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Exciton, heavy-hole, and electron g factors in type-I GaAs/Al$_x$Ga$_{1-x}$As quantum wells

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The magnetic g factor for $n=1$ heavy-hole–electron excitons in type-I GaAs/Al$_x$Ga$_{1-x}$As quantum wells has been determined at 1.8 K as a function of well width (L_z) from the Zeeman splitting of the luminescence line below 2 T. Combined with previously published g-factor measurements for electrons and heavy holes this gives a complete picture of the variation of the magnitudes and signs of the three g factors. The variation of electron g factor can be understood in terms of the nonparabolicity of the conduction band of GaAs using three-band $\mathbf{k}\cdot\mathbf{p}$ perturbation theory, but that of the hole and exciton g factors is not reproduced by existing theory, implying a well width dependence of the Luttinger parameters κ and q.

The study of magnetic g factors and Zeeman splittings of free electrons, holes, and excitons in quantum wells is important because of the insights it provides to subband structure[1,2] and to coupling between exciton states.[3,4] It is also relevant for many phenomena, notably quantum Hall effects, magneto-optical polarization measurements,[5] and electron-nuclear spin coupling.[6] For bulk semiconductors, the best data come from optically detected magnetic resonance but this has worked only in narrow type-II GaAs/AlAs quantum wells[7] and not in type-I systems because the lifetimes of photoexcited carriers are too short.[8] Consequently, until now, the behavior of g factors has not been investigated systematically over a wide range of quantum-well widths (L_z). In this paper we report measurements of Zeeman splitting of the excitonic recombination line at 1.8 K in undoped GaAs/Al$_x$Ga$_{1-x}$As samples, and assemble other evidence concerning g factors of electrons, heavy holes, and excitons. This gives a complete picture of the g factors and shows that all three vary rapidly and pass through zero for L_z between 5 and 12 nm. We briefly consider the theoretical interpretation of this behavior.

van Kesteren *et al.*[7] have discussed the Zeeman Hamiltonians for electrons, holes, and excitons in type-II GaAs/AlAs quantum wells. Since their form is dictated by the axial symmetry, they also describe type-I quantum wells. We adopt the same notation and sign conventions here. The Zeeman interaction for conduction electrons is assumed to be isotropic and given by the Hamiltonian

$$H_e = g_e \beta \mathbf{B}\cdot\mathbf{S}\,, \tag{1}$$

where g_e is the electron g factor and $\mathbf{S}=\frac{1}{2}$ is the electron spin. For the valence band we assume that the separation of heavy- and light-hole states is much larger than any Zeeman splitting. Consequently, we are only concerned with the heavy-hole band and use an effective spin $\mathbf{\Sigma}=\frac{1}{2}$ to describe its sublevels; $J_z=\frac{3}{2}$ $(-\frac{3}{2})$ corresponds to $\Sigma_z=\frac{1}{2}$ $(-\frac{1}{2})$. The Hamiltonian for heavy holes then has the form

$$H_h = -g_h \beta B_z \Sigma_z\,. \tag{2}$$

This describes an anisotropic splitting which is zero for fields perpendicular to the sample axis z. In terms of the Luttinger parameters κ and q (Ref. 9) for Zeeman splitting of the valence band,

$$g_h = 6\kappa + \tfrac{27}{2} q\,. \tag{3}$$

For an exciton consisting of electron and heavy hole there are four basis states $|S_z,\Sigma_z\rangle$:

$$\Psi_1 = |\tfrac{1}{2},-\tfrac{1}{2}\rangle,\ \Psi_2 = |-\tfrac{1}{2},\tfrac{1}{2}\rangle, \tag{4a}$$

$$\Psi_3 = |\tfrac{1}{2},\tfrac{1}{2}\rangle,\ \Psi_4 = |-\tfrac{1}{2},-\tfrac{1}{2}\rangle. \tag{4b}$$

In zero field these are separated by the electron-hole exchange interaction into two doublets $\Psi_{1,2}$ and $\Psi_{3,4}$ in which the spins are parallel and antiparallel, respectively. In a field applied parallel to z there are further splittings of the doublets

$$\Delta_{12} = |g_e + g_h|\beta B_z \text{ and } \Delta_{34} = |g_e - g_h|\beta B_z\,, \tag{5}$$

respectively. 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. Thus there is a Zeeman splitting of the heavy-hole–electron excitonic emission with g factor

$$g_{\mathrm{ex}} = g_e + g_h\,. \tag{6}$$

This analysis treats only linear terms in the Zeeman splitting and so refers to the asymptotic behavior as B tends to zero. Our determinations of g factor are made at fields in the region below 2 T where the Zeeman splittings are approximately linear in field. At higher fields the splittings depart strongly from linearity, particularly for $L_z \geq 10$ nm.[10]

Figure 1 shows the assembled data. The curves for g_e and g_{ex} are guides for the eye through the data points for wells with barrier Al fraction ~ 0.36. That for g_h is the difference of these two curves [see Eq. (6)]. The open triangles are experimental values[7,11] of heavy-hole g factor in type-II GaAs/AlAs wells. We first describe our mea-

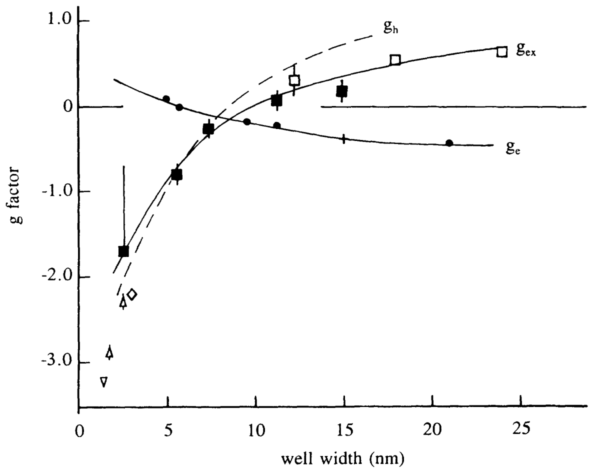

FIG. 1. The electron (g_e), heavy-hole exciton (g_{ex}), and heavy-hole (g_h) g factors in type-I GaAs/Al$_x$Ga$_{1-x}$As quantum wells. The solid circles (Ref. 2) and the cross (Ref. 14) are experimental data for g_e, and solid squares (this work) and open squares (Ref. 10) are data for g_{ex}. The triangles (Refs. 7 and 11) are values of hole g factor for type-II GaAs/AlAs wells. The diamond is the exciton g factor in a stepped barrier well (Ref. 15). The solid curves are to guide the eye through the g_e and g_{ex} points, the dashed curve is their difference g_h.

surements of g_{ex} from the Zeeman splitting of the exciton recombination (solid squares), which are in reasonable continuity with those of Ossau *et al.*[10] for wider wells (open squares).

Our samples[12] were high purity ($\sim 10^{14}$ cm^{-3} p type) multiple quantum wells grown by molecular-beam epitaxy on (001)-oriented semi-insulating GaAs substrates with Al fraction $x=0.36$ in all Al$_x$Ga$_{1-x}$As layers. Photons from a laser of energy well above the electron-hole continuum edge were incident along the growth axis of the sample and backward luminescence was collected and analyzed using a 0.5-m grating spectrometer with photon-counting detection. Although the two optically allowed transitions are broad compared to the Zeeman splittings (half width at half maximum, $\Gamma \sim 1$ to 4 meV), they can be separated because they have opposite circular polarizations, σ^+ and σ^-. The two components were recorded using a 50-kHz photoelastic modulator (oscillatory $\pm\lambda/4$ plate) and plane polarizer before the spectrometer. A twin-channel pulse-counting system, gated by a reference signal from the modulator, gave simultaneous point by point measurements of the components in the two channels as the wavelength of the spectrometer was stepped through the line.[13]

Figure 2 shows a representative set of data and illustrates the method used to determine the splitting. First, a polynomial was fitted to each component to establish the order required to describe the line shape without introducing spurious structure, usually between 7 and 13 [Fig. 2(a)]. The same order polynomial was then fitted to the data points of both components together for a series of energy displacements of the second set. The splitting was taken as that value of displacement which minimized the mean squared deviation of this fit [Fig. 2(b)]. The error indicated in Fig. 2(b) is the error associated with that particular measurement and approaches the limiting statistical uncertainty in the first moment $\Gamma/\sqrt{N}$ ($= \pm 1.5$ μeV in this example) where N is the total photon count in one component. However, there were larger uncertainties of systematic origin. The luminescence line shape was observed to vary with excitation energy and position on the wafer presumably due to well width fluctuations. This leads to a smooth variation of Zeeman splitting for a given run with scatter of a few μeV but much larger variations from run to run, typically of order ± 10 to ± 20 μeV at 2 T.

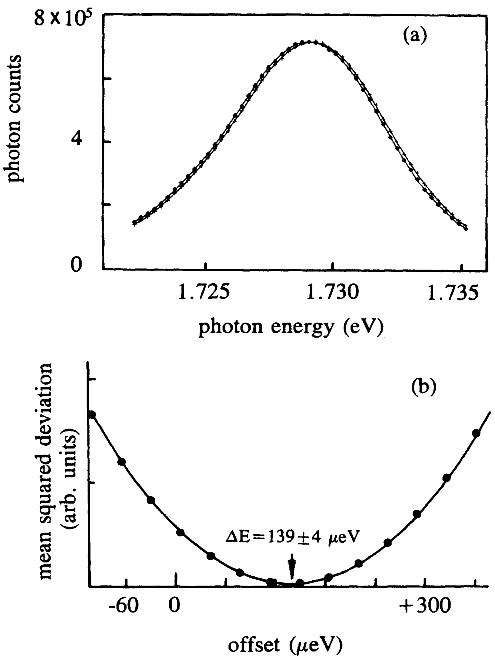

FIG. 2. (a) Measured Zeeman components for $L_z=2.57$ nm at 3.22 T. The curves are the best-fit polynomial of degree 11 to each component. (b) Variation with relative energy offset of mean-squared deviation for the fit of one of these polynomials to both components at once.

Figure 3 shows measured Zeeman splittings up to 2 T for $L_z \geq 5.6$ nm. The initial variations are linear within experimental uncertainties and the slopes give the values

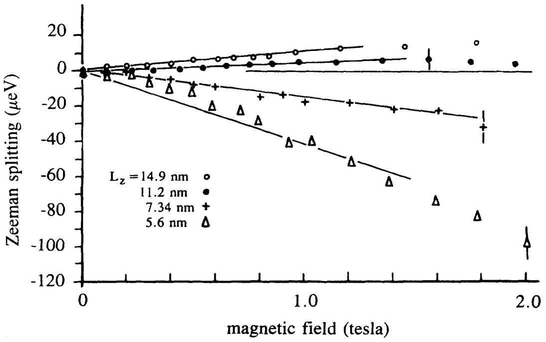

FIG. 3. Low-field Zeeman splitting of the $n=1$ heavy-hole-electron excitonic recombination line in GaAs/Al$_x$Ga$_{1-x}$As quantum wells at 1.8 K. The vertical bars represent systematic uncertainties in the splittings.

of g_{ex} which are plotted in Fig. 1 showing the change of sign for L_z between 7.34 and 11.2 nm. The splittings deviate from a linear variation at higher fields, particularly in the wider wells ($L_z \geq 11.2$ nm) where there is a sign reversal at intermediate values, as illustrated in Fig. 4.[10] For $L_z \leq 7.34$ nm we do not observe such a sign reversal up to 8 T.

For $L_z = 2.57$ nm the g factor can only be determined within broad limits by this method (see Fig. 1) because of the very nonlinear behavior of the apparent splitting below 2 T (Fig. 4). This appears to be an artifact of the analysis when the line shape of one of the optically allowed exciton states ($\Psi_{1,2}$) is perturbed as it crosses (or anticrosses) one of the optically silent levels ($\Psi_{3,4}$). In separate experiments[5] we have investigated these level crossings in detail and have used them to obtain the electron-hole exchange energy. For $L_z = 2.57$ nm a level crossing occurs at 1.1 T, where the apparent splitting has a pronounced minimum (Fig. 4), whereas no level crossings occur below 2 T for $L_z \geq 5.6$ nm. Since the level crossing leads to a minimum in the apparent splitting, the magnitude of g_{ex} should be at the upper limit of the range as indicated in Fig. 1.

The data for g_e (solid circles in Fig. 1) are from previous combined measurements[2] of the Hanle effect and of photoluminescence decay time in quantum wells containing up to $\sim 10^{11}$ cm^{-2} heavy holes, and with barrier Al content 0.3. With a high ambient hole population the Hanle depolarization is controlled by the Larmor precession of free photoexcited conduction electrons and therefore depends on g_e. The method determines both the magnitude and sign of g factor.[2] Note that for narrow wells g_e is positive and that it passes through zero near $L_z = 5.5$ nm tending to the value for bulk GaAs (-0.44) for large L_z. The cross is a measurement of g_e in a 15-nm modulation-doped n-type well by electrically detected spin resonance.[14]

The triangles in Fig. 1 are the g factor for free heavy holes in type-II GaAs/AlAs quantum wells obtained by optically detected magnetic resonance.[7,11] In these systems the holes are confined in the GaAs layers so that the measured hole g factors should approximate those of g_h in type-I GaAs/Al$_x$Ga$_{1-x}$As quantum wells of the same width, small differences arising from the differences in valence-band offsets and confinement energies. There is controversy[11] over the sign of these hole g factors, but a negative sign[7] gives the most consistent picture.

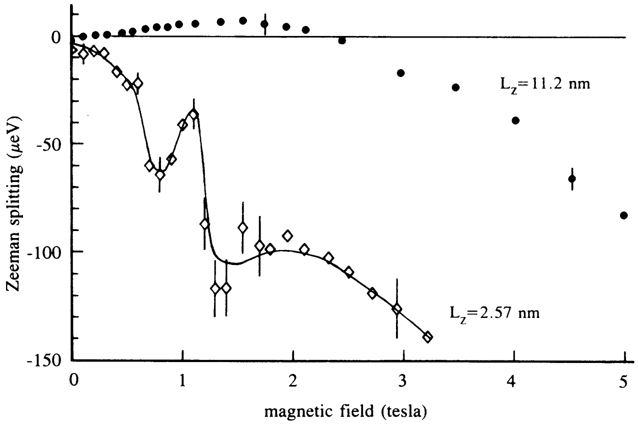

FIG. 4. Zeeman splitting for $L_z = 11.2$ nm showing sign reversal near 2.5 T, and $L_z = 2.57$ nm showing nonlinear variation associated with level crossing (or anticrossing) among the excitonic states at 1.1 T. In each case the points are the average of three independent runs with systematic uncertainties indicated by vertical bars.

The choice of signs in Fig. 1 is based on the experimental points for $L_z < 5.5$ nm. First, the sign of g_e was measured directly and is positive for narrow wells.[2] Second, the magnitudes of the hole g factors in the type-II samples exceed those we have measured for g_{ex}. Therefore, since we expect these hole g factors to be close to those of g_h in our type-I samples and since $g_{\mathrm{ex}} = g_e + g_h$, it follows that g_h and g_e must have opposite signs and that g_h and also g_{ex} are negative. Further support for the choice of signs is given by a recent quantum beat measurement[15] of exciton g factor for a "stepped" multiple quantum-well sample, shown as a diamond in Fig. 1. The sign was not determined but the magnitude is clearly greater than that of g_{ex}. The main effect of the "stepped" well should be on the electron g factor, with the hole g factor comparatively little affected. The total confinement energy in the sample was 100 meV,[15] equivalent to a 5-nm-wide regular well, for which $g_e \sim 0$ (see Fig. 1). Consequently, the exciton g factor in the stepped-well sample should approximate that of a free hole (g_h). Only with our choice of signs does the measured g factor lie close to the dashed curve for g_h.

To summarize, the electron g factor g_e has been directly determined both in magnitude and sign in wells with barrier Al fraction 0.3 and the exciton g factor g_{ex} ($= g_e + g_h$) has been measured in magnitude but not sign in samples with barrier Al fraction 0.36. The solid curves drawn through these data sets (Fig. 1) are guides for the eye and the dashed curve for g_h is their difference. Direct measurements of the hole g factor in wells with barrier Al fraction 1, are consistent only with a negative sign for g_h and therefore of g_{ex} for narrow wells.

We have previously shown that the variation of g_e is consistent with nonparabolicity of the conduction band of bulk GaAs.[2] A three-band $\mathbf{k}\cdot\mathbf{p}$ model calculation of the electron g factor in bulk GaAs at a particular energy above the conduction-band minimum gives approximate agreement with the measured g factor in a quantum well having an equal electron confinement energy. The effect of penetration of the wave function of the electron into the barrier is found to be small, and specific quantum-well effects are also small.

A similar analysis of the hole g factor must take account of the complexity of the valence bands. Bauer[4] has emphasized the importance of field-induced level interactions among different exciton states in determining Zeeman splittings in finite fields. However, such interactions do not affect the asymptotic behavior at zero field which should be determined by the parameters κ and q [Eq. (3)]. Bauer's calculations, based on constant values for κ and q ($\kappa \gg q$), do not reproduce the observed L_z dependence of g_h (or g_{ex}), particularly the sign reversal. Therefore κ, and perhaps also q, must vary with L_z. A theory for this variation needs to be constructed as has been done for the conduction-band g factor.

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