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Zeeman splitting and g factor of heavy-hole excitons in $In_xGa_{1-x}As/GaAs$ quantum wells

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Zeeman splittings have been investigated for $n=1$ heavy-hole excitons $In_xGa_{1-x}As/GaAs$ strained-layer quantum wells at 1.8 K and at magnetic fields up to 6 T applied parallel to the growth axis (001). The sign and magnitude of the splitting to precision of ± 2 μeV were obtained from the shift in the exciton photoluminescence line upon switching between right and left circularly polarized detection. Measurements have been made for well widths between 3 and 12 nm and for x values of 0.075 and 0.11. Linear field dependence is observed below 1.5 T giving exciton g factors. For higher fields in narrow wells the dependence becomes nonlinear. We have calculated the g factor using an eight-band $\mathbf{k}\cdot\mathbf{p}$ model and obtain satisfactory agreement with experiment by using the Luttinger parameter κ for $In_xGa_{1-x}As$ as a variable parameter. From this we obtain an empirical concentration dependence $\kappa \approx 7.68x + 1.1(1-x) - 4.0x(1-x)$.

Recent investigations of the g factors and Zeeman splittings of carriers in $GaAs/Al_xGa_{1-x}As$ quantum wells have demonstrated strong variations with quantum well parameters,[1–3] anisotropy of electron, hole, and exciton g factors,[4] and also strong nonlinearity of Zeeman splitting at high fields.[2,3] This is important for interpretation of magneto-optic or magnetotransport measurements and also can provide an excellent test of theoretical descriptions of the band structure comparable to that obtained from calculations of effective mass. For $In_xGa_{1-x}As/GaAs$ quantum wells the built-in strain must be included, giving an additional test of theory. We describe here direct polarization-selective spectroscopic measurements, similar to those of Ref. 2, of the g factors and Zeeman splitting for magnetic fields up to 6 T of the $n=1$ heavy-hole exciton luminescence in (001)-grown $In_xGa_{1-x}As/GaAs$ strained-layer quantum wells with x between 0.075 and 0.11 and well widths between 3.0 and 12 nm. In spite of the inhomogeneous broadening (typically 1–2 meV), our technique gives the Zeeman splitting to ± 2 μeV. This precision is as good as that available from "sub-inhomogeneous" laser spectroscopic techniques such as quantum beats[5] and hole-burning[6] and moreover in our measurements the sign of the Zeeman splitting is directly determined. We have also made calculations of the Zeeman splittings based on $\mathbf{k}\cdot\mathbf{p}$ theory including the strain[7] which give a satisfactory description of the sign and magnitude of the g factors. The conduction band makes only a small contribution to the splitting, which is therefore particularly sensitive to the rich spin structure in the valence band. To date there have been few reported studies of this. Detailed comparison of the calculations with the experimental data gives insight to the concentration dependence of the Luttinger parameter κ.

For purposes of definition, we take the Zeeman Hamiltonian for the $n=1$ heavy-hole exciton in a magnetic field oriented along the growth axis of the quantum well (z) to be[2,8,9]

$$H=\beta B_z(g_e S_z - g_h \Sigma_z) + H_{\text{exch}}, \tag{1}$$

where $\mathbf{S}=\frac{1}{2}$ is the spin quantum number of the conduction electrons, $\Sigma=\frac{1}{2}$ is an *effective spin* quantum number describing the heavy-hole valence-band states ($J_z=\pm\frac{3}{2}$), β is the Bohr magneton, and g_e and g_h are the electron and heavy-hole g factors, respectively. The electron g factor is expected to show a small variation with field direction,[4,10] whereas in the above effective spin formalism the heavy-hole splitting factor is strongly anisotropic, being zero by symmetry for a field perpendicular to the growth axis.[8] H_{exch} represents the spin-dependent exchange interaction of the electron and hole.[8,9]

The four exciton basis states $|S_z,\Sigma_z\rangle$ are

$$\psi_1=|\tfrac{1}{2},-\tfrac{1}{2}\rangle, \quad \psi_2=|-\tfrac{1}{2},\tfrac{1}{2}\rangle,$$
$$\psi_3=|\tfrac{1}{2},\tfrac{1}{2}\rangle, \quad \psi_4=|-\tfrac{1}{2},-\tfrac{1}{2}\rangle. \tag{2}$$

In zero magnetic field these are separated by the exchange term into two doublets $\psi_{1,2}$ and $\psi_{3,4}$ in which the spins are antiparallel and parallel, respectively. We expect the exchange splitting to be very small for $In_xGa_{1-x}As/GaAs$ because of the weak quantum confinement in this system[9] and indeed we have found no evidence of level crossings in applied magnetic field resulting from zero-field splitting of the kind observed in $GaAs/Al_xGa_{1-x}As$ samples.[9] In a field B_z there are splittings of the two doublets given by

$$E_1-E_2=(g_e+g_h)\beta B_z,$$
$$E_3-E_4=(g_e-g_h)\beta B_z. \tag{3}$$

Electric-dipole-allowed recombination occurs only from states ψ_1 and ψ_2 with emission of σ^+ and σ^- circularly polarized photons propagating along z; ψ_3 and ψ_4 are not optically allowed. This means that the heavy-hole exciton emission line shows a Zeeman splitting with g factor

$$g_{\text{exc}}=g_e+g_h. \tag{4}$$

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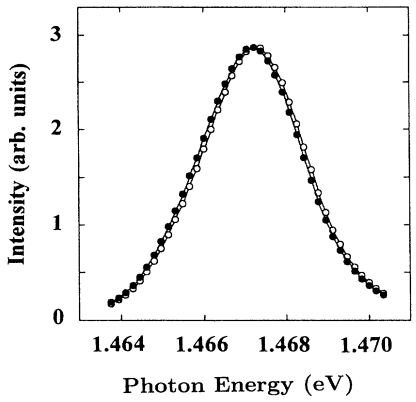

FIG. 1. Zeeman components of the heavy-hole exciton luminescence observed in σ^+ (○) and σ^- (●) polarization for well width 8 nm, indium concentration 0.075, applied field $B_z = 1.07$ T, and temperature 1.7 K.

It also shows that the two Zeeman components can be distinguished and their separation measured in a polarization-selective measurement. This analysis assumes that the splittings are linear in field. Our measurements show this is the case up to 1.5 T but at higher fields the measured Zeeman splittings become nonlinear due to field-induced admixture of other excitonic states.[11,12] In principle this admixture may change the polarization characteristics of the luminescence, resulting in an error in the splitting measurements, but we do not expect this to affect our results significantly.

Four $In_xGa_{1-x}As/GaAs$ samples were investigated. All were undoped and grown by molecular-beam epitaxy (MBE) on (001)-orientated semi-insulating GaAs substrates with a 0.5-μm GaAs buffer layer between substrate and quantum wells. One contained three quantum wells of nominal thicknesses 3, 6, and 10 nm separated by 30-nm GaAs barriers, and the others contained single 4-, 8-, and 12-nm quantum wells, respectively. The well widths for the three-well sample were found from electron microscopy to be close to the nominal values and we assume the nominal widths for the other samples to be correct. The nominal indium concentration was 0.11 for all samples. In order to obtain independent estimates of the concentrations we made photoluminescence excitation measurements of the 4.2-K light- and heavy-hole exciton energies in each sample and compared these with calculations based on the Kane model using the set of material parameters given by Warburton and co-workers[7,13] and assuming the nominal well widths. This indicated that the indium concentration for the three-well sample was 0.11 ± 0.02, whereas for the three single-well samples it was 0.075 ± 0.01.

Zeeman measurements were made at 1.8 K and at fields up to 6 T applied along the sample growth direction (see Figs. 1 and 2). The luminescence was excited using a HeNe laser and detected in a direction parallel to the magnetic field using a $f = 0.25$ m grating spectrometer and photomultiplier. The inhomogeneous broadening only allows direct resolution of the Zeeman splitting of the line without polarization selection at much higher fields.[13,14] In the present measurements we used double modulation and dual channel lock-in detection of the photomultiplier current; one channel was

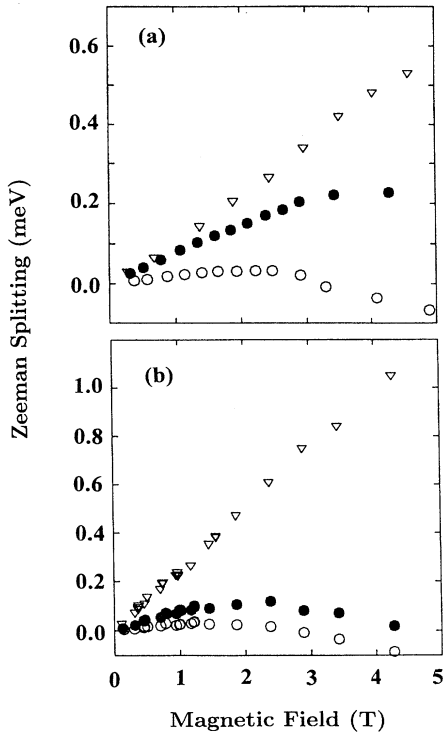

FIG. 2. (a) Zeeman splitting for $x = 0.075$ for well widths of 12 (▽), 8 (●), and 4 nm (○). (b) Zeeman splittings for $x = 0.11$ for well widths of 10 (▽), 6 (●), and 3 nm (○).

locked to a 2-kHz chopper in the HeNe excitation beam the second channel was locked to a 50-kHz photoelastic modulator (oscillatory wave plate) and linear polarizer positioned in the input beam to the spectrometer. The signal at 2 kHz gave the sum of the two circularly polarized Zeeman components while that at 50 kHz gave their difference. Addition and subtraction of these two signals then gave the two Zeeman components point by point across the inhomogeneous line. A typical set of data is shown in Fig. 1. The method has excellent immunity from drifts and allows the separation to be obtained to high precision using the algorithm described in Ref. 2.

The precision of the splitting obtained by this method was shown in Ref. 2 to approach the theoretical limit $\pm\Gamma/\sqrt{N}$, where Γ is the inhomogeneous linewidth and N is the equivalent wavelength-integrated photon count recorded in the spectrum. The precision can therefore be much less than the inhomogeneous width and, given the stability of the modulation measurement technique, can rival that from laser techniques which avoid the inhomogeneous broadening.[5,6] For the samples studied here, unlike those of Ref. 2, systematic variations of the splittings across the sample surface were found to be small and the overall accuracy was $\sim \pm 2$ μeV. The sign of the splitting between the components in the luminescence was determined directly by comparison with the signal obtained when a standard σ^+-polarized beam was passed through the detection system.

In the region below 1.5 T (Fig. 2) we observe Zeeman splittings proportional to the field and use these to obtain the excitonic g factor shown in Fig. 3, which also shows the

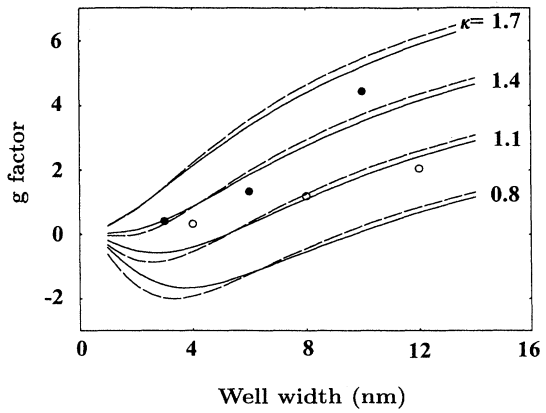

FIG. 3. Experimental (points) and calculated (curves) exciton g factors; closed circles and solid curves for $x=0.75$, open circles and dashed curves for $x=0.11$. Calculations are shown for a range of values of Luttinger κ in the $In_xGa_{1-x}As$ well and comparison with the experimental points leads to the values quoted in the text and plotted in Fig. 4.

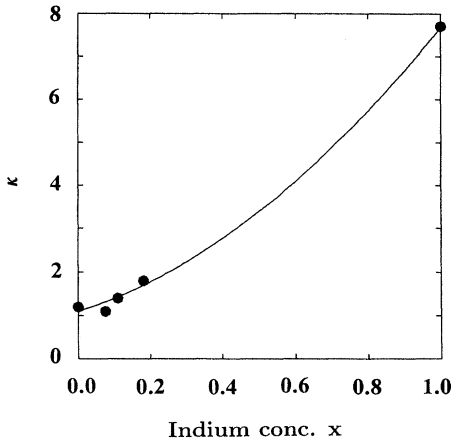

FIG. 4. Experimental Luttinger κ in $In_xGa_{1-x}As$ compared with the empirical curve $\kappa=7.68x+1.1(1-x)-4.0x(1-x)$.

results of calculations discussed below. The g factor is positive for all the samples investigated and increases monotonically with well width. At a given width the g factor falls with concentration. At higher fields the splittings become nonlinear, as shown in Fig. 2. This effect is particularly marked for narrow wells where the Zeeman splitting is observed to pass through zero.

We have made calculations of the Zeeman splittings based on an eight-band $\mathbf{k}\cdot\mathbf{p}$ theory, which has been discussed in detail elsewhere.[7,13] In Fig. 3 we present results for the g factors, i.e., the asymptotic low-field region, and we will publish calculations of the nonlinear, high-field region for both $In_xGa_{1-x}As/GaAs$ and $GaAs/Al_xGa_{1-x}As$ systems elsewhere.[15] We have calculated the electron and heavy-hole Zeeman splittings separately and combine them to give the excitonic splitting [see Eq. (4)]; the hole g factor is positive and is at least ten times the magnitude of the electron g factor, which has a negative sign. We have used the same parameters as in Refs. 7 and 13 except that we have used the Luttinger parameter κ of the $In_xGa_{1-x}As$ well as an adjustable to give the theoretical curves in Fig. 3. This parameter represents the major contribution to Zeeman splitting of the valence band in bulk material. In this way we obtain estimates of $\kappa=1.1\pm0.1$ for 8% indium and 1.4 ± 0.1 for 11% indium, while previous transport studies[7] have suggested $\kappa=1.8$ for 18% indium. These values are plotted in Fig. 4 together with those for GaAs (Ref. 16) and InAs (Ref. 17) and can be fitted by

$$\kappa=7.68x+1.1(1-x)-4.0x(1-x), \qquad (5)$$

where x is the indium concentration. It can be seen from Fig. 4 that the experimental value of κ for $x=0.08$ is below the curve and this might be taken to indicate a lower value of κ than 1.2 for GaAs. Indeed, a value of 0.7 has been found recently[18] in magneto-optic experiments. However, our investigations of Zeeman splittings in $GaAs/Al_xGa_{1-x}As$ wells[15] do not support this lower value and we believe κ to be close to the more generally accepted value of 1.2 in GaAs.[16] We therefore believe that the low value of κ for $x=0.08$ simply reflects the existence of significant bowing in the concentration dependence combined with uncertainties in the analysis of the data.

The origin of the strong concentration and well-width dependence of the Zeeman splittings is the coupling of heavy- and light-hole valence bands. The first spin-down ($J_z=-\frac{3}{2}$) heavy-hole state is not influenced by this interaction but the spin-up ($J_z=+\frac{3}{2}$) state is. This means that in this case, where $\kappa>0$, the heavy-hole Zeeman splitting is reduced by the interaction since the mixing causes repulsion of the spin-up state away from the (type-II) light-hole levels. The heavy- to light-hole splitting increases with both indium concentration and well width, leading to the calculated increase of g factor which corresponds very satisfactorily with the observed behavior. This situation is simpler than that which occurs in the $GaAs/Al_xGa_{1-x}As$ system[15] for which the light- to heavy-hole splitting passes a maximum value for a well width of about 4 nm.

In conclusion, the measured Zeeman splittings for $In_xGa_{1-x}As/GaAs$ strained-layer quantum wells show linear field dependence up to about 1.5 T. The g factors obtained from this region are compared with an eight-band $\mathbf{k}\cdot\mathbf{p}$ model which gives generally good agreement. From this we obtain estimates of the valence band Luttinger parameter κ for various indium concentrations, x, and obtain an empirical formula for $\kappa(x)$. For higher values of applied field the Zeeman splittings show strong nonlinearity which for narrower wells leads to a sign reversal of the splitting.

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[1] M. J. Snelling, G. P. Flinn, A. S. Plaut, R. T. Harley, A. C. Tropper, R. Eccleston, and C. C. Phillips, Phys. Rev. B **44**, 11 345 (1991).

[2] M. J. Snelling, E. Blackwood, C. J. McDonagh, R. T. Harley, and C. T. B. Foxon, Phys. Rev. B **45**, 3922 (1992).

[3] W. Ossau, B. Jäkel, E. Bangert, and G. Weimann, in *Properties of Impurity States in Superlattice Semiconductors*, Vol. 183 of *NATO Advanced Study Institutes, Series B: Physics*, edited by C. Y. Fong, Inder P. Batra, and C. Cirac (Plenum, New York, 1988), p. 285.

[4] E. L. Ivchenko and A. A. Kiselev, Fiz. Tekh. Poluprovodn. **26**, 1471 (1992) [Sov. Phys. Semicond. **26**, 827 (1992)]; V. K. Kalevich and V. L. Korenov, Pis'ma Zh. Eksp. Teor. Fiz. **56**, 257 (1992) [JETP Lett. **56**, 253 (1992)].

[5] S. Bar-Ad and I. Bar-Joseph, Phys. Rev. Lett. **66**, 2491 (1991); O. Carmel, H. Shtrikman, and I. Bar-Joseph, Phys. Rev. B **48**, 1955 (1993); A. P. Heberle, W. W. Ruhle, and K. Ploog, Phys. Rev. Lett. **72**, 3887 (1994); R. M. Hannak, M. Oestreich, A. P. Heberle, W. W. Ruhle, and K. Kohler, Solid State Commun. **93**, 313 (1995).

[6] H. Wang, M. Jiang, R. Merlin, and D. G. Steel, Phys. Rev. Lett. **69**, 804 (1992).

[7] R. J. Warburton, R. J. Nicholas, L. K. Howard, and M. T. Emeny, Phys. Rev. B **43**, 14 124 (1991); R. J. Warburton, R. W. Martin, R. J. Nicholas, L. K. Howard, and M. T. Emeny, Semicond. Sci. Technol. **6**, 359 (1991).

[8] H. W. van Kesteren, E. C. Cosman, W. A. J. van der Poel, and C. T. B. Foxon, Phys. Rev. B **41**, 5283 (1990).

[9] E. Blackwood, M. J. Snelling, R. T. Harley, S. R. Andrews, and C. T. B. Foxon, Phys. Rev. B **50**, 14 246 (1994).

[10] G. Hendorfer and J. Schneider, Semicond. Sci. Technol. **6**, 595 (1991).

[11] G. E. W. Bauer and T. Ando, Phys. Rev. B **37**, 3130 (1988).

[12] G. E. W. Bauer, in *High Magnetic Fields in Semiconductor Physics II*, edited by G. Landwehr, Springer Series in Solid State Sciences Vol. 87 (Springer-Verlag, Berlin, 1989), p. 170.

[13] R. J. Warburton, R. J. Nicholas, S. Sasaki, N. Miura, and K. Woodbridge, Phys. Rev. B **48**, 12 323 (1993).

[14] Th. Wimbauer, K. Oettinger, Al. L. Efros, B. K. Meyer, and H. Brugger, Phys. Rev. B **50,** 8889 (1994).

[15] R. J. Warburton, N. J. Traynor, and R. T. Harley (unpublished).

[16] K. Hess, D. Bimberg, N. O. Lipari, J. U. Fishbach, and M. Altarelli, in *Physics of Semiconductors: Proceedings of the 13th International Conference, Rome, 1976*, edited by F. G. Fumi (Elsevier, New York, 1976), p. 142.

[17] *Semiconductors*, edited by O. Madelung, Landolt-Börnstein, New Series, Group III, Vol. 17 (Springer-Verlag, Berlin, 1982).

[18] A. Fasolino, G. Platero, M. Potemski, J. C. Maan, K. Ploog, and G. Weimann, Surf. Sci. **267**, 509 (1992).