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PHOTOLUMINESCENCE STUDIES OF MODULATION DOPED COUPLED DOUBLE QUANTUM WELLS IN MAGNETIC FIELDS

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ABSTRACT

We have studied the photoluminescence spectra of a series of modulation doped couple double quantum well structures in parallel and perpendicular magnetic fields to 62 tesla at 4K and 77K. At 4K, for B//z, the spectra display distinct Landau level transitions which show anti-crossing with the e1-hh1 exciton. At high fields, the lowest conduction band-valence band exciton approaches the extrapolated 0-0 Landau level. About 25 tesla, there is valence band mixing of the e1-lh1, e1-hh2, e1-hh1 transitions. The spectral peaks display a diamagnetic shift in low in-plane magnetic fields which become linear in high fields. At magnetic fields beyond 40T, spin splitting is observed for both B//z and B⊥z geometries. The partial energy gap discovered in conductance measurements in in-plane fields was not conclusively observed using photoluminescence spectroscopy, although anomalies in the energy dependence of the lowest level with magnetic field were evident at similar field values.

1 Introduction

The electrical and optical properties of quantum well structures have been the subject of considerable investigations for a number of years. Coupled double quantum well (CDQW) structures, where the two wells are separated by a thin barrier, are of interest due to an enhanced quantum Stark effect and provide an ideal system for studying tunneling dynamics.[1-3] Modulation-doping of a CDQW provides two parallel two dimensional electron gas (2DEG) layers. This additional electronic degree of freedom in the growth (z-direction) can be controlled by varying the barrier thickness, external gate voltages and magnetic fields. In high magnetic fields for B// z, Coulomb interactions dominate leading to a tunneling gap.[4] By contrast, in a purely in-plane field, single particle dynamics dominate the interactions between the 2DEGs and there is a linear shift in the canonical momentum $\hbar k$ in one quantum well with respect to another. The primary effect is to produce a partial energy gap and a strong modulation of the in-plane conductance due to an anti-crossing of the two quantum well energy-dispersion curves.[5-7]

In photoluminescence (PL) studies, the 2DEG screens the photo-created electron-hole pairs and the electron-phonon interactions. Coulomb interaction between the photo-created holes and the free carriers can lead to band gap renormalization and Fermi edge singularities. Many body effects are particularly sensitive to magnetic fields as the density of states (DOS) is strongly modified in 2DEG systems. At low temperatures, the broad PL spectra due to band to band excitation, characteristic of a 2DEG with moderate to high carrier concentration, breaks into inter Landau level transitions for B//z. However, our samples have relatively low carrier concentrations, and, in addition to inter-Landau transitions, we also observe magneto-excitons. These excitations exhibit diamagnetic shifts at low fields and linear shifts at high fields.[8,9] The evolution of the valence band (VB) in a magnetic field is complicated by a mixing among several subbands and the splitting

of degeneracies due to the confinement. This results in strong non-parabolicity of the various hole state dispersions which can lead to anomalous spectral intensities including an unusual ordering of the higher energy exciton states. For B⊥z, the magnetic confinement couples to the QW confinement. In the low field regime the excitations follow a diamagnetic shift. As the applied in-plane field increases, the energy of the lowest hybrid Landau-subband states smoothly approach $\frac{1}{2}\hbar\omega_c$. At magnetic fields beyond 25T, spin splitting is observed for both B//z and B⊥z geometries.

CDQWs exhibit a valence band structure where the antisymmetric heavy hole (hh2) state is located between the first symmetric heavy-hole (hh1) state and the first symmetric light-hole (lh1) state. In addition, Simmons et al.[5-7] have demonstrated that in a modulation-doped CDQW can exhibit an anti-crossing of the two dispersion curves in a B⊥z (in-plane) magnetic field. The anti-crossing can produce a partial energy gap, yielding large in-plane B-field tunable distortions in the Fermi surface and the DOS. Large maxima and minima are observed in the in-plane conductance. The optical properties of the same samples using PL techniques in perpendicular (B// z) and in-plane (B⊥z) magnetic fields to 50T at 4K and 62T at 77K have been investigated and the results are presented in the following sections.

2 Experiment

The structures used in this study were modulation doped CDQ structures (A,B, and C), each consisting of two GaAs QWs of equal width w separated by an $Al_{0.3}Ga_{0.7}As$ barrier of thickness t. Table 1 lists the values of w and t , the densities n_1 , n_2 , and the mobilities μ_1, μ_2 of the top and bottom QWs, respectively. Magneto-PL measurements were performed at 4K and 77K using 140/600 µm diameter fiber optic systems in a 20 tesla superconducting magnet and a 50/60 tesla pulsed magnet. The data were recorded using a f/4 0.275m spectrograph equipped with a 1200l/mm grating and a cooled CCD detector. The PL studies were obtained under the following conditions for both magnets: The laser excitation energy was 2.54 eV (488nm); the power density on the sample did not exceed $2mW/cm^2$; and the spectral resolution was approximately 0.05meV. The pulsed field spectra were recorded in a 2ms time interval using a Pockels cell shutter timed to coincide with the 'flat-top' region at the peak of the magnetic field. Field values were monitored by a calibrated pick-up coil situated directly above the sample.

TABLE 1. Sample parameters.

	w/t	n (10^{11} cm^{-2})		μ(10^5 cm^2/Vs)		calculated subband energy (meV)				
Sample	(Å)	n_1	n_2	μ_1	μ_2	e_1	e_2	hh_1	hh_2	lh_1
A	150/25	1.4	1.5	2.7	2.2	10.3	13.6	4.1	4.8	10.3
B	100/35	1.2	1.2	1.2	0.6	20.1	24.4	11.1	12.6	22.6
C	150/15	0.7	0.9	0.6	0.2	3.4	9.5	8.3	9.3	12.5

3 Results and Discussion

Fig. 1 shows typical PL spectra taken at 4K of sample A as a function magnetic field for B⊥z . At B=0, the spectrum consists of one broad peak corresponding to the CB-VB subband transitions of the 2DEG. In an undoped CDQW, the most dominant peak is the first electron to heavy-hole subband symmetric-symmetric transition (e1-hh1). Weaker peaks are attributed to a symmetric-symmetric transition involving e1 and its corresponding lh-state (e1-lh1) and the antisymmetric transitions involving the next higher electron and hole states, namely, e2-hh2 and e2-lh2.[8,9] In doped CDQW systems parity conservation rules may be broken by the built-in field created by the planar-doping layer and/or by the presence of impurities which are also known to break the Landau conservation rule. The energy levels of these structures were calculated by self-consistently solving the Schrödinger and Poisson equations. From these calculations, we found that only the e1 state has any appreciable electron density. The next e-subband (e2, antisymmetric) state is unoccupied. With increasing magnetic field, additional emission peaks are observed. We observe a series of transitions associated with a Landau fan. Clear anti-crossings of these inter Landau levels with the e1-hh1 transition (See Fig. 1 and 2 for sample A) are observed. Sample B (not shown) had anti-crossing also with e1-lh1 transition. The 'fan' consists of a series of peaks that have their origin below the fundamental e1-hh1 transition. The solid lines in Fig. 2 are a fit to the Landau fan with $h\omega_c$= 0.73±0.01 meV/T taken from

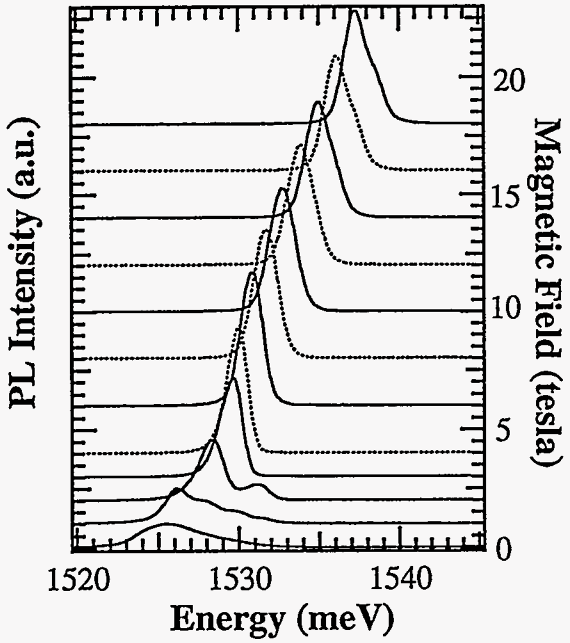

Figure 1. Magnetic field (B//z) dependence of the PL spectra for sample A

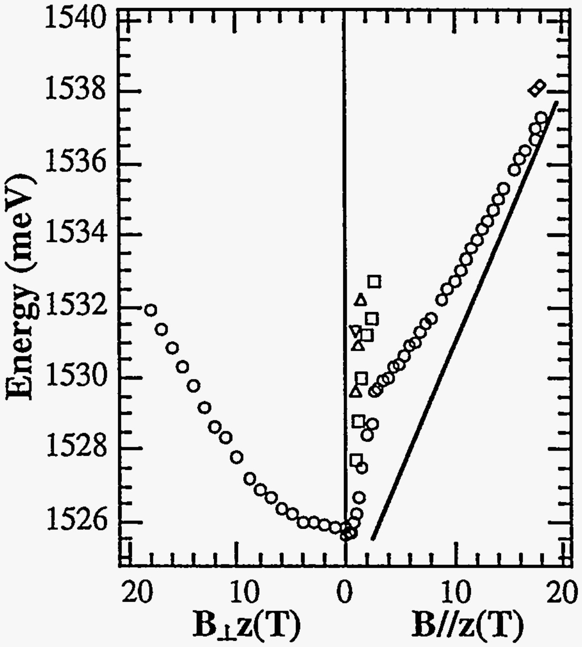

Figure 2. PL energy vs. magnetic field for sample A at T=4K.

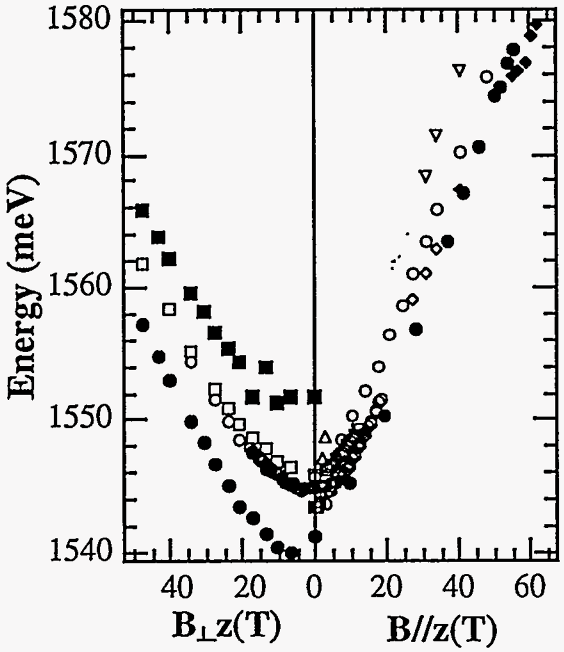

Figure 3. PL energy vs. magnetic field for sample B. Open and filled markers indicate T=4K and 77K data, respectively

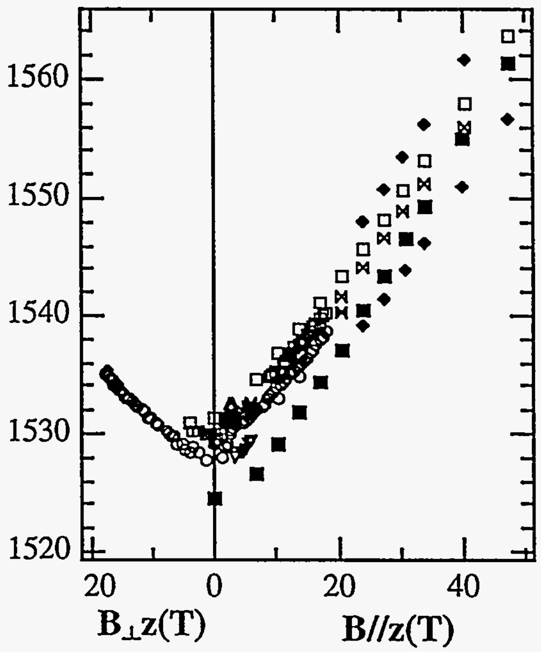

Figure 3. PL energy vs. magnetic field for sample C.

the PL peak positions energies for sample A shown in fig. 1. This value is the same for all three samples. The corresponding effective cyclotron reduced mass is 0.079 m_e. At high fields, the slope of the PL peak probes the dispersion in a large *k* region, where non-parabolicity is not negligible. The e1-hh1, e1-hh2, and the e1-lh1 at B = 0 are obtained by extrapolation to zero field and are estimated to be at about 1529, 1531, and 1534 meV, respectively; the basis for Landau fan is located at about 1524.5 meV. These energy separations are confirmed in the 77K data where all the hole states are populated. From these values, e1, hh1, hh2, and lh1 are estimated to be at ~10, 4, 6, and 9 meV, respectively and are in reasonable agreement with the calculated energies for this CDQW from the parameters given in Table 1 for sample A. The reduced effective masses for the electron-heavy and -light hole transitions in the high field (linear) region were is 0.079 and 0.065 m_e, respectively.

The higher Landau transitions rapidly disappear as the peaks intersect the Fermi level. Only in sample C did we observe a weak indication of the 0-0 Landau transition. After the anticrossing of the 0-1 transition with the e1-hh1 transition around 3T, the latter showed a showed a diamagnetic shift characteristic of a magneto-exciton. It asymptotically approached the 0-0 line from the fan base at high fields. (See Fig. 3)

For B⊥z, the main peak shows a diamagnetic shift at low fields. It becomes linear at high fields with a slope of 0.5-0.6 meV/T. The effective reduced in-plane mass is approximately 0.12 m_e. Spin splitting was observed beyond 40T for both the e1-hh1 and the e1-lh1 transitions even at 77K.

Sample B showed an anomalous energy dependence for the lowest transition in in-plane fields. From 0-5.5T the peak showed no shift. A step occurred a 5.5T and another at 8.5T. After 9T, the transition followed a diamagnetic shift which finally became linear at high fields beyond 20T. The steps are in the region where the partial minigap is formed by the induced anticrossing of the two quantum energy dispersion curves by the in-plane field.[5-7]

4 Summary

PL measurements of modulation doped CDQW have been made in high magnetic fields applied parallel and perpendicular to the in-plane 2DEG. Anti-crossing of Landau levels with magneto-exciton energy states occur in the low magnetic field region prior to their intersection with the Fermi level. Both allowed and forbidden symmetry transitions of a CDQW structure are observed due to the built-in electric field and VB mixing at high magnetic fields. Spin splitting is seen for many of the transitions above about 40 T. Anomalous steps in the energy of the lowest transition are observed at 5.5 and 8.5 T in the narrowest pair of CDQWs (sample B) with in-plane magnetic fields. These steps are in a region where a partial minigap is formed by when an in-plane magnetic field which induces an anti-crossing of the two displaced energy-dispersion parabolas.

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