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**MAGNETOOPTICS OF (Ga,In)As QUANTUM WELLS : EXCITON BINDING ENERGIES AND CARRIER EFFECTIVE MASSES**

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Transmission measurements, in magnetic fields of up to 16T, have been performed on a series of undoped (Ga,In)As-InP quantum wells. Transitions with Landau indices up to  $l=15$  and energies up to 400meV above  $E_g$  are seen. A fit of the experimental data to a theoretical model for excitons at high magnetic fields in very anisotropic systems allows us to deduce values for the carrier effective masses, the electron non-parabolicity and the exciton binding energy.

Interband magneto-optical measurements have yielded much valuable information about the band parameters of semiconductor quantum wells and superlattices. For example Rogers et al studied a series of high quality GaAs-Ga<sub>x</sub>Al<sub>1-x</sub>As multiple quantum wells (MQWs) and obtained values for the effective masses and exciton binding energies for carriers confined in the wells [1]. Similar measurements have been attempted with (Ga,In)As-InP [2] and (Ga,In)As-(Al,In)As MQW [3], but the lower quality of the structures and the high free carrier densities restricted the amount of information which could be derived from the measurements.

In this paper we report a study of the transmission spectra, in magnetic fields from 0 to 16T, of a series of high quality Ga<sub>0.47</sub>In<sub>0.53</sub>As-InP MQWs grown by Atmospheric Pressure Metal Organic Vapour Phase Epitaxy (AP-MOVPE) on semi-insulating (100) InP substrates. The growth sequence was: i) a 250 nm undoped InP buffer layer, ii) 32 or 50 Ga<sub>0.47</sub>In<sub>0.53</sub>As quantum wells of width 10-20 nm separated by 20 or 50 nm thick InP barriers. Further details of the growth procedure, characterisation and modeling of the optical transitions are given in [4]: the transmission apparatus has been described previously [3].

Fig 1 shows a series of absorption spectra taken at various magnetic fields and at 1.6 K for a 50 period 10 nm MQW with 50 nm InP barriers. At zero field four excitonic transitions are clearly seen which are, in order of increasing energy, H1-C1, H1-C1, H2-C2 and L2-C2 (subband notation: L=light-hole, H=heavy hole, C=electron). In a magnetic field the spectra are dominated by a series of Landau level transitions arising from the zero field H1-C1 transition [1]. Figure 2 shows a plot of the measured transition energies against magnetic field. Up to 15 Landau Levels are visible, indicating the high quality of the samples. Figs 3 and 4 show similar plots for the 15 and 20 nm MQW samples respectively. These samples contain 32 wells with 20 nm InP barriers.

The excitonic Landau levels are treated using a model of excitonic states in an anisotropic system in the high-field limit (ie the Landau level energy is much greater than the excitonic effective Rydberg)[1,5]. Under these conditions, the excitonic binding energy of the  $l$  th Landau level transition is given by:

$$E_B(B,n,R^*,\mu_{ex}) \approx 3 \left( \frac{\hbar B}{2(2l+1)\mu_{ex}^2 R^*} \right)^{1/2} R^* D_1 \quad (1)$$

where  $R^*$  is the exciton effective Rydberg,  $\mu_{ex}$  the exciton reduced mass and  $D_1$  is a dimensionless constant representing the dimensionality of the exciton: for a 3D exciton  $D_1 = 0.25$ , whilst for a purely 2D case  $D_1=1$ . The zero field exciton binding energy is given by  $E_B(0)=4R^*D_1$  [1].

In order to complete the fit a description of the dispersion relationships in the plane of the wells is required for the carriers. In recent treatments of magneto-optical measurements on GaAs-(Ga,Al)As quantum wells [6,7], the conduction band dispersion relationships have been treated using a development of the 3-band k.p expression of Palik et al.[8]: this allows the asymmetry in the electron non-parabolicity introduced by the well itself [6,7] to be described. Unfortunately, the expression used is only valid for electron energies much less than the band-gap, a condition which is

fulfilled in the case of the GaAs-(Ga,Al)As MQW [6,7] but not in this case. The high quality of the wells and the comparatively narrow band-gap of (Ga,In)As mean that transitions to electron states more than  $E_g/2$  above the conduction band-edge are seen. A description of the conduction band is therefore attempted using the expression of Bowers and Yafet [9], which is valid for electron energies  $<< E_g + 2\Delta/3$ : the expression also has the virtue of never yielding negative gradient Landau levels, no matter how high the energy of the electrons. The non-parabolic Landau levels are thus given by:

$$E_e(B,l,E_g^*) = (E_g^*/2) \left( \left[ (4/E_g^*) \{ (\hbar e B (l + \frac{1}{2}) / m_e^*) + T_z \} + 1 \right]^{\frac{1}{2}} - 1 \right) \quad (2)$$

where  $m_e^*$  is the band-edge effective mass (taken to be  $\approx 0.041$  [10]) and  $T_z$  is given by:

$$T_z = E_{e0} \{ 1 + E_{e0}/E_g^* \} \quad (3)$$

with  $E_{e0}$  the  $N=1$  electron subband (C1) confinement energy, which is obtained from envelope function fits to all of the zero-field transitions using the measured well-widths from TEM and the accepted conduction band offsets: this method has previously been shown to yield reasonably accurate energies for the  $N=1$  subbands [1].  $E_g^*$  is treated as an adjustable parameter, to compensate for the inadequacies of the 2-band k.p theory whence the expression was derived [9]. The expression has the disadvantage that the electron non-parabolicity due to confinement motion and in-plane motion is not distinguished: in GaAs-(Ga,Al)As MQW these have been shown to be different [6,7]. However, all of the wells in this study are  $> 10$  nm wide, giving C1 confinement energies  $< 40$  meV in all cases, and so the errors introduced will be small.

Recent experiments in GaAs-(Ga,Al)As quantum wells have shown that at low fields the heavy-hole subband Landau levels are highly non-parabolic [11], but that at higher fields the observed effective mass becomes large and more slowly varying, as theoretically predicted [12]. As the exciton model is only valid in the high-field limit, we treat the heavy-hole Landau levels as parabolic, and use the heavy-hole effective mass  $m_{hh}^*$  as an adjustable parameter [1]: since the heavy-hole effective mass is much greater than the electron effective mass, the errors introduced by this approximation should be small. The total transition energy is then:

$$E = E_g + E_{h0} + E_e(B,l,E_g^*) + (\hbar e B (l + \frac{1}{2}) / m_{hh}^*) - E_B \quad (4)$$

where  $E_{h0}$  is the heavy-hole subband zero-field confinement energy and  $E_g$  is the true band-gap. The fit then involves varying  $m_{hh}^*$ ,  $E_g^*$  and the exciton binding energy.

Results of the fitting process are shown in Figs 2,3 and 4 for the three samples studied, and the fitting parameters are given in table 1. The best fit is obtained for the 10 nm MQW where, apart from some discrepancies at intermediate energies the fit is excellent. For the 15 nm and 20 nm MQW samples it is more difficult to obtain a good fit, as the H1-C1 Landau levels in these samples are often masked by higher-order transitions. At around 14 T, Landau levels arising from the higher subband transitions (H2-C2 or H3-C3) also cross the H1-C1 Landau levels, causing an apparent change of slope. Unfortunately, the higher order subband Landau levels are only visible at high fields and it is difficult to extrapolate them accurately to zero field and hence determine their origin. Values for the true energy gap of the (Ga,In)As in the wells are also shown in table 1.  $E_g$  does not quite correspond with the lattice matched composition value (813 meV), showing that the wells are slightly strained: this has been previously deduced using the measured H1-L1 splitting [4].

It will be noted that the fitted H1 masses are relatively large compared to the bulk Ga<sub>0.47</sub>In<sub>0.53</sub>As value of  $0.465m_0$  determined in magneto-optical experiments [13]. Large H1 in-plane masses are also seen at high fields in GaAs-(Ga,Al)As MQW [1,6]: the enhancement results from coupling between the light and heavy hole bands due to the quantum confinement. Away from the Brillouin zone centre, (sampled for  $B >$  a few T) anticrossing of the two bands causes a flattening of the heavy hole band and a corresponding heavier mass [12].

In the case of (Ga,In)As-InP MQW, the fits are fairly insensitive to the value used for the zero-field exciton binding energy  $E_B(0)$ . For the 10nm sample a value of  $5.5 \pm 1$  meV gives an acceptable fit. The fits for the 15 and 20nm samples are less good and it is more difficult to determine a value for  $E_B(0)$  in these samples; the fits of Figs 3 and 4 use  $E_B(0) = 4 \pm 1$  meV. The exciton binding energy is expected to increase from its three dimensional value of  $\approx 3$  meV to 12 meV for a purely 2D exciton: however, the wells in this study have a comparable thickness to the exciton radius, and the situation is also complicated by the fact that the exciton 'leaks' into the barrier material as the well width is reduced [14]. Both of these mechanisms act to reduce the exciton binding energy, and the maximum enhancement seen in GaAs-(Ga,Al)As MQW is a factor of 2 for narrow (5 nm) wells. The slightly enhanced value found in this work is thus not surprising and is in reasonable agreement to a value of 6 meV found for a 11nm (Ga,In)As-InP MQW using a

lineshape fit to absorption spectra [15].

The fitted band-gap in equation (2) was found to be  $650 \pm 20$  meV for all the samples. In order to compare this with existing data, we use the 3-band k.p expression of Palik [8] for the energy dependent effective mass ( $m_{0bs}^*$ ):

$$(1/m_{0bs}^*) = (1/m_c^*)(1+2K_2E/E_g) \quad (6)$$

where  $K_2$  is a negative constant. Some rearrangement of (2) reveals  $K_2 = E_g/E_g'$  as  $E \rightarrow 0$ , and values are shown in table 1. 3-band k.p theory gives a value of  $-0.85$ : however, this method has been shown to result in an under estimate in the case of GaAs [eg 7]. Bulk cyclotron resonance (CR) in n-(Ga,In)As yields an apparent value of  $K_2 = -1.6$ : there will be a considerable polaron contribution to this figure, possibly as much as 25% [7]. Thus, the MQW electron non-parabolicity due to in-plane motion is probably of a similar size to the bulk band non-parabolicity: this result was also recently obtained in a GaAs-(Ga,Al)As MQW [7]. The in-plane non-parabolicity in this work is also in reasonable agreement with earlier experiments on lower quality (Ga,In)As wells [2,3], which yielded  $K_2 \approx -1$ .

Finally, it should be noted that, if presently accepted values for the conduction band offset of  $\sim 230$  meV are correct, the above results indicate the existence of electron Landau levels well above the conduction band edge of the InP barriers. However, the magnetic field is perpendicular to the well plane and so the magnetic and electric quantisations will be exactly decoupled: the subband Landau levels will still retain a  $k$  parallel to the field which is characteristic of confinement in the well. Therefore no sharp changes in the electron effective mass etc. are seen as the Landau levels become level with the barrier tops.

In conclusion, we have studied the inter-band transmission, in magnetic fields up to 16T, of a series of (Ga,In)As-InP MQWs. The results have enabled values for the electron non-parabolicity, heavy hole effective mass and exciton binding energy to be deduced. The values obtained for the conduction band non-parabolicity are larger than those predicted by three-band k.p perturbation theory, in qualitative agreement with measurements using cyclotron resonance in bulk (Ga,In)As.

Sample	Exciton B.E./meV	$m_{hh}^*$	Fitted $E_g'/eV$	Actual $E_g/eV$	$K_2$
10 nm	$5.5 \pm 1$	0.9	0.650	0.827	-1.27
15 nm	$4.0 \pm 1$	0.95	0.650	0.821	-1.26
20 nm	$4.0 \pm 1$	1.0	0.650	0.827	-1.27

Table 1: Parameters used in magneto-optical fits:  $E_g'$  is the adjustable gap used in the Bowers-Yafet formula (eqn.(2)) and  $E_g$  is the actual measured gap.  $K_2$  is the Palik non-parabolicity constant (see equation 6).

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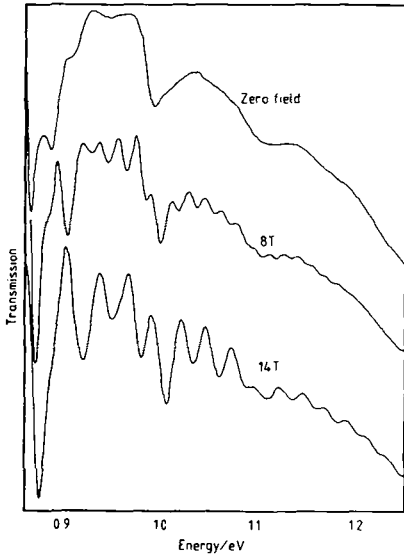


Fig 1). Typical spectra for the 10nm sample.

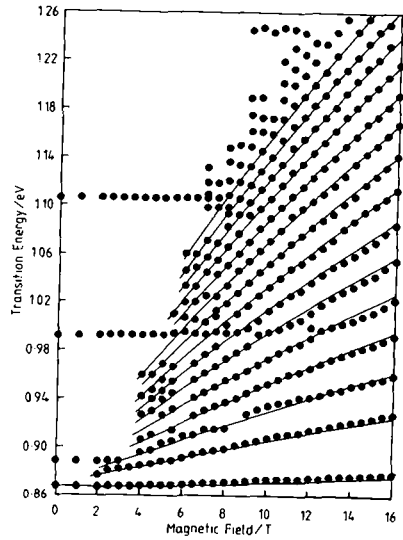


Fig 2). Transition energies as a function of magnetic field for the 10nm sample. The solid lines are a theoretical fit to the experimental data. The line through the lowest transition is a guide to the eye.

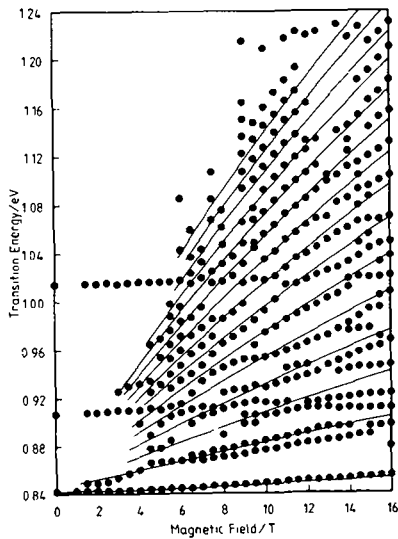


Fig 3). Transition energies as a function of magnetic field for the 15nm sample. The solid lines are a theoretical fit to the experimental data. The line through the lowest transition is a guide to the eye.

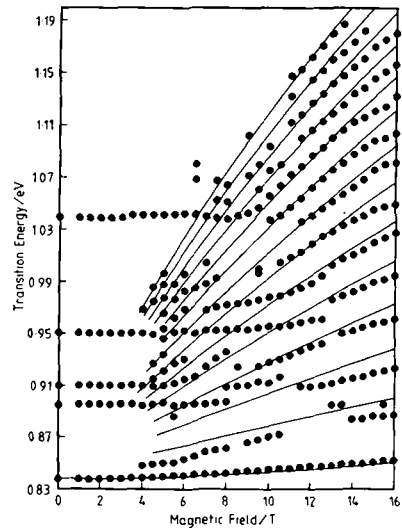


Fig 4). Transition energies as a function of magnetic field for the 20nm sample. The solid lines are a theoretical fit to the experimental data. The line through the lowest transition is a guide to the eye.