SAND99-1313J

Coulomb Driven New Bound States at the Integer Quantum Hall States in $GaAs/Al_{0.3}Ga_{0.7}As$ Single Heterojunctions

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(May 6, 1999)

Coulomb driven, magneto-optically induced electron and hole bound states from a series of heavily doped $GaAs/Al_{0.3}Ga_{0.7}As$ single heterojunctions (SHJ) are revealed in high magnetic fields. At low magnetic fields (ν >2), the photoluminescence spectra display Shubnikov de-Haas type oscillations associated with the empty second subband transition. In the regime of the Landau filling factor ν <1 and 1< ν < 2, we found strong bound states due to Mott type localizations. Since a SHJ has an open valence band structure, these bound states are a unique property of the dynamic movement of the valence holes in strong magnetic fields.

In the last several years, many optical studies focused on the regime of the integer and fractional quantum Hall states of semiconductor quantum wells (QWs), where electrons and holes have confined energy levels.[1–8] Since a SHJ has only one interface, it is easier to fabricate high quality devices with ultrahigh mobilities. In a SHJ, the conduction band electrons are confined in a wedge-shaped quantum well near the interface, whereas the photocreated valence holes are not confined and tend to move to the GaAs flat band region. This has often been considered to be a disadvantage in optical experiments since the dynamic movement of valence holes due to the open structure makes it difficult to judge their location. To avoid this problem, intentional acceptor doping techniques have been employed to study optical transitions from SHJs.[5,6] For example, magnetophotoluminescence (MPL) experiments have been carried out on acceptor doped SHJs to investigate transitions associated with the integer quantum Hall effect (IQHE) and fractional quantum Hall effect (FQHE).[5,6]

In this Letter, we report the observation of strong discontinuous transitions at the ν=2 and ν=1 integer quantum Hall states and we belive these new transitions are the consequence of the formation of Coulomb-driven strong bound states. In a heavily doped single heterojunction, there are two factors that enhance the second subband (E1) exciton transition. The first is due to the close proximity between the Fermi energy and the E1 subband;[4,8] the second is due to the spatially indirect nature of conduction and valence band structure, the wavefunction overlap between the E1 subband and the valence hole is much larger than that of the first subband (E0) and the valence hole.[4] As the magnetic field changes, the 2DEG modifies the valence hole self-energy.[8,9] This in turn causes the E1 exciton transition to display strong oscillatory behavior in its transition energy and peak intensity at magnetic fields smaller than the ν=2 integer quantum Hall state.[4,8] Near ν=2, however, the E1 exciton transition loses its intensity and a new feature emerges at a lower energy. This transition rapidly increases its intensity for 2> ν >1 but then diminishes in strength and disappears as the magnetic field approaches the ν=1 quantum Hall state. In its place, another new peak appears at lower energy which swiftly grows in intensity for ν <1. These two red-shifted transitions are attributed to the formation of new bound states due to electron and hole localization and can still be observed to temperatures as high as 40K. In addition, we found that the strong bound states at ν=2 and ν=1 were not observed for low electron density samples (sample 1 and 2). These samples have a relatively large separation between the Fermi energy and the E1 subband and only the E0-hole free carrier transitions were observed.

A series of samples grown by different growth techniques was used for this study. One set was grown using a metal-oxide chemical vapor deposition (MOCVD) technique[10] and the other group was fabricated using a molecular beam epitaxy (MBE) technique. Table 1 shows the various parameters for six samples. The high magnetic fields were generated using a recently commissioned 60T quasi-continuous (QC) magnet, which has 2-second field duration. A pumped ^{3}He cryostat were used to achieve temperatures of 0.4-70K. For MPL experiments, a 630nm low power diode laser (<1.5mW/cm^2 to the samples) was used as the excitation source and a single optical fiber (600mm diameter; 0.16 numerical aperture) provided both the input excitation light onto sample and the output PL signal to the spectrometer.[11] The spectroscopic system consisted of a 300 mm focal length f/4 spectrometer and a charge coupled device (CCD) detector, which has a fast refresh rate (476Hz) and high quantum efficiency (90% at 500nm). This fast detection system allowed us to collect approximately 500 PL spectra/second during the duration of the magnet field pulse.

The σ+ polarization MPL spectra for sample 3 as a function of magnetic field taken in the QC magnet is dis-

played in Fig. 1. The corresponding MPL intensities for both the $\sigma+$ and $\sigma-$ polarizations are shown in Fig. 2. Two dramatic intensity changes with high magnetic fields near the $\nu=2$ and $\nu=1$ integer quantum Hall states were observed for these heavily doped samples. Our self-consistent calculations of the conduction band energies (Fig. 3) indicate that the Fermi energy lies close proximity to the E1 subband for heavily doped samples and the discontinuous MPL transitions are associated with the Fermi edge enhanced E1 exciton transitions.[4] The energy shifts of the peaks are displayed in Fig. 4a as a function of magnetic field B. As the magnetic field increases further, the transition (P2) that occurred at $\nu=2$ disappears near $\nu=1$ and another transition (P1) emerges at the $\nu=1$ quantum Hall state. Fig. 4b shows oscillatory behaviors of the MPL transitions at low magnetic fields.

As indicated in Fig. 3 for hevily doped SHJs, the Fermi energy lies close to the E1 subband (<1meV) which induces E1 exciton transition.[4] The emergence of the P2 transition at the $\nu=2$ quantum Hall state can be explained as follows: At low fields ($\nu>2$), valence holes are unbound and are free to move to the GaAs flat band region due to the open structure of the valence band (see Fig. 2 inset). As the magnetic field varies, the Fermi energy sweeps continuously from localized states to extended states, which changes the dielectric screening of the valence holes. When this happens, there are two factors to be considered in an optical transition. One is the hole self-energy and the other is the vertex correction aroused by the exciton effect. The hole self-energy gives rise to a blue shift,[8,9] whereas the vertex correction term gives a red-shift due to the exciton binding energy. Since the hole self-energy correction is bigger than the exciton effect[9] the free carrier transition shows a blue shift at even Landau filling factors. For the E1 exciton transition measured in these heavily doped samples, the valence hole self-energy is already modified by the E0 free carriers and hence it shows blue shift at even filling factors for $\nu>2$ (see Fig. 4b). Unlike transitions at even filling factors for $\nu>2$, the P2 transition at $\nu=2$ shows a large red-shift. This means that the vertex correction at $\nu=2$ in a heavily doped SHJ is much larger than the other effects which give a blueshift in the transition energy. At the $\nu=2$ quantum Hall state, electrons are strongly localized and the screening within the 2DEG becomes negligible. In the absence of screening effects, holes migrate back towards the interface because of the strong Coulomb attraction between the electrons and holes. As a result, holes are localized near the interface and form a new bound state (P2) at the $\nu=2$ quantum Hall state. This Coulomb-driven hole localization induces a large vertex correction that give rise to a giant red-shift in the transition energy. For sample 3, the P2 transition has a binding energy of about 8.2meV which decreases to 5meV at $\nu=1$ where it disappears. The amount of the red-shift would correspond to binding energy of the new bound state. The red-shift in this field regime is analogous to a Mott type transition,[12,13] since it is similar to the metal to insulator transition in the hydrogen system originally suggested by Mott,[14] of which the transition is induced when the screening length exceeds a critical value caused by the expanding the lattice constant. The relative binding energy ($\Delta E2$) of the new bound state (P2) increases with increasing 2DEG density. This is consistent with the reduction in the screening at the $\nu=2$ QHS. When the screening is turned off, the higher density sample has the stronger Coulomb attraction between electrons and holes. Hence, a higher 2DEG density sample has a larger binding energy than a lower electron density sample.

Near $\nu=1$, the P2 transition disappears and a new peak designated as P1 emerges on the lower energy side of the P2 transition. Like the P2 transition, the P1 transition also rapidly increases in intensity with increasing magnetic field as seen in Fig. 2. Near $\nu=1$, the screening strength within the 2DEG in the well is greatly reduced and once again the localization of the valence hole induces the discontinuous transitions and intensity changes at $\nu<1$. As indicated in Table 1, the amount of the $\Delta E1$ and the $\Delta E2$ measured at $\nu=1$ and $\nu=2$, respectively, are almost the same for a given 2DEG density.

There are numerous magneto-optical studies near the $\nu=1$ filling state where a red-shift in transition energy has been observed as 'shake-up' process at the Fermi energy.[7,15–17] However, our circular polarized MPL measurements show completely different results from others.[7,17] In our experiments, we found that both the P1 and P2 transitions were strongly left circularly polarized (σ-) as seen in Fig. 2. The intensity of the P2 σ- transition is about three times that of the $\sigma+$ transition, whereas P1 has about a 5:1 ratio for $\sigma-/\sigma+$. The E1 transition, on the other hand, shows no appreciable intensity differences between the two spin polarizations. This means that for a unbound exciton state (E1), both spins are almost equally populated, whereas for the strongly bound exciton states (P1 and P2), they are strongly polarized to the excitonic ground state (σ-). Though not shown here, the temperature dependence of the MPL experiments show that the P2 transition disappears at 40K, whereas the P1 transition disappears at 10K. This is due to the fact that the thermal broadening of the 2DEG density of states closes the Zeeman gap of the Landau levels which does not contribut the reduction of the screening at the odd integer filling states at 10K.

It has been suggested[18–20] that within the quantum Hall phase diagram, the mobility of the sample strongly affects the quantum Hall liquid (QHL) to quantum Hall insulator (QHI) phase transition, as the induced electron localization can take place at different quantum Hall states. For example, for a highly disordered structure the phase transition occurs near $\nu=2$, but for a moderately disordered one the phase transition is near $\nu=1$. As the samples used in this study have high mobilities ($>10^6$cm^2/Vs), we may expect to see other bound states near $\nu=1/3$ fractional quantum Hall state caused by the quantum Hall phases transition. This would be manifested by another minimum in the intensity for sample 3 at about 69T for ν=1/3. Unfortunately, this is just beyond the current high field limit of 60T for the QC magnet at NHMFL-LANL but there is some evidence that this is may be about to take place as the intensity of the P1 transition shows a rapid decreases between 50 and 60T (see Fig. 2).

In conclision, we have presented MPL studies on a series of high mobility SHJs in high magnetic fields to 60T using a QC magnet at NHMFL-LANL. At low magnetic fields (ν >2), the photoluminescence spectra display Shubnikov de-Haas type oscillations associated with the empty second subband transition. In the high field regime, we observe the formation of Coulomb driven, magneto-optically induced electron and hole bound states near Landau filling factors ν=2 and ν=1 (with some evidence that there may be another at ν=1/3). A discrete phase transformation from a dynamic hole to a bound hole state due to a Mott-type transition is thought to be responsible for the large red-shift that occur near the ν=2 and ν=1 Landau filling states. Both bound state transitions are strongly spin polarized (σ-) states. The appearance of these bound states appears to be a unique property of heavily doped SHJs and the associated dynamic movement of the holes in strong magnetic fields due to their open valence band structure.

Authors gratefully acknowledge the engineers and technicians at NHMFL-LANL for their efforts on operating 60T QC magnet. Work at NHMFL-LANL is supported by NSF Cooperative Agreement DMR 9527035 and US DOE. Work at Sandia National Laboratories and UCLA is supported by DOE under Contract DE-AC04-94AL85000 and by NSF Cooperative Agreement DMR 9705439, respectively.

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FIG. 1. Approximately 1000 MPL spectra taken in a 2-second magnetic field sweep of the 60T QC magnet for sample 3 at T=1.5K for σ+ polarization. The peaks labeled P1, P2 and E1 are described in the text.

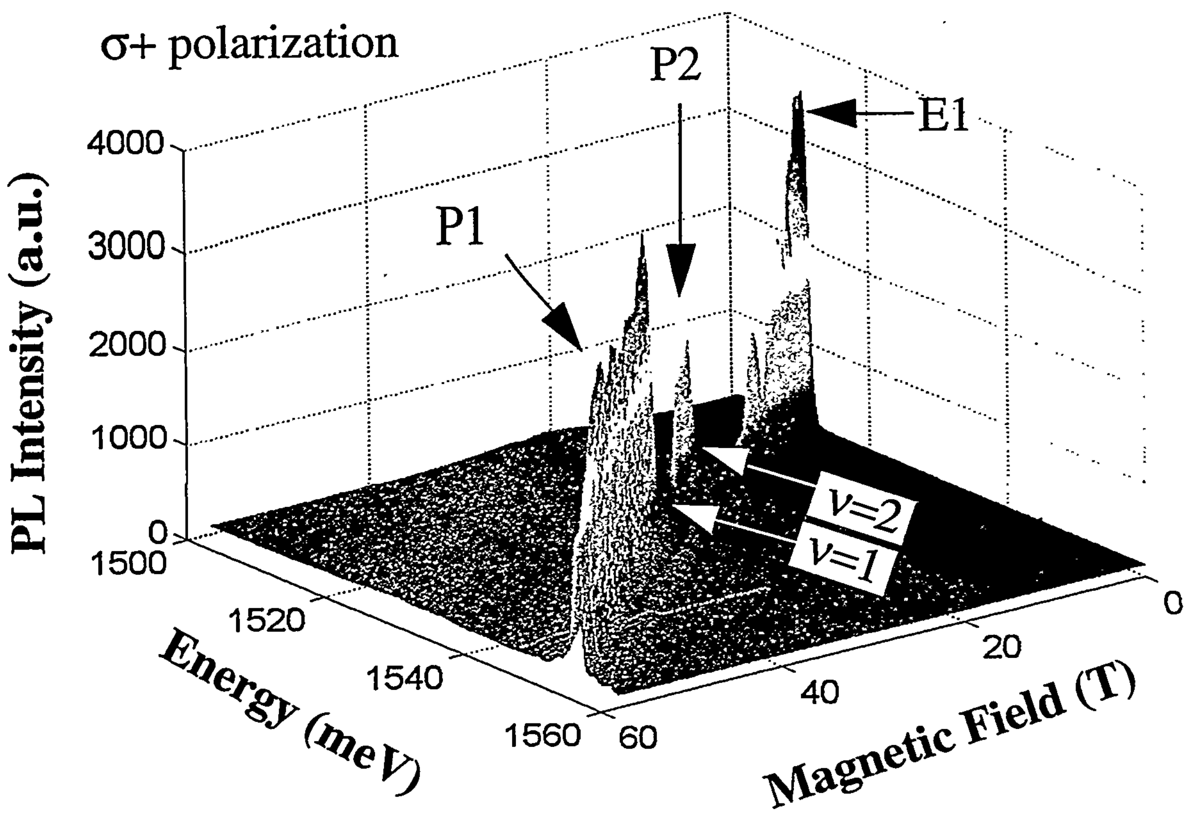
FIG. 2. A plot of the PL transition intensity vs magnetic field for sample 3. The E1 transition intensity rapidly diminished for ν <2. At ν=2 and ν=1, two new transitions assigned as P2 and P1, respectively, emerge on the lower energy side of the E1 transition. Compared with the E1 transition, which is unpolarized, the P2 and P1 transitions are strongly polarized (σ-/LCP). The inset depicts a SHJ structure and the inferred movement of the valence hole at ν <2.

FIG. 3. The results of self-consistent calculations for SHJ subband energy levels with respect to the spacer thickness under laser illumination. The vertical arrows indicate the samples used for this study. The right axis is the energy difference (Δ) between the Fermi energy and the E1 subbnad.

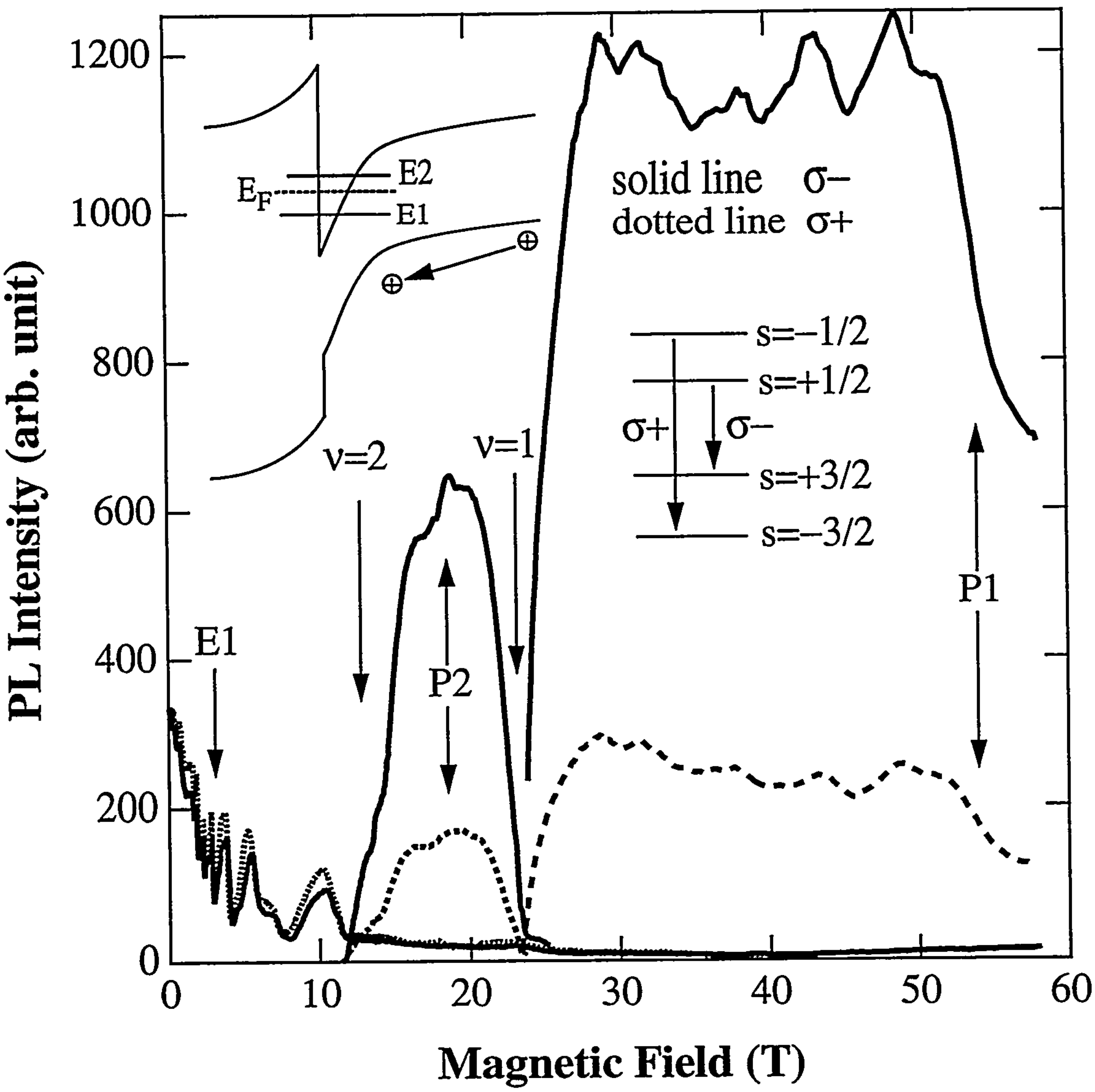
FIG. 4. (a) A plot of the transition energies vs magnetic field for E1, P1 and P2 for sample 3. Note the large discontinuous transitions at ν=2 and ν=1. (b) Expanded view of E1 vs. magnetic field, showing the Shubnikov de-Haas type oscillations in the transition energy and intensity. The blue-shifts in the transition energy at even integer filling states are due to the variation of the hole self-energy. The intensity oscillations are due to the interaction between the Fermi energy and E1 subband (see text).

TABLE I. Sample parameters. The electron density (n_{2D}) under laser illumination were determinded by transport experiments. The intensity oscillations in Fig. 3 are in phase with measured Shubnikov de-Haas oscillations. $\Delta E1$ and $\Delta E2$ are the values at ν=1 and ν=2, respectively, and these are almost the same for a given n_{2D}.

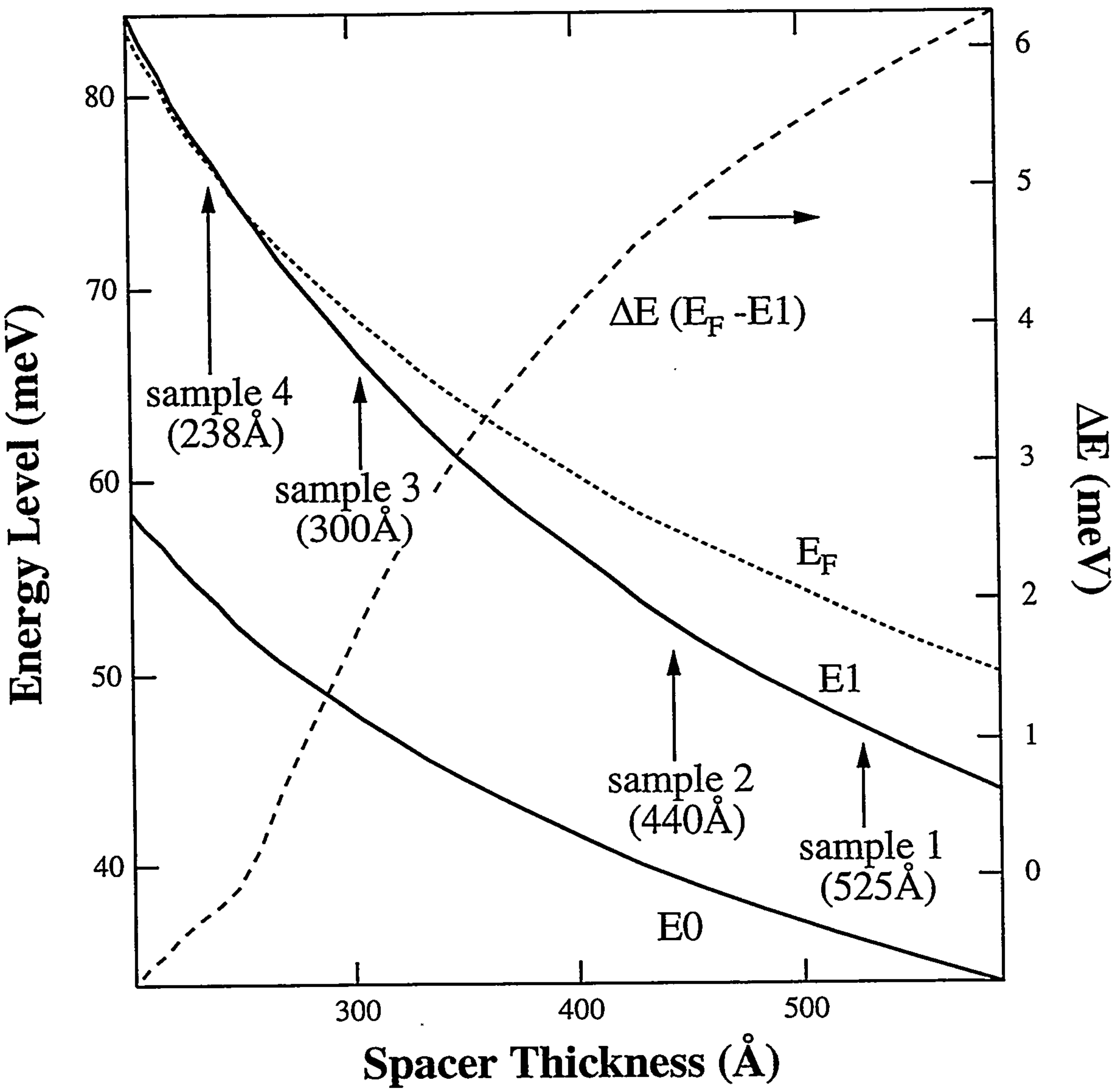
	n_{2D}(dark) ($10^{11}/cm^2$)	n_{2D}(illu) ($10^{11}/cm^2$)	$\Delta E2$ (meV)	$\Delta E1$ (meV)	growth technique
Sample 1	2.1	3.0	-	-	MOCVD
Sample 2	2.3	3.5	-	-	MOCVD
Sample 3	3.6	5.8	8.4	8.0	MOCVD
Sample 4	4.5	7.2	9.4	9.4	MOCVD
Sample 5	3.1	6.2	8.6	8.5	MBE
Sample 6	-	14.4	12.0	-	MBE



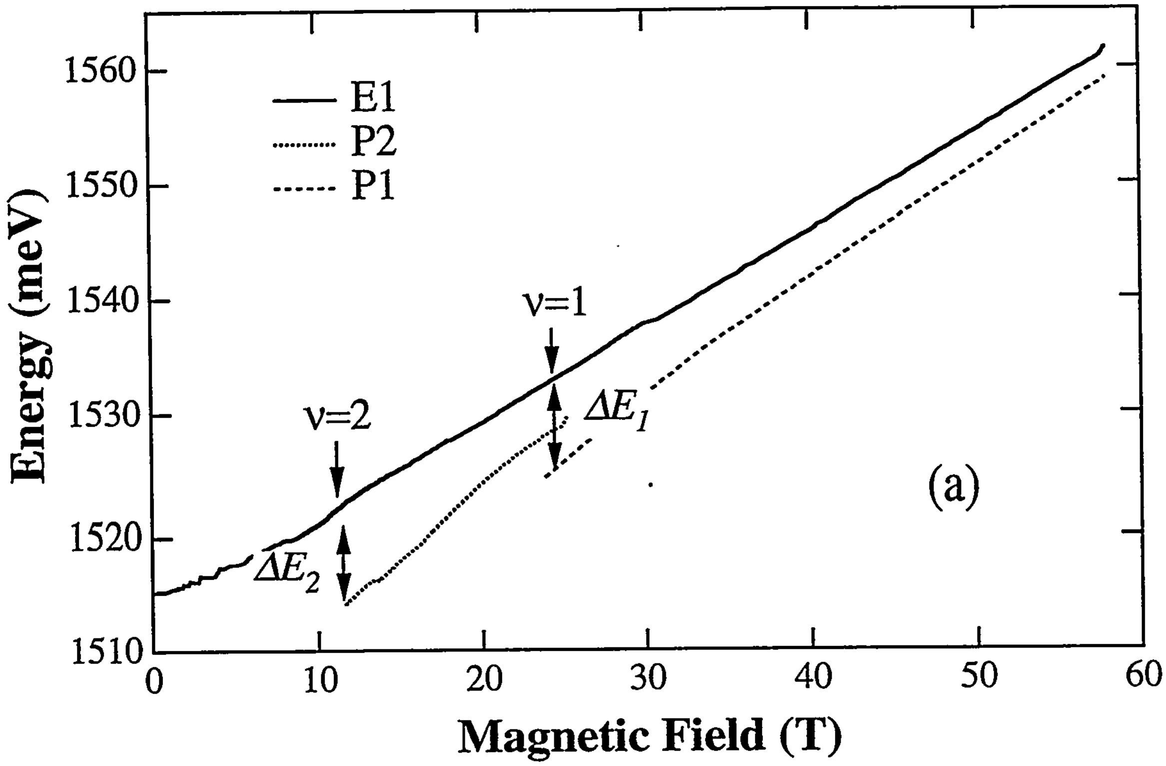
sub PRL Kim et. al. Fig. 1

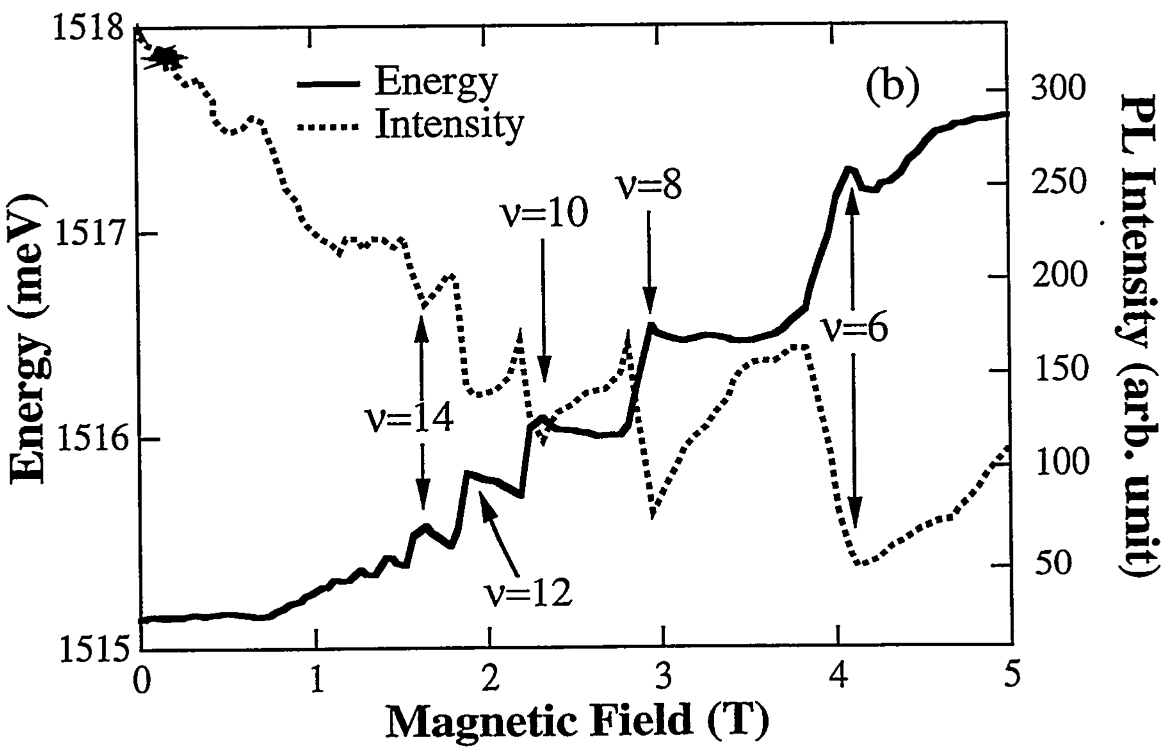


sub PRL kim et. al. Fig. 2



sub PRL Kim et. al. Fig. 3





sub PRL Kim et. al. Fig. 4