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Superlattice modification of the valence-band spin splitting in $In_xGa_{1-x}As/GaAs$ superlattices up to 45 T

R. J. Warburton
Clarendon Laboratory, Department of Physics, Oxford University, Parks Road, Oxford OX1 3PU, United Kingdom

R. J. Nicholas
Clarendon Laboratory, Department of Physics, Oxford University, Parks Road, Oxford OX1 3PU, United Kingdom and Institute for Solid State Physics, University of Tokyo, Roppongi, Minato-ku, Tokyo, Japan

S. Sasaki and N. Miura
Institute for Solid State Physics, University of Tokyo, Roppongi, Minato-ku, Tokyo, Japan

K. Woodbridge
Department of Electronic and Electrical Engineering, University College London, Torrington Place, London WC1E 7JE, United Kingdom

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We report interband magneto-optics on a series of $In_xGa_{1-x}As/GaAs$ superlattices in pulsed magnetic fields up to 45 T. The experiments demonstrate that the heavy-hole spin splitting is strongly dependent on the degree of interwell coupling in the valence band. Calculations of the Landau levels in these structures give very good agreement with the experimental data and show that the heavy-hole spin splitting passes through zero at low fields for a weakly coupled superlattice, but that this moves up to ~ 40 T when strong interwell coupling occurs.

The band structures induced in semiconductor superlattices are relatively straightforward for the conduction bands, due to their almost isotropic nature. This is not true of the valence band, where the strong mixture of the p-like wave functions leads to anisotropy and a consequent mixing of the motion both within and along the direction of the layers forming the superlattice potential. We report an example of this behavior in a study of $In_xGa_{1-x}As/GaAs$ superlattices using interband magneto-optics up to magnetic fields of 45 T. A range of samples was available, with heavy-hole superlattice miniband widths from 5 meV to < 0.2 meV. Unusual features in the spectra can be related directly to the valence band because the conduction band has straightforward Landau levels, with a near-zero g factor. We find that the heavy-hole spin splittings show a surprisingly strong dependence on the degree of interwell coupling, even when the magnetic field is applied along the growth axis.

The samples were a series of four $In_xGa_{1-x}As/GaAs$ superlattices grown by molecular-beam epitaxy at the Philips Research Laboratories, Redhill, with a constant well thickness of nominally 50 Å, indium concentration $x \simeq 5\%$, and barrier thicknesses nominally 50, 100, 150, and 200 Å. Moore *et al.*[1] have presented an optical study of these samples, which demonstrates the formation of superlattice minibands. The exact sample parameters, as determined by x-ray diffraction, are listed in Table I of Ref. 1 and differ by $\leq 10\%$ from the nominal growth parameters. Each sample consists of a 20-period superlattice and a 1-μm buffer layer grown onto a GaAs substrate. The x-ray measurements show that there is almost no lattice relaxation within the strained layer superlattice.

The experiments consisted of a series of transmission measurements taken with a long (10-mS) pulse magnet. The coil was cooled to liquid-nitrogen temperatures and the field was applied parallel to the sample growth direction. The sample, immersed in liquid helium, was illuminated with light in the 1.5-eV region of the spectrum and the transmitted light was collected with an optical fiber bundle and ultimately detected using an intensified optical multichannel analyzer detector, gated on for 500 μS at maximum field during each pulse.

A typical series of absorption traces is shown in Fig. 1 for the 50/150-Å sample. There is a strong $E1$-HH1 $1s$ (where HH denotes heavy hole) excitonic absorption which starts at 1.49 eV at zero field and moves up rapidly as the field increases. Above this is a series of further transitions, as discussed by Moore *et al.*,[1] the strongest of which comes from the $1s$ $E1$-LH1 exciton. At intermediate fields, a number of level crossings and mixings occur, which are associated with crossings both in the valence band and in the conduction band. This has been discussed recently by Lawless *et al.*,[2] and will not be pursued further here; instead, we concentrate on the high-field behavior. Figure 2 shows spectra for three of the samples at intermediate field, 11 T, and at high field, 41 T, and reveals a strong sample dependence of the optical absorption. There is the immediate and obvious difference between the strongly coupled 50/50-Å sample, for which the resonance is relatively broad at low fields but sharp and strong at high field, and the weakly coupled 50/100- and 50/150-Å samples, where the low-field traces are sharp and the high-field traces are broad. The high-field trace for the 50/150-Å sample can be seen to develop a clear spin splitting at high field. The light-hole exciton has a more complicated response, but does not show such a pronounced sample dependence.

In order to understand these results, we have performed eight band $\mathbf{k}\cdot\mathbf{p}$ calculations of the Landau levels, based on the Hamiltonian as given in Weiler or Trebin, Rössler, and Ranvaud,[3,4] within the axial approximation. The results for the conduction band are completely straightforward, with a conventional series of Landau levels with dispersions which are not influenced by any motion along the superlattice direction. The conduction-band spin splittings are very small for this material system, < 0.1 meV for $B < 40$ T, because the conduction-band g factor is very small. By contrast, the valence-band levels, particularly those originating from the heavy hole, are very strongly influenced by the superlattice structure, as shown in Fig. 3, a comparison of the first Landau levels ($n_{ll} = 0$) at the Γ point for the 50/50 and 50/150 samples. The levels are labeled with their spin, $|M_J| = \frac{3}{2}$ for the heavy holes and $|M_J| = \frac{1}{2}$ for the light holes.[5] In the case of the 50/50 sample, there is a significant HH miniband width (5 meV at zero field) and so the $n_{ll} = 0$ levels are shown also at the Π point. The difference between the 50/50 Γ and Π points shows particularly the strong influence of the superlattice coupling: the $M_J = +\frac{3}{2}$ state has an *inverted* superlattice dispersion above 10 T and above 15 T the highest valence-band state occurs at the Π point, so that the system becomes indirect at high field, as first pointed out by Warburton, Lawless, and Nicholas.[6] The HH spin splitting at Γ is also seen to reverse at 37 T for the 50/50 sample, but this occurs at much lower field, close to 10 T, for 50/150. In fact, the calculations show that the field at which the HH spin splitting is zero moves up continuously in field as the barrier width decreases. The consequence is that, at 40 T, the spin splitting of the 50/150 sample is much higher than that of the 50/50.

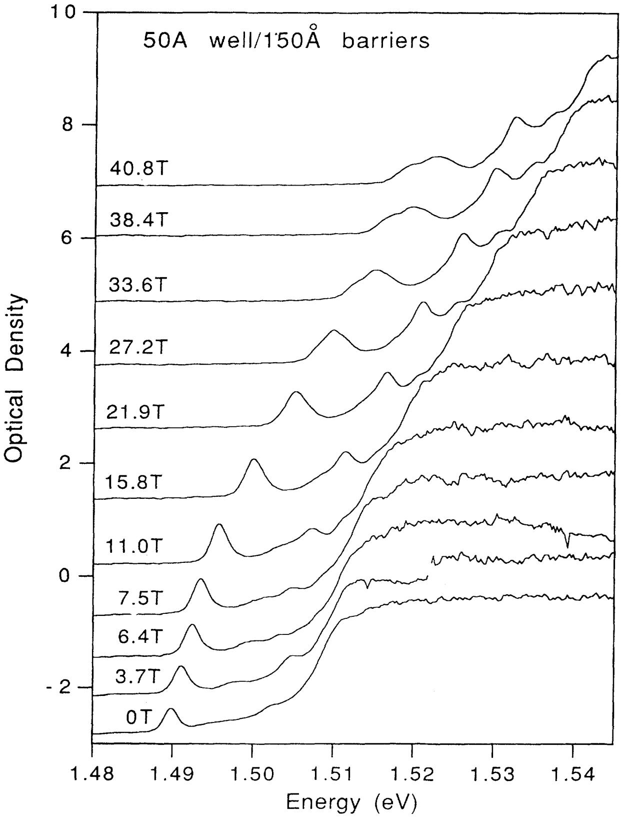

FIG. 1. Typical experimental traces of the absorption coefficient for the 50/150-Å sample taken at a series of magnetic fields. The traces are offset for clarity.

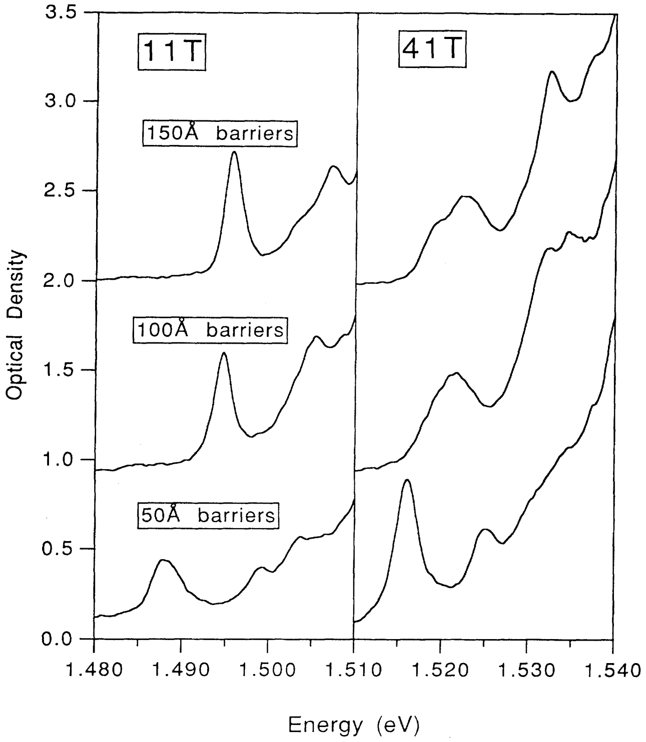

FIG. 2. Experimental traces of the absorption coefficient for three of the samples at 11 T and 41 T, showing, at high fields, a sharpening for the strongly coupled structure and a splitting for the weakly coupled 50/150 case.

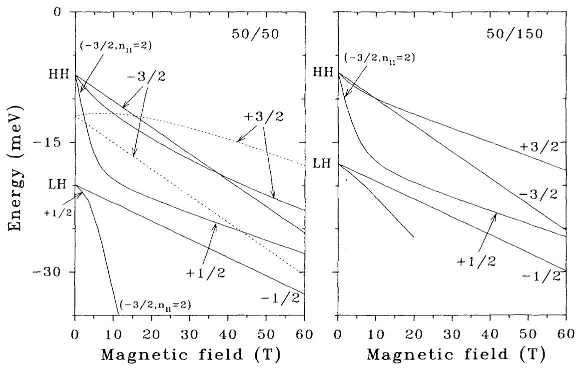

FIG. 3. The first Landau levels for the heavy hole ($M_J = \pm\frac{3}{2}$) and light hole ($M_J = \pm\frac{1}{2}$), calculated for the 50/50- and 50/150-Å samples. The solid lines are at the Γ point; the dashed lines for the 50/50 sample are at the Π point. The energy zero is at the top of the $\mathrm{In}_x\mathrm{Ga}_{1-x}\mathrm{As}$ well.

The light-hole (LH) Landau levels are very similar for all the samples, as illustrated for the 50/50 and 50/150 structures in Fig. 3, so that the spin splitting at high field is largely insensitive to barrier width. The light-hole levels are somewhat complicated at low field by an anticrossing. Figure 3 shows two levels, one originating from the HH with $M_J = -\frac{3}{2}$, $n_{ll} = 2$ and the other originating from the LH with $M_J = +\frac{1}{2}$, $n_{ll} = 0$, which anticross[7] between 5 and 10 T, so that at high field the characters of the levels are reversed. This interaction gives the LH exciton an unusual behavior, and we have identified this experimentally in both $\mathrm{In}_x\mathrm{Ga}_{1-x}\mathrm{As/GaAs}$ and $\mathrm{In}_x\mathrm{Ga}_{1-x}\mathrm{Sb/GaSb}$ superlattices.

In order to make a direct comparison with the experimental data, we have calculated the total interband energies. The conduction-band Landau levels were calculated within the same $\mathbf{k}\cdot\mathbf{p}$ approach, and the usual selection rules were adopted. An estimate of the magnetoexciton binding energy was made by scaling the results of Makado and McGill[8,9] on a three-dimensional hydrogen atom in intense magnetic field. We took zero-field exciton binding energies of 4.5 (2.5) and 6.5 (2.5) meV for the 50/50 and 50/150 HH (LH) excitons, respectively. Figure 4 is a plot of the measured and calculated energies versus magnetic field for the 50/50 and 50/150 samples. It can be seen that the agreement of the calculations with the Γ point HH exciton is excellent. In particular, the theory demonstrates that the sharpening of the resonances around 10 T for the wider barrier structures is due to the collapse of the spin splitting, which then clearly becomes resolved by 40 T. By contrast, the spin splitting of the 50/50-Å sample is close to its peak at 10 T, leading to the broad resonance seen experimentally, while the sharpening of the peak at high field is again caused by the collapse of the spin splitting. The agreement with the LH levels is also good, although the theory does seem to underestimate the magnitude of the splitting slightly.

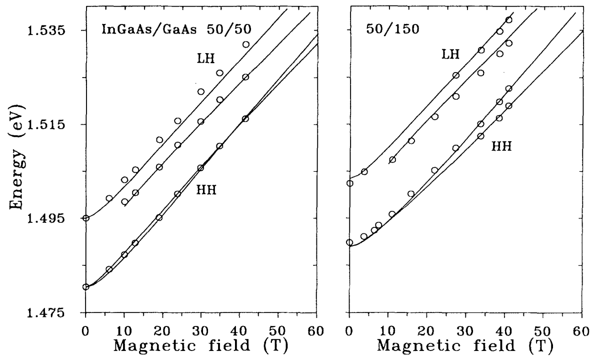

FIG. 4. Fan diagrams for the 50/50- and the 50/150-Å samples. The symbols mark the experimental points and the solid lines show the calculated energies.

In conclusion, we may state that we have clear evidence for the influence of superlattice valence-band coupling on the heavy-hole spin splitting in semiconductor superlattices, as predicted recently by Warburton, Lawless, and Nicholas.[6] This is caused by mixing of the heavy-hole and light-hole bands. In particular, we have found that the spin splitting of the uppermost valence-band level goes through zero at a magnetic field determined by the superlattice parameters, leading to a distinct sharpening of the excitonic absorption.

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[1] K. J. Moore, G. Duggan, A. Raukema, and K. Woodbridge, Phys. Rev. B **42**, 1326 (1990).

[2] M. J. Lawless, R. J. Warburton, R. J. Nicholas, N. J. Pulsford, K. J. Moore, G. Duggan, and K. Woodbridge, Phys. Rev. B **45**, 4266 (1992).

[3] M. H. Weiler, in *Semiconductors and Semimetals*, edited by R. K. Willardson and A. C. Beer (Academic, New York, 1981), Vol. 16, p. 119.

[4] H.-R. Trebin, U. Rössler, and R. Ranvaud, Phys. Rev. B **20**, 686 (1979).

[5] Note that M_J and n_{ll} are not exact quantum numbers, but rather label the dominant component in the admixture of basis states making up the wave function, with one exception, the $M_J = -\frac{3}{2}$, $n_{ll} = 0$ level, which is the only "pure" state. The levels plotted in Fig. 3, at fields far from the obvious anticrossing, have dominant contributions not less than 75%.

[6] R. J. Warburton, M. J. Lawless, and R. J. Nicholas, Surf. Sci. **267**, 365 (1992).

[7] The mixing between the $M_J = -\frac{3}{2}$, $n_{ll} = 2$ and $M_J = +\frac{1}{2}$, $n_{ll} = 0$ levels occurs because both have the same axial quantum number 0. The other $n_{ll} = 0$ light-hole level, with $M_J = -\frac{1}{2}$, also has an anticrossing with a heavy-hole level (the $M_J = -\frac{3}{2}$, $n_{ll} = 1$ level), but this is very weak (as can be anticipated by a parity argument) and so is omitted from Fig. 3.

[8] P. C. Makado and N. C. McGill, J. Phys. C **19**, 873 (1986).

[9] To estimate the magnetoexciton binding energy, a reduced mass is calculated at each magnetic field from the dispersions of the two relevant levels. This reduced mass is then used to scale the results of Makado and McGill. This procedure is likely to be reasonably accurate for the HH exciton, as it should account for nonparabolicity in an appropriate way. However, Fig. 3 shows that the $M_J = +\frac{1}{2}$, $n_{ll} = 0$ level at high field has a dispersion which extrapolates back at zero field to somewhere between the LH and HH, making the $M_J = +\frac{1}{2}$ LH exciton calculation slightly ambiguous.