Interband magnetoabsorption of $In_{0.53}Ga_{0.47}As$

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Interband magneto-optical absorption in the Faraday and the Voigt configurations has been studied near liquid-He temperature in $In_{0.53}Ga_{0.47}As$ grown by liquid-phase epitaxy on InP. Using a quasi-Ge model analysis with exciton corrections, the interband data has yielded $E_g = 0.813 \pm 0.001$ eV, $m_0(1/m_c + 1/m_{hh}) = 26.5 \pm 0.5$, $m_0(1/m_c + 1/m_{lh}) = 44.0 \pm 1.0$, and $\gamma_3 - \gamma_2 = 0.7 \pm 0.2$. Using $E_p = 25.3$ eV and $\Delta = 0.36$ eV (from linear interpolation between InAs and GaAs) and $m_c/m_0 = 0.041$ (from earlier intraband measurements), the present interband data has yielded a set of parameters for the quasi-Ge model; in particular, $m_{hh} \simeq 0.47 m_0$ and $m_{lh} \simeq 0.050 m_0$. A precise determination of E_p requires a direct measurement of Δ and g_c.

I. INTRODUCTION

In this article we present results of an interband magnetoabsorption study of $In_{0.53}Ga_{0.47}As$ grown by liquid-phase epitaxy on InP. This ternary material is an end member of the family of $In_{1-x}Ga_xAs_yP_{1-y}$ alloys lattice-matched to InP that are of both fundamental and technological interest. Although many interesting device applications have been pursued using members of this alloy family,[1] systematic band-parameter measurements have been mostly limited to the measurement of the conduction-electron effective mass m_c,[2,3] and the energy gap E_g.[4,5] Interband magneto-optical studies, which are useful in the investigation of the conduction- and valence-band parameters, were initially employed[6] for the quaternary alloy $In_{0.75}Ga_{0.25}As_{0.52}P_{0.48}$.

II. EXPERIMENTAL

Most measurements were made on a 4.4 μm thick film of $In_{1-x}Ga_xAs$ ($x = 0.47$) grown by liquid-phase epitaxy on an InP substrate of (100) orientation. The film is lattice-matched to the substrate, to within $|\Delta a|/a < 6 \times 10^{-4}$, the limit of resolution of our x-ray apparatus, where a is the lattice constant of InP and Δa is the difference between the lattice constant of the alloy and the substrate. The net impurity concentration determined by the Hall effect is $N_D - N_A = 1.4 \times 10^{16}$ cm^{-3}, where N_D and N_A are the donor and acceptor concentrations, respectively. The value of the electron mobility is 24000 cm^{2}V^{-1}s^{-1} at 77 K. The sample was mounted on a liquid-He cold finger placed in the bore of a Bitter solenoid. Light from a tungsten filament was chopped, then passed

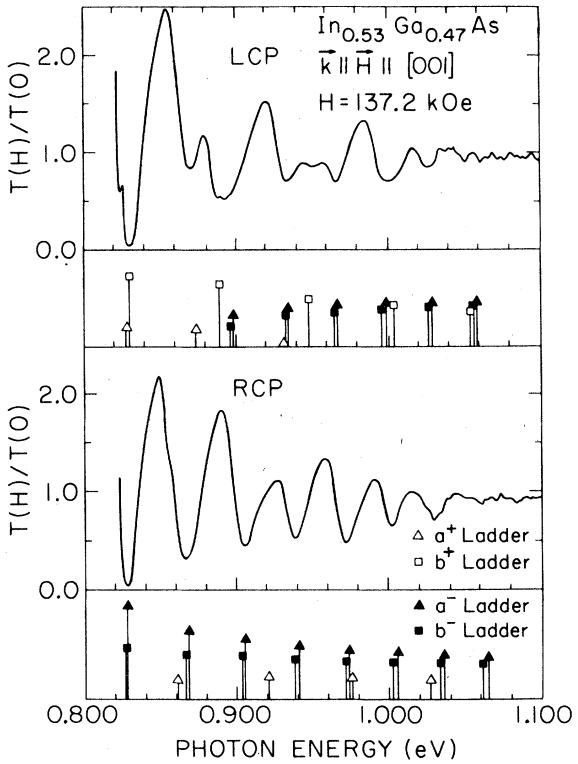

FIG. 1. Faraday configuration magnetotransmission spectra for left and right circularly polarized light (LCP and RCP) taken at 137.2 kOe in the sample in contact with a liquid-He cold finger. The intensity bars beneath each spectrum indicate calculated energy positions, and their heights are proportional to the square of matrix elements for optical transitions from light (+) and heavy (−) hole to conduction-electron Landau levels. Light-hole intensity bars are reduced by a factor of $(m_{hh}/m_{lh})^{1/2}$ to reflect the difference between light- and heavy-hole densities of state approximately.

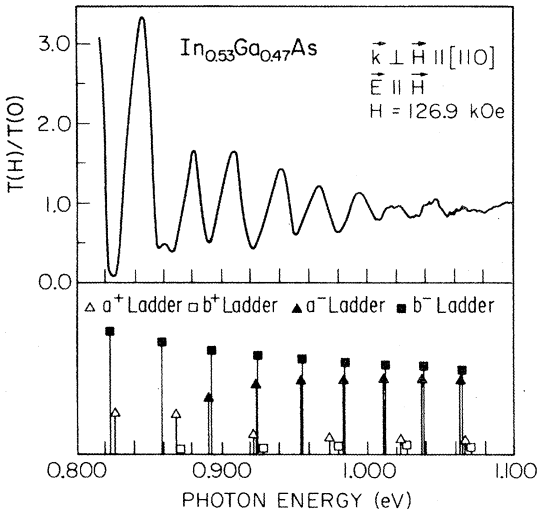

FIG. 2. Magnetotransmission spectrum in the Voigt configuration for light polarized with $\vec{E} \parallel \vec{H}$ taken at $H = 126.9$ kOe with the sample in contact with a liquid-He cold finger. For a description of the bars under the spectrum, see Fig. 1 caption.

through a grating monochromator, filters, polarizers, and finally focused on the sample. The transmitted light was focused onto a room-temperature PbS detector and was measured using a lock-in amplifier and punched for computer analysis using analog-to-digital converters. Sweeping the wavelength, several oscillatory magnetoabsorption spectra were taken at several field values up to 154.4 kOe for the following polarizations: in the Faraday configuration with right (RCP) and left (LCP) circularly polarized light (with $\vec{k} \parallel \vec{H} \parallel [001]$), and in the Voigt configuration ($\vec{k} \perp \vec{H}$) using linearly polarized light with $\vec{E} \parallel \vec{H} \parallel [110]$ and $\vec{E} \perp \vec{H} \parallel [110]$, where $\vec{k}$ is wave vector of the incident light, $\vec{H}$ is the static magnetic field, and $\vec{E}$ is the electric field of the light. Typical spectra are shown in Figs. 1 and 2 .

III. ANALYSIS

Photon energies of the minima appearing in the transmission spectra were plotted as a function of magnetic field for each polarization, as shown by dots in Figs. 3–5, and were interpreted as being energies corresponding to Landau-level transitions from light- and heavy-hole bands to the conduction band. The coupled-band theory of Pidgeon and Brown[7] was used to obtain a set of appropriate band parameters which would identify the transitions corresponding to the experimental points and would best predict their energies. Following Vrehen[8] the effect of the exciton binding energy was included in an approximate manner by reducing the calculated transition energies

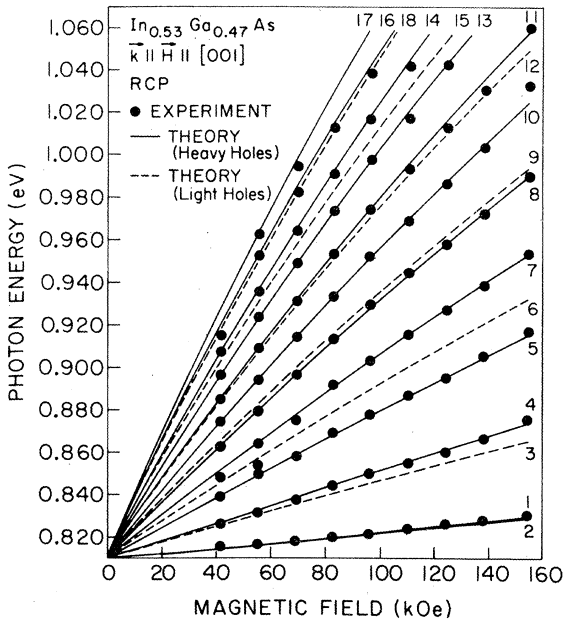

FIG. 3. Photon energy vs magnetic field for the interband transitions in the Faraday configuration with RCP light. Dots represent experimental data (minima in transmission spectra). Lines represent calculated transition energies and are numbered according to Table I of Ref. 11.

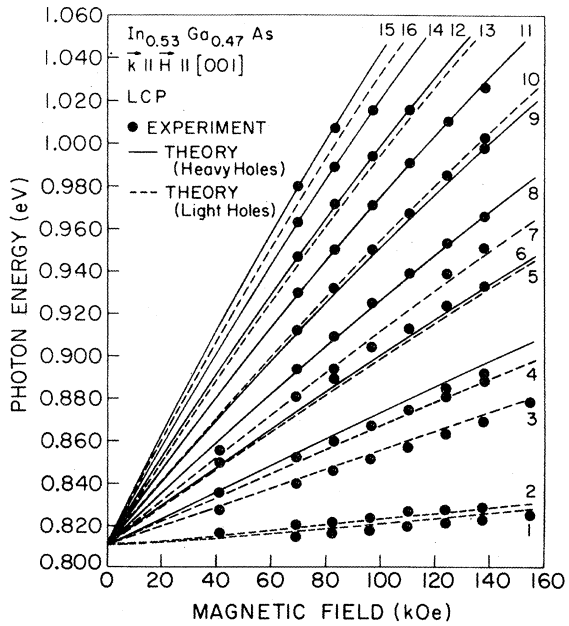

FIG. 4. Photon energy vs magnetic field for the interband transitions in the Faraday configuration with LCP light. The calculated transition lines are labeled according to Table I of Ref. 11. The unnumbered line corresponds to the two close-lying transitions $a^-(1)a^c(2)$ and $b^-(1)b^c(2)$.

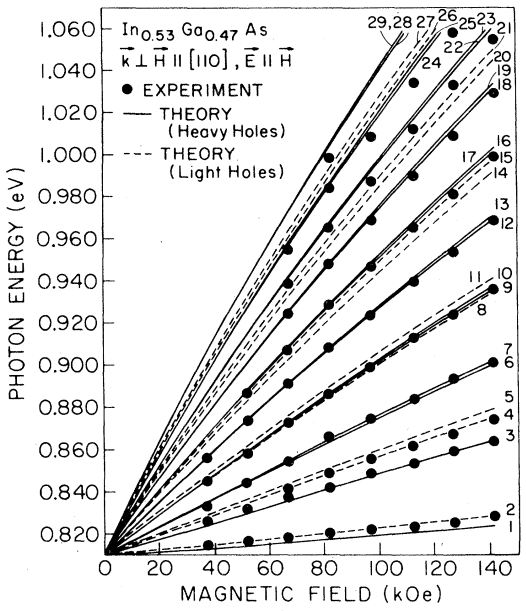

FIG. 5. Photon energy vs magnetic field for the interband transitions in the Voigt configuration for light polarized with $\vec{E} \parallel \vec{H}$. The calculated transition lines are numbered according to Table I given in this article.

by

$$\Delta E(n,H) = \Delta E\left(0, \frac{H}{2n+1}\right) ,$$

where n is the Landau quantum number of the conduction-band final state. We used $\Delta E(0,H) \simeq \Delta E(0,\gamma)$ R, where $\Delta E(0,\gamma)$ is calculated from a hydrogenic model by Larsen[9] in units of an *effective* Rydberg R, as a function of the reduced field γ which, in our case, ranges from 0 to about 5. (We follow the common designation of γ for the reduced field. This is not to be confused with the band parameters γ_i and γ_i^L used below. These parameters, as well as the other band parameters used in this paper are defined in Ref. 12.) We used expressions for R and γ as given in Weiler,[10] and used $\kappa_e = 13.8$ for the static dielectric constant, as obtained from linear interpolation between InAs and GaAs. The calculated lines in Fig. 5 are numbered as listed here in Table I, and the ones in Figs. 3 and 4 are numbered as given by Reine *et al.*[11] in their Table I. For labeling and numbering the Landau levels, we have followed Ref. 11. It was found that calculated relative intensities for transitions from b^+ light-hole series for RCP, and from a^+ light-hole series for LCP, were mostly too weak to be observed.[11] Also, a few weak transitions are seen as inflection points rather than minima and, finally, some close-lying transitions are seen as one being due to the linewidths. The quasi-Ge model coupled-band formalism used in our analysis is described in Weiler,[12] and for F and N_1, which describe the contribution of higher bands to the conduction-band effective mass m_c and g factor g_c,[12] we have used the expressions obtained by Hermann and Weisbuch,[13] which explicitly consider the Γ_8^c and Γ_7^c bands. The following observations were made in generating the calculated transition energies using a minimization routine.[14]

Interband magneto-optical data give to within a narrow range the values for the following parameters: (i) the energy gap E_g, (ii) the inverse reduced mass $m_0/\mu_\pm \equiv m_0/m_c + m_0/m_\pm$ involved in transition from heavy (−) and light (+) holes to the conduction band, and, (iii) the anisotropy factor $\gamma_3 - \gamma_2$ (when data is taken with H along two different crystal axes). Here m_0 is the free-electron mass, and γ_3 and γ_2 are defined in Ref. 12. In fact, for a wide range of m_c ($m_c/m_0 = 0.041 \pm 0.003$) and the interband coupling energy[12] E_p (from 20.5 to 27.9 eV), best fits were ob-

TABLE I. Identification of interband transition lines in the Voigt configuration for $\vec{E} \parallel \vec{H}$.

Label	Transition	Label	Transition	Label	Transition
1	$b^-(1)a^c(0)$	11	$b^+(2)a^c(1)$	21	$b^+(4)a^c(3)$
2	$a^+(-1)b^c(0)$	12	$a^-(3)b^c(4)$	22	$a^-(6)b^c(7)$
3	$b^-(2)a^c(1)$	13	$b^-(5)a^c(4)$	23	$b^-(8)a^c(7)$
4	$a^+(0)b^c(1)$	14	$a^+(2)b^c(3)$	24	$a^-(7)b^c(8)$
5	$b^+(1)a^c(0)$	15	$b^+(3)a^c(2)$	25	$b^-(9)a^c(8)$
6	$a^-(1)b^c(2)$	16	$a^-(4)b^c(5)$	26	$a^+(4)b^c(5)$
7	$b^-(3)a^c(2)$	17	$b^-(6)a^c(5)$	27	$b^+(5)a^c(4)$
8	$a^+(1)b^c(2)$	18	$a^-(5)b^c(6)$	28	$a^-(8)b^c(9)$
9	$a^-(2)b^c(3)$	19	$b^-(7)a^c(6)$	29	$b^-(10)a^c(9)$
10	$b^-(4)a^c(3)$	20	$a^+(3)b^c(4)$		

tained with

$$E_g = 0.813 \pm 0.001 \text{ eV} ,$$

$$(m_0/m_c + m_0/m_{hh}) = 26.5 \pm 0.5 ,$$

$$(m_0/m_c + m_0/m_{lh}) = 44.0 \pm 1.0 ,$$

and

$$\gamma_3 - \gamma_2 = 0.7 \pm 0.2 ,$$

where m_{hh} and m_{lh} are heavy- and light-hole masses along [001], respectively. The spin-orbit splitting energy Δ was estimated to be 0.36 eV. This was based on the observation that values of Δ for InAs and GaAs are close to each other, 0.38 and 0.341 eV, respectively.[13] (We expect that a direct measurement of Δ is possible by using a technique such as electroreflectance, and, in fact, Δ has been measured for an InGaAsP alloy using this technique.[15]) Nicholas *et al.*[2] have measured m_c using magnetophonon resonance, Shubnikov-de Haas resistance oscillation, and cyclotron resonance measurements and have obtained $m_c/m_0 = 0.041 \pm 0.001$. The value for E_p cannot be precisely determined from their data or our interband data; however, we obtain somewhat better fits when we use values close to 25.3 eV obtained from linear interpolation between the values $E_p = 22.2$ eV for InAs and $E_p = 28.9$ eV for GaAs.[13] To determine a definite value for E_p, one needs to measure g_c and Δ in addition to E_g, since it turns out that a three-band model with $F = 0$, $N_1 = 0$ is quite sufficient to determine g_c within a few percent in terms of E_p, Δ, and E_g.[13] The energy difference between the $b^-(1) \rightarrow b^c(0)$ transition (RCP) and the $b^-(1) \rightarrow a^c(0)$ transition (Voigt $\vec{E} \parallel \vec{H}$) is $-g_c \mu_B H$, but these two transitions are not sufficiently resolved to determine g_c accurately.

Figures 3–5 show a best fit to the data obtained by setting $E_g = 0.813$ eV, $E_p = 25.3$ eV, $\Delta = 0.36$ eV, and $m_c = 0.041 m_0$. The other parameters generated by the minimization routine[14] subject to the approximation

$$\kappa^L = \gamma_3^L + \tfrac{2}{3}\gamma_2^L - \tfrac{1}{3}\gamma_1^L - \tfrac{2}{3} ,$$

(Ref. 7) are as follows:

$$\gamma_1 = 0.62, \quad \gamma_2 = -1.02, \quad \gamma_3 = -0.36 , \quad \kappa = -1.91,$$

$$\gamma_1^L = 11.01, \quad \gamma_2^L = 4.18, \quad \gamma_3^L = 4.84, \quad \kappa^L = 3.29 ,$$

$$F = -2.3, \quad q = 0.38, \quad N_1 = -0.03 .$$

These parameters yield

$$m_c = 0.041 m_0, \quad m_{lh} = 0.0503 m_0 ,$$

$$m_{hh} \equiv m_-[001] = 0.465 m_0 ,$$

$$m_-[110] = 0.56 m_0, \quad m_-[111] = 0.60 m_0 ,$$

$$\gamma_3 - \gamma_2 = 0.66, \quad g_c = -4.50 .$$

It should be mentioned that best results are obtained when m_c/m_0 is between 0.0395 and 0.042, and for m_c/m_0 values larger than 0.042 or smaller than 0.039, unreasonable fits and unreasonable heavy-hole-mass values are obtained. We have also tried to fit our present data by ignoring higher-band contributions to m_c and g_c ($F = 0, N_1 = 0$). A reasonable fit can be obtained if we use $E_p = 21.18$ eV or close to it, but the g_c value obtained is about 30% lower, and the fit is not quite as good, compared to the fit presented here.

IV. CONCLUSION

In conclusion, we have described a set of magneto-absorption experiments in InGaAs presenting our data and a set of band parameters which give a reasonable fit to our data. We suggest that interband magneto-optical data should be supplemented by direct measurement of g_c as well as Δ (and higher-energy gaps) to yield a direct value for E_p and facilitate better estimation of higher-band corrections, to obtain band parameters for InGaAs and other members of the InGaAsP alloy family.

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