', y')\bar{z}$ , and  $z(x' + iy', x' \pm iy')\bar{z}$  backscattering configurations where  $z$  is normal to the layers, and  $x'$  and  $y'$  are along the directions  $[110]$  and  $[\bar{1}\bar{1}0]$ . The acceptor lines were found to be unpolarized in all cases, presumably because of the resonant nature of the scattering. More details are given in ref. [11].

Uniaxial stress was applied to the samples along  $[110]$  (parallel to the layers) using a simple screw device. The stress was indirectly monitored by measuring the position of the HH1 free-exciton luminescence. At the highest stress achieved, the exciton peaks shift by less than  $\approx 6$  meV in all samples. Their widths remained constant in the whole range, indicating good stress homogeneity.

### 3. Results and discussion

Acceptor states in bulk GaAs derive mainly from the four-fold degenerate  $\Gamma_8(J = 3/2)$  states of the valence bands. This degeneracy is partially lifted under confinement, giving rise to two Kramers doublets of symmetries  $\Gamma_6$  and  $\Gamma_7$  [4]. In the bulk, the dominant Raman feature is the transition  $1S_{3/2}[\Gamma_8] \rightarrow 2S_{3/2}[\Gamma_8]$  [15]. The expected *three* Raman lines at low temperatures resulting from the splittings of these levels were identified in our work. The corresponding transitions are labelled A, B, and C in fig. 1, which also shows the calculated [4]  $L$ -dependence of the states associated with  $1S_{3/2}[\Gamma_8]$  and  $2S_{3/2}[\Gamma_8]$ .

Raman spectra from two samples are displayed in fig. 2. The top trace shows, for  $L = 70$  Å, the transition  $1S_{3/2}[\Gamma_6] \rightarrow 1S_{3/2}[\Gamma_7]$  (labelled C in fig. 1) which has been previously observed [15] in stressed bulk GaAs. The bottom spectrum shows the A and B lines in a sample with  $L = 165$  Å. The C-line could not be seen in this structure; the expected splitting of the  $1S_{3/2}[\Gamma_8]$  state is too small to be resolved in our experiments.

The measured positions of the A, B, and C transitions in a series of center-doped samples [11] show good agreement with theoretical predictions [4]. For edge-doped QWS's we find relatively large discrepancies [11] that are tentatively attributed to the inadequacy of the matching boundary condi-

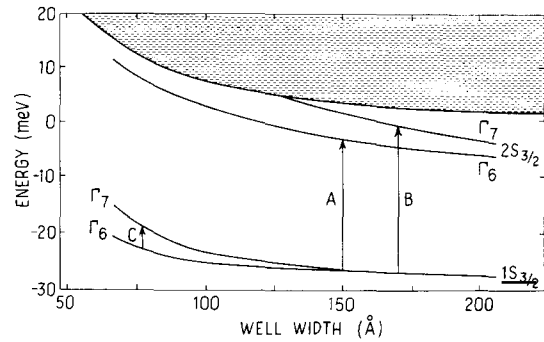


Fig. 1. The calculated well-width dependence of the spectrum of an acceptor at the center of a GaAs-Al<sub>0.3</sub>Ga<sub>0.7</sub>As quantum-well structure [4]. Only the levels associated with the bulk states  $1S_{3/2}[\Gamma_8]$  and  $2S_{3/2}[\Gamma_8]$  are shown. Energies are given with respect to the position of the valence-band edge in the bulk. The dashed region denotes the continuum. Labels A, B, and C refer to corresponding Raman features in figs. 2 and 3.

tions used in the theoretical work [4]. The width of the acceptor lines in center-doped structures is also close to theoretical predictions [4], given the nominal doping profile of the samples. This is an indication of negligible impurity segregation during growth.

Other than the A, B, and C lines, the spectra of our QWS's reveal features occurring above the estimated acceptor binding energy, as shown by the three peaks labelled X in the structure with  $L = 165$  Å (the calculated binding energy for this sample is  $\sim 30$  meV [4]). The origin of these lines is not clear. The two higher-energy components are in the expected range of interface phonons [16] and were identified as such in our previous report [11]. However, all X lines shift appreciably under stresses that also shift the A, B, and C peaks, but not the LO phonons (see below). In addition, undoped samples fail to show X-type scattering. This suggests that the nature of the scattering is electronic, and due to acceptor transitions into resonant states derived from higher hole subbands (such transitions have been observed in Raman spectra of donors in QWS's [10]). A definitive assignment of the X-lines is prevented by the fact that their positions show only a weak dependence on the well width [11], which is unexpected for acceptor transitions. Other factors that complicate the identification are the presence in the spectra of

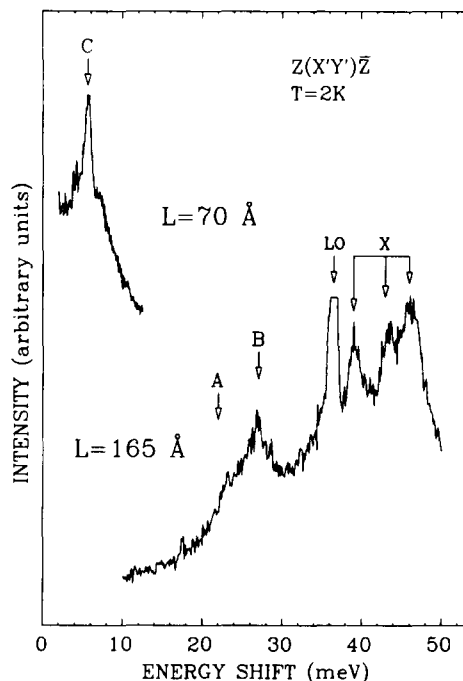


Fig. 2. Raman spectra for two center-doped quantum-well samples showing acceptor transitions A, B, and C. The truncated peak at 36.9 meV is due to LO scattering from the GaAs layers. Features labelled X are discussed in the text. Spectra were obtained at  $\omega_L = 1.744$  (1.646) eV for  $L = 70$  (165) Å.

nearby Al<sub>0.3</sub>Ga<sub>0.7</sub>As LO phonons, and the possibility of impurity-induced scattering by interface modes [16]. Furthermore, coupling of these phonons to acceptor transitions cannot be excluded.

The temperature dependence of the spectra reveal some interesting features, particularly in the behavior of the A and B lines. With increasing temperature, the A scattering intensity increases at the expense of the B counterpart [11]. To discuss this effect, it is important to recognize that the character of A (B) becomes more  $\Gamma_7 \rightarrow \Gamma_6$  ( $\Gamma_7 \rightarrow \Gamma_7$ ) and less  $\Gamma_6 \rightarrow \Gamma_6$  ( $\Gamma_6 \rightarrow \Gamma_7$ ) as  $T$  increases (each line should actually give rise to two components at high  $T$ , but their expected separation [4] is much smaller than the peak widths). This suggests that the intensity exchange may be simply an indication of a much larger cross section for transitions between states of different symmetries. However, we do not have an explanation as to why these transitions should dominate.

Under [110] stress, all acceptor lines exhibit a positive Raman shift (1–2 meV) while the HH1 photoluminescence moves by 4–6 meV towards higher absolute energies (quoted values are for the largest stress obtained before breaking the samples). Absolute magnitudes of the stress will require a calculation of the exciton energy versus uniaxial pressure. Stress was used mainly to differentiate between electronic and impurity-induced vibrational scattering. Further splittings of acceptor transitions were neither expected nor observed, as quantum-confinement lifts all but the spin degeneracy of the impurity spectrum. The most interesting feature of the stress data is the pronounced broadening of the C-transition with increasing stress, as shown in fig. 3. We tentatively attribute this behavior to coupling of the acceptor transition to GaAs transverse acoustic phonons showing a highly peaked density of states at  $\approx 8$ –10 meV [17]. Coupling to acoustic phonons has been previously proposed to account for the broad

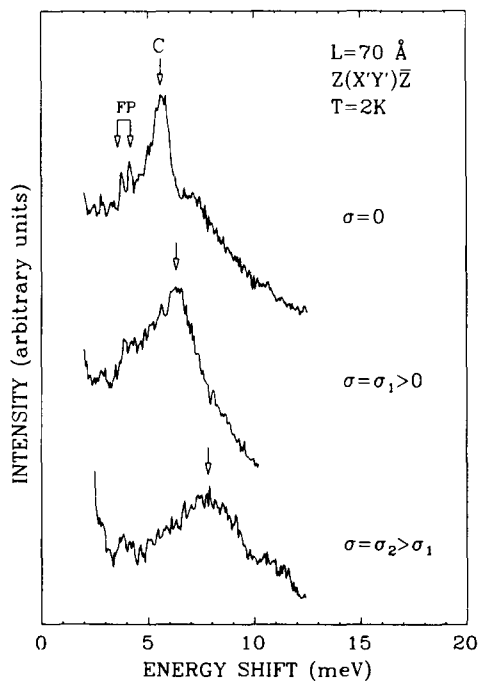


Fig. 3. Stress ( $\sigma$ ) dependence of the C line. The stress is along [110], parallel to the layers. The weak features labelled FP are folded acoustic phonons.

and complex lineshapes exhibited by C-like excitations in bulk GaAs [15] and GaP [19,19], where uniaxial stress is required to split the  $1S_{3/2}$  state. The latter results were obtained under non-resonant conditions, and the interpretation of the spectra is complicated by the presence of “phonon wings”, i.e., processes involving the excitation of the acceptor with the simultaneous creation of a phonon [15,18,19]. Such processes were not observed in our resonant spectra. This, and the fact that the C-line is already well defined at zero stress suggests that further Raman work on QWS's could help elucidate the nature of the coupling.

### Acknowledgements

This work was supported by the US Army Research Office under Contract No. DAAG-29-85-K-0175, and JSEP under Grant No. N00014-84-C-0149.

### References

- [1] G. Bastard, E.E. Mendez, L.L. Chang and L. Esaki, Solid State Commun. 45 (1983) 367, and references therein.
- [2] C. Mailhot, Y.-C. Chang and T.C. McGill, Phys. Rev. B26 (1982) 4449.
- [3] See R.L. Greene and K.K. Bajaj, Phys. Rev. B31 (1985) 913, and references therein.
- [4] W.T. Masselink, Y.-C. Chang and H. Morkoç, Phys. Rev. B32 (1985) 5190.
- [5] R.C. Miller, A.C. Gossard, W.T. Tsang and O. Munteanu, Phys. Rev. B25 (1982) 3871.
- [6] See P.W. Yu, S. Chaudhuri, D.C. Reynolds, K.K. Bajaj, C.W. Litton, W.T. Masselink, R. Fischer and H. Morkoç, Solid State Commun. 54 (1985) 159, and references therein.
- [7] A. Petrov, M.C. Smith, C.H. Perry, J.M. Worlock, J. Warnock and R.L. Aggarwal, Solid State Commun. 55 (1985) 865.
- [8] B.V. Shanabrook and J. Comas, Surface Sci. 142 (1984) 504.
- [9] N.C. Jarosik, D.D. McCombe, B.V. Shanabrook, J. Comas, J. Ralston and G. Wicks, Phys. Rev. Letters 54 (1985) 1283, and references therein.
- [10] T.A. Perry, R. Merlin, B.V. Shanabrook and J. Comas, Phys. Rev. Letters 54 (1985) 2623, and references therein.
- [11] D. Gammon, R. Merlin, W.T. Masselink and H. Morkoç, Phys. Rev. B33 (1986) 2919.
- [12] W.T. Masselink, P.J. Pearch, J. Klem, C.K. Peng, H. Morkoc, G.D. Sanders and Y.-C. Chang, Phys. Rev. B32 (1985) 8027.
- [13] B. Jusserand and J. Sapriel, Phys. Rev. B24 (1981) 7194.
- [14] R. Dingle, W. Wiegmann and C.H. Henry, Phys. Rev. Letters 33 (1974) 827.
- [15] K. Wan and R. Bray, Phys. Rev. B32 (1985) 5262.
- [16] See, e.g., A.K. Sood, J. Menendez, M. Cardona and K. Ploog, Phys. Rev. Letters 54 (1985) 2115, and references therein.
- [17] See, e.g., G. Dolling and R.A. Cowley, Proc. Phys. Soc. (London) 88 (1966) 463.
- [18] C.H. Henry, J.J. Hopfield and L.C. Luther, Phys. Rev. Letters 17 (1966) 1178.
- [19] L.L. Chase, W. Hayes and J.F. Ryan, J. Phys. C10 (1977) 2957.