Zeeman splitting of the excitonic recombination in $In_xGa_{1-x}As/GaAs$ single quantum wells

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We report magnetoluminescence investigations of undoped $In_xGa_{1-x}As/GaAs$ single quantum wells. At the highest available magnetic fields (11 T) the excitonic recombination shows well resolved spin splittings. For low indium content the splitting is dominated by the heavy-hole valence-band splitting as confirmed experimentally. The theoretical analysis allows us to determine the electron as well as the heavy-hole g values in $In_xGa_{1-x}As$ on GaAs within the composition range $0< x <0.27$ for quantum well thicknesses $L_z > 120$ Å.

I. INTRODUCTION

In the presence of a magnetic field the spin degeneracy of the electron or hole energy levels of a two-dimensional electron and/or hole gas (2DEG and/or 2DHG) is lifted. The magnitude of spin splitting is determined by the magnetic splitting factor g^* of electrons and holes and it is of prime importance when describing band structure properties theoretically.[1,2] Recent research concentrated on the determination of the Lande g^* factor of conduction-band electrons in various semiconductors including $Al_xGa_{1-x}As/GaAs$, $In_xGa_{1-x}As/InP$, and InAs/GaSb heterostructures and quantum wells.[3–5] The techniques employed were Shubnikov–de Haas measurements in tilted magnetic fields and magnetoluminescence resolving the Landau level splittings. There are only a few reports[6–8] on the properties of hole g^* values in a 2DHG most conveniently studied when a strain splitting in the valence band is present.[9] Tailoring band masses by introducing strain is realized in the materials systems $In_xGa_{1-x}As$ grown on GaAs or on InP. For $In_xGa_{1-x}As/GaAs$ quantum wells on which we report here the large disparity between electron and hole masses as present in bulk crystals vanishes. The uniaxial component of the strain leads to a decoupling of the heavy- and light-hole states.[6] The in-plane heavy-hole mass consequently becomes light and a considerable reduction from $m_{hh\|} = 0.34$ (bulk) to $m_{hh\|} = 0.15$ is found as has been reported by several investigators.[6–8] For all compositions the heavy hole is on top of the valence band (type-I quantum well) whereas it is of type II for the light-hole band. The hole spin splitting is thus within the $m_j = \pm\frac{3}{2}$ states and the g^* factor of the 2DHG was found to be very anisotropic. However, spin-splitting renormalization due to many-body interactions can lead to the so-called exchange enhancement of g^* factors.[10–12] It was, therefore, our interest to obtain the relevant information of g^* of the heavy holes in undoped $In_xGa_{1-x}As/GaAs$ single quantum wells. Using magnetoluminescence experiments for wide quantum wells (L_z>120 Å) and various indium contents we observed well resolved spin splittings at high magnetic fields. They are mainly caused by the large and anisotropic heavy-hole g^* factor as demonstrated experimentally. The analysis takes into account the finite spin splitting of the electrons in the conduction band and their composition dependence. A simple perturbative approximation shows that the magnitude of the heavy-hole g^* value is connected with the Luttinger parameters $\kappa, \gamma_1, \gamma_2$ and the heavy hole in plane mass.

II. EXPERIMENTAL DETAILS

The samples were grown by molecular-beam epitaxy at the Daimler Benz Forschungszentrum. Three samples were studied with indium concentrations of 10, 18, and 27%. Each sample contained four undoped single quantum wells with thicknesses between 22 and 200 Å. The spin splittings were observed on the widest wells, which were L_z= 200 Å ($x = 0.1$), L_z= 160 Å (x=0.18), and L_z= 120 Å (x=0.27). For the higher indium concentrations the well thickness had to be reduced below the critical layer thickness to avoid misfit dislocations. The magnetoluminescence experiments were carried out in Zeeman configuration in a 12 T solenoid type superconducting magnet. Excitation (Ar^+-ion laser) and luminescence passed through a single fiber onto and from the sample. Measurement temperature was 6 K, the spectral analysis was done by a $f/4$ 25 cm single monochromator in connection with a liquid nitrogen cooled Ge detector. The resolution was better than 0.7 meV. The sample could be rotated with respect to the static magnetic field; for details see Ref. 13.

III. EXPERIMENTAL RESULTS

In Fig. 1 we show the steady state luminescence of the sample with x=0.1. Four transitions corresponding to the well thicknesses of 22, 45, 90, and 200 Å can be seen. All of them show a diamagnetic behavior in magnetic

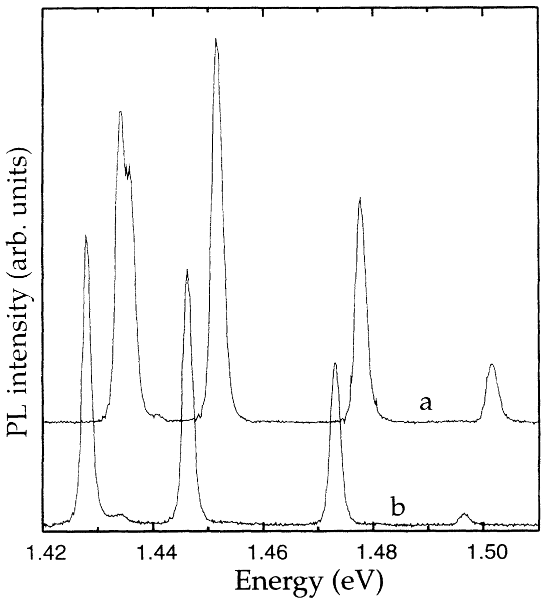

FIG. 1. Photoluminescence of the single multiple $In_xGa_{1-x}As/GaAs$ quantum wells (x=0.1, L_z=22, 45, 90, and 200 Å) at T=6 K, Ar^+-ion excitation. Curve a is measured at 11 T, b at 0 T.

field, i.e., for low magnetic fields (<4 T) the transition energy shifts with a B^2 dependence to higher energies [see Figs. 1(a) and 1(b) and Fig. 2]. It is nearly linear for higher magnetic fields (>4 T). This is a characteristic feature of excitonic recombination in the absence of carriers, since the quantum wells were undoped. Only the widest quantum well, L_z= 200 Å, experiences a splitting at higher magnetic fields. At 11 T it amounts to 1.5 meV. For all compositions the heavy-hole band is on top of the valence band (type-I quantum well). Thus the experimentally observed splittings can either be caused by the spin splitting in the conduction band or in the valence band (or a combination of both). However, since the conduction-band spin splitting is expected to be small (the electron g value in GaAs is −0.44) it rather points to spin splitting of the heavy-hole valence band at least for low composition values. To prove this assumption we performed an angular dependence study where the sample was rotated with respect to the static magnetic field (see Fig. 3). A simple consideration shows what one expects. For $J = S$=3/2 the heavy-hole–light-hole splitting can be approximated by the D term in the Hamiltonian[14]

$$H = g^* \mu \vec{H} \cdot \vec{S} + D[S_z^2 - S(S+1)], \quad (1)$$

where g^* is the heavy-hole g value and $\vec{H}$ the magnetic field. The Eigenwert solution within the effective spin formalism ($S' = 1/2$; $D \gg h\nu$) gives for the g values

$$g_{\parallel}^{*'} = 3g_{\parallel}^*, \quad g_{\perp}^{*'} = 0, \quad (2)$$

where $g_{\parallel}^*$ is the effective spin g factor with the magnetic field parallel to the growth direction, $g_{\perp}^{*'}$ describes the effective spin g factor with the magnetic field perpendicular to this direction, and $g_{\parallel}^*$ is the real g factor of the $J = S$=3/2 system. The energy splitting is given by

$$\Delta E = g_{\parallel}^{*'} \mu_B H. \quad (3)$$

In an angular dependence it varies as $g_{\parallel}^{*'} \cos\theta$ and it is this behavior we observe (see Fig. 3). In our experimental setup we were limited to values of $\theta \leq 60°$, so small departures from a $\cos\theta$ behavior could not be resolved. The otherwise good agreement (drawn line in Fig. 3) can be taken as strong evidence that the heavy-hole spin splitting is dominating. Similar results were obtained for x=0.18 and x=0.27. The energy splittings observed at 11 T are collected in Table I.

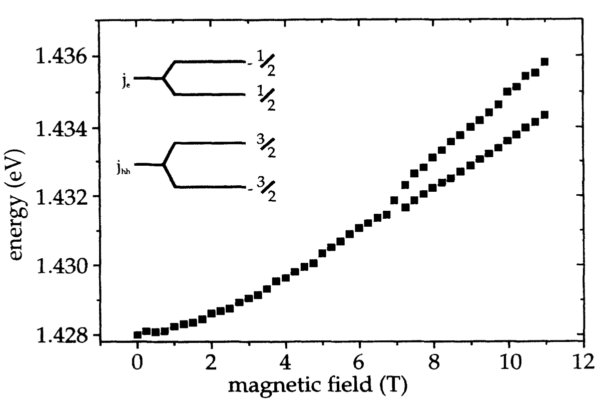

FIG. 2. Diamagnetic shift and Zeeman splittings of the L_z = 200 Å $In_xGa_{1-x}As/InP$ quantum well (x=0.1).

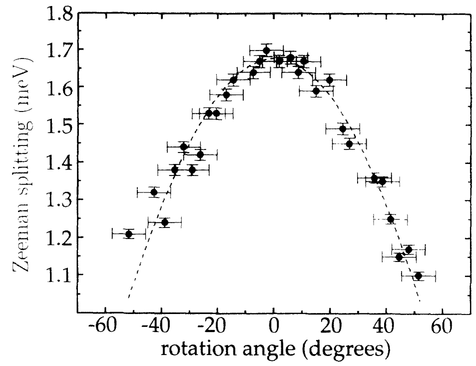

FIG. 3. Orientation dependence of the Zeeman split lines (see inset in Fig. 2) for the L_z = 200 Å $In_xGa_{1-x}As/GaAs$ (x=0.1) quantum well (B=11 T, T=6 K). The drawn line shows a cosine behavior; for details see text.

TABLE I. + obtained by a fit to Eqs. (2) and (3). Experimental data and fitting parameters for the Zeeman splitting of the $In_xGa_{1-x}As/GaAs$ quantum wells. $g_{\parallel}^*$ is the heavy-hole g factor with magnetic field parallel to the growth direction.

$In_xGa_{1-x}As$ composition x	L_z Å	Splitting at 11 T in meV	Heavy hole$^+$ mass in units of m_0	g_e^*	$3g_{\parallel}^*$	$g_{\parallel}^*$
0.1	200	1.5	0.143	-1.9	4.3	1.43
0.18	100	2.27	0.121	-3.0	6.8	2.26
0.27	120	1.92	0.116	-4.3	7.5	2.5

IV. ANALYSIS AND DISCUSSION

To analyze the data, both the splittings in the conduction as well as in the heavy-hole valence band have to be taken into account (see inset in Fig. 2). The conduction-band spin splitting is given by $(S = 1/2)$

$$\Delta E = g_e^* \mu_B H. \tag{4}$$

The bulk g^* values are $g_e^* = -0.44$ for GaAs and $g_e^* = -15$ for InAs.[15] For a 100-Å InAs/AlSb quantum well Smith and Fang[16] reported values between −7.8 and −8.7. We thus assume that the x dependence of g_e^* can vary between the following two extremes:

$$g_e^*(x) = -0.44 - 7.56x, \tag{5}$$

$$g_e^*(x) = -0.44 - 14.56x. \tag{6}$$

A possible enhancement by many-body effects is not considered here since we are dealing with undoped quantum wells. The effective g^* factor of holes on the lowest quantum size level can be obtained in second order perturbation theory. The quantization energy of holes in the quantum well is much larger than the energy of in-plane movement in the magnetic field. In this case zero and first order contributions to the magnetic energy are described only by diagonal elements in the Luttinger Hamiltonian.[17] Nondiagonal elements in this Hamiltonian mixing light- and heavy-hole quantum size levels contribute to the magnetic energy only in second order perturbation theory. As a result an energetic distance between two hole sublevels with $J_z = \pm 3/2$ can be written in the following form:

$$\epsilon_{3/2} - \epsilon_{-3/2} = -\hbar\omega_0(3\kappa - S_2), \tag{7}$$

where $\omega_0 = eH/m_0c$ is the cyclotron frequency of the free electron, m_0 is the free electron mass, and κ is the Luttinger constant.[18] The contribution in second order perturbation theory to the g^* factor, S_2, in a quantum well with the axes oriented along the $\langle 100 \rangle$ lattice direction can be written

$$S_2 = \frac{6}{m_0} \sum_n \frac{|\langle \mathrm{lh}, n | \gamma_3 \hat{p}_z | \mathrm{hh} \rangle|^2}{E_{\mathrm{lh},n} - E_{\mathrm{hh}}}, \tag{8}$$

where $E_{\mathrm{lh},n}$ and $|n, \mathrm{lh}\rangle$ are the energy and the wave function of the nth quantum size level of light holes in the quantum well. E_{hh} and $|\,\mathrm{hh}\rangle$ are the energy and the wave function of the ground state quantum size level of heavy holes. $\hat{p}_z$ is the momentum operator in the direction of the quantum well axes. A similar consideration in Ref. 20 or Ref. 19 using perturbation theory gives an expression for the in-plane effective mass m_{hh}, for the lowest heavy-hole quantum size level:

$$\frac{m_0}{m_{\mathrm{hh}}} = \gamma_1 + \gamma_2 - S_2, \tag{9}$$

where γ_1 and γ_2 are the usual Luttinger constants. Using Eq. (7) and Eq. (9) we obtain a connection between the hole g^* factor and the in-plane effective mass of the heavy holes:

$$\epsilon_{3/2} - \epsilon_{-3/2} = -\hbar\omega_0 \left(3\kappa - \gamma_1 - \gamma_2 + \frac{m_0}{m_{\mathrm{hh}}} \right). \tag{10}$$

For the Luttinger parameters in ternary $In_xGa_{1-x}As$ compounds we used the following linear interpolations:[21]

$$\kappa = 1.72 + 5.96x,$$
$$\gamma_1 = 7.65 + 12.02x,$$
$$\gamma_2 = 2.41 + 5.96x. \tag{11}$$

The measured splittings are hence given by the sum of Eqs. (4) and (10), but require the knowledge of m_{hh}^*. To check the consistency we first assume that for the quantum well with the lowest In content (x=0.1) the splitting is entirely due to the heavy holes, i.e., g_e^*=0. From Eq. (10) we obtain m_{hh}=0.166 which falls into the range of values commonly cited in the literature.[6,22–24] We now take into account a finite spin splitting in the conduction band [Eqs. (5) and (6)] and thus derive the mass values as shown in Fig. 4 [full squares using Eq. (6), full circles using Eq. (5)]. The differences are small for low indium contents. Iaffe *et al.*[22] obtained for x=0.12, m_{hh}=0.144 for 2.2×10^{11} cm^{-2} carriers (full rhombus in Fig. 4). Schirber *et al.*[23] for x=0.2 report for 2.7×10^{11} cm^{-2} carriers a value of m_{hh}=0.13 (full triangle in Fig. 4). Since the heavy hole is strongly nonparabolic, values at the bottom, i.e., in undoped quantum wells of the valence band, are probably 6–10 % lower. Fritz *et al.*[24] demonstrated the mass enhancement as a function of carrier density (x=0.2, L_z=90 Å) and for very low carrier densities ($<0.2\times10^{11}$ cm^{-2}) got $m_{\mathrm{hh}} = 0.11$ (in Fig. 4 drawn as open triangle). In the decoupled limit, the in-plane heavy-hole mass is given by $m_{\mathrm{hh}} = (\gamma_1 + \gamma_2)^{-1} = 0.1$ very close to the experimental results. This comparison with available experimental results and theoretical predictions thus favors a bulklike behavior for the conduction spin splitting and we consequently consider Eq. (6) to give the g_e^* dependence on composition. For the wide quantum wells studied (L_z> 120 Å) confinement effects are expected to be small and an enhancement over the three-dimensional bulk values can certainly be neglected. The hole g^* value increases from 4.3 (x=0.1) over 6.8

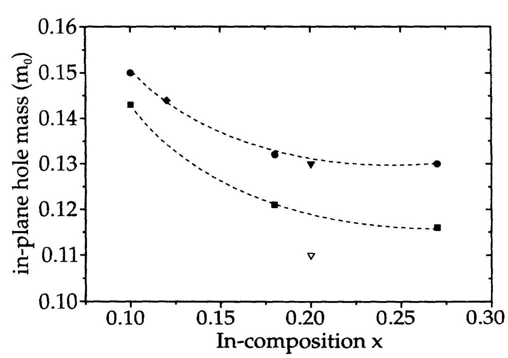

FIG. 4. In-plane heavy-hole mass as a function of indium concentration for $In_xGa_{1-x}As$/GaAs undoped single quantum wells (full squares and full circles assume different electron g^* values, full triangle is from Ref. 23, open triangle is from Ref. 24, and full rhombus is from Ref. 22, respectively; for details see text).

(x=0.18) to 7.5 for x=0.27 [equal to $3g_{\parallel}^*$, see Eq. (2)]. The experimental values are collected in Table I. Our analysis predicts that for wide wells $g_{\parallel}^*$ is positive and varies between 1.4 and 2.5 for 0.1< x <0.27 (see Table I).

To interpret the spin splitting we used a simple perturbation approach, neglect nonparabolicity effects as well as heavy- and light-hole mixing (as mentioned above it enters in second order perturbation theory). Certainly one can discuss whether the choice of Luttinger parameters is correct. A recent publication on the $In_xGa_{1-x}As/InP$ system[25] concluded that within an error margin of ±10% the Lawaetz[21] interpolations can be used. We want to stress that it is not the intention to obtain very precisely the in-plane heavy-hole mass from an analysis of the Zeeman splittings. Assuming a three-dimensional-like behavior for the electron spin splittings gives best agreement with current available results on the in-plane heavy-hole mass.

The in-plane mass significantly changes as a function of quantization, i.e., well width. Mitchell *et al.*[26] reported that the mass varied from $m_{\rm hh}^*$=0.18 (L_z=120 Å) to $m_{\rm hh}^*$=0.26 (L_z=60 Å). Based on Eq. (10) this leads to smaller spin splittings with increasing hole masses. This might in part explain the lack of spin splittings for the narrower quantum wells. Indeed for L_z = 90 Å and x=0.1 only an asymmetric line shape is found at high magnetic fields, but not pronounced enough to deliver further conclusive experimental results. A second argument is that with decreasing well width the photoluminescence linewidth increases considerably and resolution is lost.

V. CONCLUSION

In conclusion, we presented experimental data on the spin splitting of the excitonic recombination in wide $In_xGa_{1-x}As/GaAs$ quantum wells. They are dominated by the g^* factor of the heavy-hole valence band. In the analysis we take into account the finite spin splitting of the electron in the conduction band for which 3D values give a consistent description.

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