Magnetic-circular-dichroism study of heavy- and light-hole g factors in $In_xGa_{1-x}As/InP$ quantum wells

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Intersubband transitions in $In_xGa_{1-x}As/InP$ quantum wells have been studied by magnetic circular dichroism (MCD) of the absorption. The g values of the heavy and light holes in the different subbands are deduced from the intensity dependence of the MCD signals on the applied magnetic field: $g^*_{\mathrm{hh1}}=-0.68\pm0.1$, $g^*_{\mathrm{hh2}}=-1.81\pm0.4$, and $g^*_{\mathrm{lh1}}=8.87\pm1.2$. These results are in good agreement with effective-mass-theory calculations and allow one to estimate the in-plane effective masses of the second heavy-hole ($m^*_{\mathrm{hh2}}=0.85m_0$) and the first light-hole ($m^*_{\mathrm{lh1}}=0.17m_0$) subbands. An observed increase of the half-width of the subband transitions with increasing transition energy and increasing magnetic field is qualitatively explained by statistical fluctuations of the quantum-well width. [S0163-1829(97)06615-0]

I. INTRODUCTION

To study the magnetic g factors of electrons, holes, and excitons in low-dimensional semiconductor systems is important because it provides insight into the subband structure. Furthermore, it is important for the interpretation of magneto-optic and magnetotransport measurements and can also provide a test of the theoretical description of the band structure comparable to that obtained from studies of the effective mass.[1]

For practical reasons, most of the information obtained so far has been about the lowest (highest) lying electron (hole) sublevels. These states dominantly determine the luminescence properties of undoped quantum wells and are easily measurable. Information concerning the higher-lying states can be obtained by absorption spectroscopy. However, in most quantum-well systems, such as $GaAs/Al_xGa_{1-x}As$ the quantum size effect increases the intersubband transition energies to values greater than the band-gap energy of the underlying substrate material. To apply absorption spectroscopy would thus require preparing substrate free samples, which is a difficult task. The situation is better for $In_xGa_{1-x}As$ quantum wells grown on a GaAs or InP substrate. There the intersubband transition energy is less than the band-gap energy of the substrate. Thus it was possible to apply magnetoabsorption spectroscopy to study the diamagnetic shift of two-dimensional excitons in lattice-matched $In_{0.53}Ga_{0.47}As/InP$ samples and to deduce the carrier effective masses.[2] However, due to the large linewidth a Zeeman splitting could not be observed directly for magnetic fields up to 8 T and information on the g values could not be obtained.

In this paper we report on magnetoabsorption experiments using circular polarized light (MCD, magnetic circular dichroism). The differential detection of left and right circular polarized light allows one to observe the Zeeman splitting already at relatively low magnetic fields ($<$ 1 T) and the described analysis of the data enables one to determine the g^* values of the heavy holes of the first and second subbands and of the light holes in the first subband in $In_{0.53}Ga_{0.47}As/InP$ quantum wells. A comparison with effective-mass theory (EMT) shows very good agreement for the (hh1,e1) transition. For the other two transitions EMT is used to calculate the effective mass of the involved carriers. Line broadening, which depends on the transition energy and the magnetic field, is explained in terms of statistical fluctuations of the quantum-well width.

II. EXPERIMENTS

All samples were grown by low-pressure metalorganic chemical vapor deposition (LP MOVPE).[3] The undoped samples have 15 $In_{1-x}Ga_xAs$ quantum wells ($x=0.47$), grown lattice matched onto InP. The wells are 100 Å wide and are separated by 300 Å of InP. The buffer layer to the semi-insulating InP substrate is 0.5-μm-thick InP. The samples are capped with a 1.0-μm-thick layer of InP.

Absorption and MCD measurements were performed at helium temperatures (liquid helium at 4.2 K or superfluid helium at 1.5 K) and in the field of a superconducting magnet capable of providing a field of up to 2 T. The measurements were performed in Faraday configuration. Light from a halogen lamp was filtered by a grating monochromator. Circular polarization was produced by a combination of a linear polarizer and an electro-optic modulator operating at 50 kHz. The light was detected by a cooled germanium detector. Using the lock-in technique, the measured signal intensity I_{MCD} is proportional to the difference between the left (I_+)- and right (I_-) circular polarized light transmission intensities divided by their sum $I_{\mathrm{MCD}}=(I_+-I_-)/(I_++I_-)$. This method is immune to drifts and allows the determination of the MCD intensity with high precision.[4,5]

Experimental results

For the lattice-matched $In_xGa_{1-x}As/InP$ quantum wells used in our experiments, the first and second heavy-hole subbands lie above the first light-hole subband (see the inset in Fig. 1). Thus the order of the observed absorption bands with increasing energy is as follows: first heavy-hole sublevel (hh1) to first electron sublevel (e1) transition followed by the first light-hole to first electron sublevel transition (lh1,e1), and at higher energies the transitions from the sec-

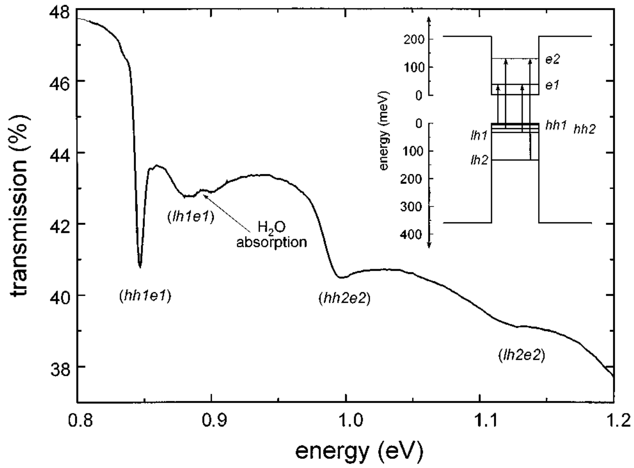

FIG. 1. Transmission spectra of the $In_xGa_{1-x}As$ quantum wells. The observed transitions are as follows: first heavy hole to first electron (hh1,$e1$), first light hole to first electron (lh1,$e1$), second heavy hole to second electron (hh2,$e2$), and second light hole to second electron (lh2,$e2$). The inset shows the self-consistently calculated band structure.

ond heavy and light hole to the second electron sublevel [(hh2,$e2$) and (lh2,$e2$)]. These four transitions are clearly visible in the transmission spectrum of Fig. 1. The energies of these transitions agree well with subband calculations reported earlier,[6] taking into account an exciton binding energy of 10 meV.[7]

In the MCD spectrum each of these transitions has a derivativelike structure (see Fig. 2). The intensity of the signal increases linearly with increasing magnetic field. An interesting feature of these MCD bands is that the (hh1,$e1$) and the (lh1,$e1$) transition signals are negative on the low-energy side and positive on the high-energy side while the opposite is true for the (hh2,$e2$) and (lh2,$e2$) transitions. As will be shown later, the energy difference between the maximum and minimum of the MCD signal gives an excellent measure of the linewidth (2σ) of the transition. One can see that the linewidth increases with increasing transition energy (Fig. 3). In a magnetic field of 0.5 T they are $2\sigma_{\mathrm{hh1}}=2.82$ meV,

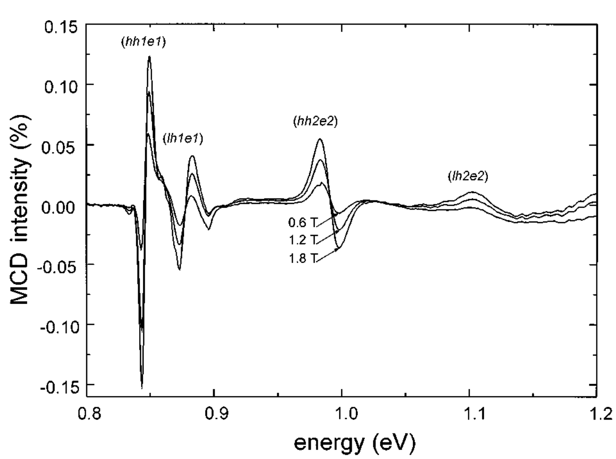

FIG. 2. MCD spectra of the $In_xGa_{1-x}As$ quantum wells at different magnetic fields. All the transitions in Fig. 1 are observed to have a derivative line shape.

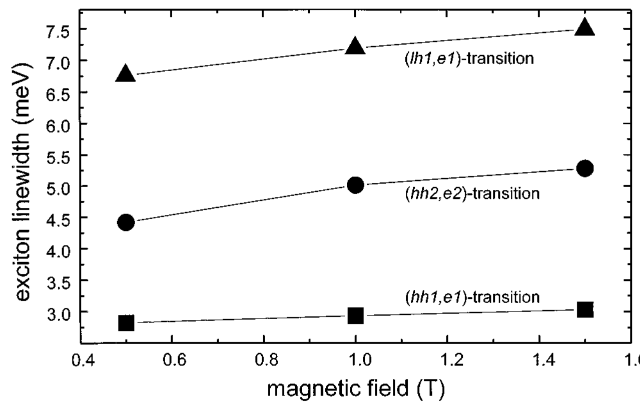

FIG. 3. Half-width of the (hh1,$e1$), the (lh1,$e1$) and the (hh2,$e2$) transitions determined from the energy separation of the maximum and minimum of the MCD spectra.

$2\sigma_{\mathrm{lh1}}=4.42$ meV, and $2\sigma_{\mathrm{hh2}}=6.76$ meV. The measurements indicate an additional increase of the linewidth as a function of magnetic field (Fig. 3).

In a transverse static magnetic field the energy of the excitonic transitions is expected to show a diamagnetic shift and to be split due to the Zeeman effect. In the range of magnetic fields used in our experiment the diamagnetic shift is expected to be small and to shift the position of the absorption lines only slightly.[2] It is not relevant to the MCD line shape and will not be discussed further. In our experiment the exciton Zeeman splitting is much less than the energy separation between the maximum and the minimum of the MCD signal. Its extraction from the data therefore demands a special analysis.

The half-width of excitonic lines in quantum wells does not depend on the spins of the electron and hole states. Thus the absorption coefficients for both left and right circular polarized light are described by the same function of the energy, $\alpha_+=f(E-E_+)$ and $\alpha_-=f(E-E_-)$, respectively, where E_+ and E_- are the energies of the excitonic Zeeman levels. Assuming that the half-width of the exciton line is much larger than the Zeeman splitting, $\Delta E=E_+-E_-$, and that Beer's law is valid, i.e., $I_\pm=I_0\exp(-\alpha_\pm d)$, where I_0 is the intensity of the incident light, and d is the thickness of the sample, one can easily obtain the intensity and the shape of the MCD signal:

$$I_{\mathrm{MCD}}=\frac{1}{2}\frac{\partial f}{\partial E}\Delta E d. \tag{1}$$

The shape of the signal is essentially given by the derivative of the function f. The positions of the maximum and the minimum of the MCD signal are determined by the condition $\partial f/\partial E=0$. The intensity (I_{MCD}) of the signal is proportional to the Zeeman splitting ΔE and increases linearly with magnetic field. However, in order to get an absolute value of the splitting we have to scale the MCD signal with the logarithm of I_{sum}/I_0. With the help of Beer's law and $\alpha_\pm(E)d\approx f(E)d$ we obtain

$$\frac{I_{\mathrm{MCD}}}{\ln(I_{\mathrm{sum}}/I_0)}=\frac{1}{2f(E-E_0)}\frac{\partial f}{\partial E}\Delta E, \tag{2}$$

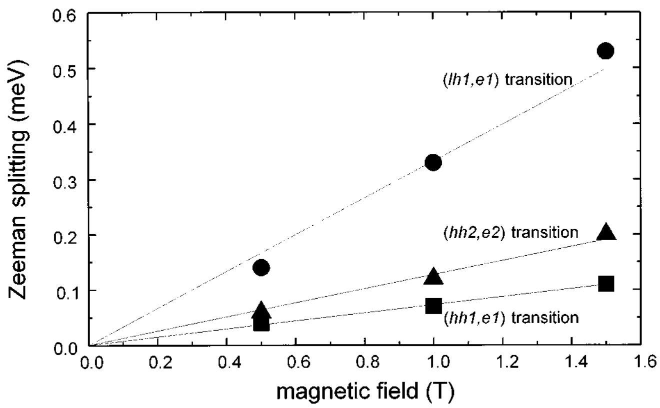

FIG. 4. Zeeman splitting of the different transitions as a function of the magnetic field.

where $I_{\mathrm{sum}}=I_{+}+I_{-}$ and E_0 is the energy position of the unsplit exciton line. For a Gaussian absorption line with half-width σ,

$$f(E-E_0)=\frac{C}{\sqrt{2\pi}\sigma}\exp\left(-\frac{(E-E_0)^2}{2\sigma^2}\right), \tag{3}$$

where the constant C is proportional to the oscillator strength of the corresponding optical transition, the MCD signal line shape should have a typical derivative shape with extrema separated by 2σ. The normalized MCD signal [Eq. (2)] can thus be rewritten:

$$\frac{I_{\mathrm{MCD}}}{\ln(I_{\mathrm{sum}}/I_0)}=\frac{E-E_0}{2\sigma^2}\Delta E. \tag{4}$$

The intensity of the MCD (I_{MCD}) divided by the logarithm of the transmission intensity $[\ln(I_{\mathrm{sum}}/I_0)]$ is inversely proportional to the square of the half-width of the absorption line and proportional to the Zeeman splitting ΔE. At the maximum or minimum of the MCD intensity, i.e., at $E=E_0\pm\sigma$, this relation becomes $\Delta E/2\sigma$. This provides a tool for the experimental determination of the Zeeman splitting from a measurement of the MCD and the transmission spectrum, both of course for identical experimental conditions.

The above described analysis should hold for the case of experimentally well determined optical transitions, i.e., no other effects influence either the MCD or the transmission spectrum. In our case of excitonic transitions in a quantum well, two complications arise: (1) to obtain ''pure'' transmission spectra, reflectivity effects have to be taken into account; and (2) the exciton lines are superimposed on the intersubband transitions of free electrons and holes. In the MCD spectra these effects do not cause any signal. However, they modify the transmission spectrum. In order to determine the transmission due to the excitonic transitions only, we considered the reflectivity of GaAs in the spectral range of interest to be constant and substracted constant values taken at appropriate energies below the excitonic lines. This analysis gives the dependence of the Zeeman splitting for the (lh1,$e1$), (hh2,$e2$), and (hh1,$e1$) transitions on magnetic field as shown in Fig. 4.

III. DISCUSSION

It is known that a magnetic field splits the ground state of the two-dimensional exciton in each subband into four Zeeman sublevels, but only two of them are optically active in the Faraday excitation geometry. Right circular polarized light (I_{+}) excites the $|+3/2,-1/2\rangle$ exciton state in the heavy-hole subbands and the $|+1/2,+1/2\rangle$ state in the light-hole subband (the numbers here are the hole and electron spin projections, respectively). Left circular polarized light (I_{-}) excites the $|-3/2,+1/2\rangle$ and $|-1/2,-1/2\rangle$ exciton states correspondingly. This results in the left wing or the right wing of the MCD signal being positive, depending on the relative order of these excitonic states.

In general, data on the excitonic Zeeman splitting and the MCD signal shape are not sufficient to extract the electron *and* hole g factors. There are four algebraic combinations of electron and hole g factors that can describe the MCD data, depending on their relative values and signs. But for the $In_{0.53}Ga_{0.47}As$/InP quantum wells, which are the object of this study the electron g factor is well determined to be $g_e^*=-3.3$,[8] and this enables us to determine the g factor of the holes.

The MCD signal of the first heavy-hole subband has a positive right wing and the smallest Zeeman splitting (see Figs. 2 and 4). This is the situation illustrated in Fig. 5(b) and the splitting is determined by $\Delta E=\mu_B B(|g_e^*|-3|g_{\mathrm{hh1}}^*|)$ if $|g_e^*|>3|g_{\mathrm{hh1}}^*|$, and we obtain $g_{\mathrm{hh1}}^*=-0.68\pm0.1$.

The positive right wing for the MCD signal for the light-hole transitions indicated in Fig. 5(b) is possible only if $g_{\mathrm{lh}}^*>|g_e^*|>0$, and the splitting energy of the (lh1,$e1$) transition is $\Delta E=\mu_B B(g_{\mathrm{lh1}}^*-|g_e^*|)$. As a result, we obtain for the light-hole g factor $g_{\mathrm{lh1}}^*=8.87\pm1.2$.

The positive left wing of the MCD signal for the heavy-hole transitions [see Fig. 5(a)] is only possible if $g_{\mathrm{hh}}^*<0$ and $3|g_{\mathrm{hh}}^*|>|g_e^*|$, thus for the (hh2,$e2$) transition $\Delta E=\mu_B B(3|g_{\mathrm{hh2}}^*|-|g_e^*|)$. This results in a heavy-hole g factor for the second subband of $g_{\mathrm{hh2}}^*=-1.81\pm0.4$.

The weak MCD signal intensity of the (lh2,$e2$) transition does not allow the determination of the g factor; thus we excluded this transition from the analysis.

In order to be able to compare the g values obtained by the above analysis we also performed effective-mass calculations. In effective-mass theory the g values can be calculated from the Luttinger parameters and the in-plane effective mass $m_{\mathrm{hh}n}^*$ of the nth heavy-hole subband:[9]

$$g_{\mathrm{hh}n}^*=\frac{2}{3}\left(3\kappa-\gamma_1-\gamma_2+\frac{1}{m_{\mathrm{hh}n}^*}\right), \tag{5}$$

where κ,γ_1, and γ_2 are the Luttinger valence-band parameters. For $In_{0.53}Ga_{0.47}As$ quantum wells these parameters are $\gamma_1=10.8$, $\gamma_2=4.2$, and $\kappa=3.7$;[10] the heavy-hole mass was determined in Ref. 11 to be $m_{\mathrm{hh1}}^*=0.35m_0$. With these values we obtain $g_{\mathrm{hh1}}^*=-0.69$, which clearly falls within the limitations given by the experimental line shape $(0>3g_{\mathrm{hh1}}^*>g_e^*)$ and agrees well with the value obtained from the analysis above.

The in-plane effective mass of the second heavy-hole subband has not been experimentally determined yet, therefore a similar comparison is not possible. But the good agreement

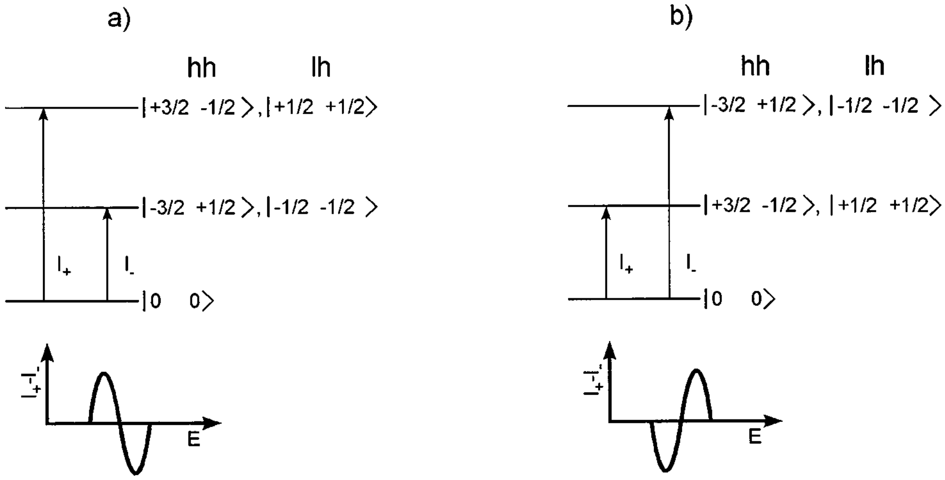

FIG. 5. The schematic structure of the possible transitions: (a) schemes leading to a positive left wing for the MCD signal. (b) schemes leading to a positive right wing for the MCD signal. The allowed optical transitions are marked with arrows.

between the EMT calculations and the MCD analysis demonstrated for the (hh_1, e_1) transition may allow one to estimate this effective mass using Eq. (5). With the g value of $g_{\mathrm{hh2}}=-1.81$, we calculate for the second heavy-hole band an effective mass of $m^*_{\mathrm{hh2}}=0.85$.

Effective-mass theory can also give a relation between the effective g factor $(g^*_{\mathrm{lh}n})$ and the effective in-plane mass $(m^*_{\mathrm{lh}n})$ for the nth light-hole subbands. Calculations similar to those for the heavy-hole subbands lead to the following relation:

$$g^*_{\mathrm{lh}n}=2(\kappa+\gamma_1-\gamma_2-1/m^*_{\mathrm{lh}n}). \tag{6}$$

With $g_{\mathrm{lh1}}=8.87$ we obtain $m^*_{\mathrm{lh1}}=0.17m_0$. This value is quite reasonable because compared to the bulk value the in-plane light-hole mass becomes heavy in a quantum well.[12]

The observed increase of the linewidth of the excitonic transition with increasing transition energy can be explained by taking fluctuations of the well width into account. Using the simplest model of a quantum well with infinity high potential barriers, one can easily see that $\Delta E=2\sigma \sim 2(E_{ne}+E_{nh})\delta L_z/L_z$, where $E_{ne(nh)}$ is the energy of the nth quantum size level of electrons (holes) involved in the optical transitions in a quantum-well thickness L_z, and δL_z is a typical fluctuation of the thickness, which is on the order of 1 ML, i.e., $\delta L_z \simeq 3$ Å. Determining the quantization energy from the transmission spectra (see Fig. 1) and the band gap of bulk $\mathrm{In}_x\mathrm{Ga}_{1-x}\mathrm{As}$,[13] we obtain $2\sigma_{\mathrm{hh1}}=1.59$ meV, $2\sigma_{\mathrm{lh1}}=3.48$ meV, and $2\sigma_{\mathrm{hh2}}=10.6$ meV. Despite the simplicity of the model, these values agree rather well with the experimentally determined half-widths.

The increase of the linewidth of the excitonic transitions with increasing magnetic field can also be explained within the model of random two-dimensional statistical fluctuations of the quantum-well thickness. A two-dimensional exciton smooths out all the thickness fluctuations that have a lateral size smaller than the exciton radius. A magnetic field decreases the radius of the exciton and increases its translational effective mass.[14] Both effects lead to the localization of the exciton within a smaller area of the quantum well, and statistical fluctuations within a smaller area are larger than those in a more extended one. This can explain the observed increase of the exciton linewidth in a magnetic field.

In the analysis of the MCD signal the line shape of the absorption coefficient was assumed to be a Gaussian. A similar analysis using a Lorentzian line shape increases the obtained values for the g^* factors only by 1.2%. The accuracy of the analysis, which depends mostly on the precise determination of the transmission, is estimated to be about ± 10 % for the g values. This uncertainty is the dominant error in the analysis.

IV. CONCLUSION

We investigated $\mathrm{In}_{0.53}\mathrm{Ga}_{0.47}\mathrm{As/InP}$ quantum wells by MCD and transmission spectroscopy. An analysis is described that allows the determination of the g factors of the holes in the first and second heavy-hole and the first light-hole subbands from the experimental data. Due to the large linewidth of the excitonic transitions this information can hardly be obtained by the otherwise more straightforward approach of Zeeman measurements. Relationships between the effective g^* factors and the in-plane effective mass of the 2D hole subbands are used to calculate the in-plane effective masses of the first light-hole and the second heavy-hole subband. The half-widths of the observed subband transitions increase with increasing transition energy and magnetic field, which can be qualitatively understood in terms of statistical fluctuations of the quantum-well thickness into account.

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