Final-state excitations in the photoluminescence spectra of $In_xGa_{1-x}As$-InP quantum wells at low and high carrier density

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Longitudinal-optic (LO) phonon and Fermi-sea shake-up excitations are studied in the magneto-optical spectra of $In_xGa_{1-x}As$-InP quantum wells. The final-state excitations are observed as low-energy satellites in photoluminescence spectra in magnetic fields up to 20 T. Clear resonant interactions between the LO-phonon and shake-up satellites are observed. In the low-density sample ($n_s = 1.15\times10^{11}$ cm^{-2}) studied, interaction between the shake-up satellite, corresponding to promotion of an electron from the $N_e=0$ to the $N_e=1$ Landau level, and the LO-phonon satellite of the $N_e=0$ Landau-level transition, is observed. The other two samples investigated have high carrier density of 9.2×10^{11} cm^{-2}; one sample has strong disorder and strong hole localization and the other weak disorder and weak hole localization. The sample with strong hole localization exhibits a Fermi-energy-edge singularity in its photoluminescence (PL) spectrum at zero magnetic field, and has strong phonon and shake-up satellites. The other high-density sample has a very weak PL signal at the Fermi energy and phonon and shake-up satellites at high field at least an order of magnitude weaker than in the sample with strong hole localization. This behavior arises since the strength of the Fermi edge singularity and the coupling to the LO phonon and shake-up excitations both depend on the degree of hole localization in the system. In addition to resonant interaction between the LO-phonon and shake-up satellites, interaction of the phonon satellites of partially filled Landau levels with the $N_e=0$ electron to $N_h=0$ hole recombination line is reported. A marked variation of the intensities of these satellites with magnetic field is observed. It is suggested that the variation of Landau-level filling with field plays an important role in determining the intensities of these satellites of partially filled Landau levels. A theoretical treatment that explains the variation of the intensities of the shake-up satellites with field, at low magnetic field in the low-density sample, is also presented.

I. INTRODUCTION

It has been shown recently that a variety of final-state excitations can be observed in the magneto-optical spectra of semiconductor quantum wells (QW's).[1–5] Both lattice (longitudinal-optical-phonon) and Fermi-sea (shake-up) excitations, have been detected in photoluminescence (PL) spectra of QWs containing high densities of carriers. The use of high magnetic field has played a key role in permitting the observation of these excitations.

In magnetic field the conduction- and valence-band densities of states are quantized into Landau levels. The dominant recombination observed in PL arises due to transitions between occupied conduction- and valence-band Landau levels. In the experiments considered here the quantum wells contain a relatively high density of electrons in the range from 10^{11} to 10^{12} cm^{-2}. The recombination of this high density of electrons with a low density of photocreated holes ($\sim10^8$ cm^{-2}) is then observed. Under such conditions, the energy of the photon detected corresponds to the energy separation between the conduction- and valence-band Landau levels, modified by many-body interactions (band-gap renormalization). When recombination destroys an electron in a filled conduction-band Landau level, the final state of the electron system then corresponds to the series of filled Landau levels, with one hole quasiparticle in the Landau level from which electron recombination occurred.[6] However, other final states of the system can also arise in which either lattice (LO-phonon) excitations, or excitations of the Fermi sea are emitted in the recombination process. When such an additional excitation is emitted during recombination, the photon which is detected will have lower energy in order to conserve total energy during the recombination.

The subject of LO-phonon-satellite excitations in semiconductor PL spectra has a long history,[7] and has recently been discussed for quantum wells.[8–10] It has been shown that the strength of the coupling to LO phonons by the Fröhlich interaction is strongly enhanced by the degree of localization of the holes which participate in the recombination; a localized hole causes greater polarization of the lattice and thus leads to strong LO-phonon coupling in the PL spectra.[7,8]

Excitations of the Fermi sea, by so-called shake-up processes, are more difficult to detect in PL spectra. At zero magnetic field, in a shake-up process an additional electron is excited across the Fermi energy during electron-hole recombination. Since there is a continuum of available states into which the additional electron can be excited, shake-up leads to a broad low-energy tail to PL spectra at zero field. In semiconductors there are many other sources of low-energy tails, with the result that the attribution of a low-energy tail to shake-up is uncertain, and is usually based upon detailed analysis of the PL line shape.[11] However, we have shown recently in experiments on an $In_xGa_{1-x}As$-InP quantum well that in magnetic field the situation is transformed and shake-up can be observed in an unambiguous way.[1] Due to the Landau-level quantization, electrons can only be excited from discrete Landau levels below the Fermi energy to discrete Landau levels above the Fermi energy. As a result the low-energy shake-up tail is transformed into a series of discrete shake-up satellites. At high carrier density the width of the observed PL band is governed by the electron Fermi energy, due to band filling effects. As a result any phonon satellites also will be very broad.[12] Landau quantization in high magnetic field leads to a discrete line spectrum and removal of the free-carrier broadening, and as a result much clearer observation of LO-phonon as well as shake-up satellites.

Phonon satellites and shake-up satellites have thus been reported in separate observations in quantum-well PL spectra.[1,8,9] It has also been shown recently that the two types of final-state excitations show strong interaction in magnetic-field ranges where the emission of either LO-phonon or shake-up excitations leads to final states which are very similar in energy.[2,3,13] Under such conditions resonant interactions between the two types of final-state excitation are observed.

In the present paper, experiments on the $In_xGa_{1-x}Ga$-InP quantum well in which shake-up was first reported[1] are extended from magnetic fields of 9.6 T up to 20 T. Extension to the higher field range permits observation of shake-up–LO-phonon satellite interaction in a sample containing a relatively low density of electrons of 1.15×10^{11} cm^{-2}. Results are then presented for two highly doped $In_xGa_{1-x}As$-InP quantum wells containing 9.2×10^{11} cm^{-2} carriers, one with strong disorder and hole localization in the quantum well, and one with weak disorder. The much higher carrier densities in these samples mean that the quantum limit, where only the lowest electron Landau level is populated, is only reached at high magnetic fields of ~19 T. The fact that a number of electron Landau levels are populated at lower field means that a wider variety of phonon satellites and shake-up excitations can arise. We observe resonant interaction phenomena of very similar form to those first reported for $Al_xGa_{1-x}As$-$In_xGa_{1-x}As$-GaAs strained-layer quantum wells containing similarly high carrier densities,[2,3] although in the present work satellites of different Landau levels are involved. Strong enhancements of the intensities of the phonon satellites of the $N_e=1$ Landau level as they approach the energy of the recombination involving the $N_e=0$ Landau level are also observed. The satellites observed for the two samples with either strong or weak hole localization are contrasted.

The paper is organized in the following way. The experimental details and main sample characteristics are summarized in Sec. II. Then in Sec. III A the magneto-PL results for the low-density $In_xGa_{1-x}As$-InP sample are discussed, together with the presentation of a simplified theoretical treatment of shake-up processes. This is followed by the results for the two high-density samples in Sec. III B and III C. Finally in Sec. IV the main conclusions of the paper are summarized.

II. EXPERIMENT

The experiments were carried out on nominally lattice matched $In_{1-x}Ga_xAs$-InP ($x=0.47$) quantum wells (QWs) grown by atmospheric pressure metal-organic chemical-vapor deposition. The most important characteristics of the three samples A, B, and C are summarized in Table I. Sample A is a nominally undoped 150-Å QW, with carrier density of 1.15×10^{11} cm^{-2} arising in the well due to a persistent photoconductivity effect under optical excitation.[14] Samples B and C are 100 Å wide modulation-doped quantum wells with InP spacer layers of 100-Å thickness, and contain the same carrier density of 9.2×10^{11} cm^{-2} under illumination. In all cases the carrier densities are those determined from the magneto-PL experiments described in the following sections. Further details of the samples can be found in Refs. 1, 13, 14, 15, and 16.

PL was excited at 4.2 K using ~25 mW/cm^2 of 633-nm radiation from a He-Ne laser, dispersed using a grating spectrometer, and detected using a cooled Ge photodiode. Magnetic fields up to 10 T were obtained from a horizontal bore superconducting magnet, and up to 20 T using a water-cooled Bitter magnet.

III. RESULTS AND DISCUSSION

A. Sample A, $n_s=1.15\times10^{11}$ cm^{-2}

The magneto-PL spectra for this sample were reported in Ref. 1 up to fields of 9.6 T. In this section the results up to 9.6 T are described briefly in order to set the foundation for subsequent discussions. Once these preliminary remarks have been made, results up to field of 20 T are presented. A simplified theoretical treatment of shake-up is also presented.

The PL spectrum at $B=0$, published in Ref. 1, consists of a zero-phonon line (ZPL) at 847.7 meV, and LO-phonon satellites in the 800–820-meV region to lower energy. In magnetic field, splitting of the ZPL into $n=0$ and 1 Landau-levels (LL's) is observed, with the $n=1$ LL depopulating at 2.4 T. At this field all electrons reside in

TABLE I. Characteristics of the three samples grown by atmospheric pressure metal-organic chemical-vapor deposition.

Sample	Well width Å	n_s cm^{-2}
A	150	1.15×10^{11}
B	100	9.2×10^{11}
C	100	9.2×10^{11}

the lowest electron LL, corresponding to a Landau-level filling actor of $\nu=2$ (the spin splitting is not resolved). From the observation of $\nu=2$ at 2.4 T, the carrier density in the QW was deduced in Ref. 1 to be 1.15×10^{11} cm^{-2}. In magnetic field GaAs and InAs LO-phonon satellites (33 and 27 meV) from the $In_xGa_{1-x}As$ QW and InP satellites (43 meV) from the barrier are clearly resolved.[1]

In addition to the ZPL and phonon satellites, shake-up satellites, labelled T_1, T_2, and T_3 in Ref. 1, are observed. These satellites arise from Fermi-sea shake-up in which an additional electron is promoted from the partially filled $n=0$ LL to higher $n=1$, 2, or 3 LL's, in a process accompanying the electron–valence-band-hole recombination. As discussed in Sec. I, the energy of the phonon emitted in the presence of shake-up is lower than in its absence, the extra energy being lost in the promotion of the additional electron to the higher LL.

The energies of all the observed recombination lines are plotted in Fig. 1 as a function of magnetic field from 0 to 20 T. The LO-phonon satellite energies run parallel to those of the ZPL as a function of magnetic field, but at 27, 33, and 43 meV to lower energy. The energy separations of the T_n shake-up satellites from the ZPL increase with increasing magnetic field, as the inter-Landau-level separation increases with field. The splitting between the ZPL and T_1, ΔE, can be expressed in terms of an apparent effective mass m_t^* by use of the expression $\Delta E=\hbar eB/m_t^*$. The variation of m_t^* with B is shown in the inset to Fig. 1. m_t^* is seen to vary from $0.038m_0$ at 2.3 T to $0.047m_0$ at 9.6 T.[17] The strong increase of m_t^* from 2.3 to 4 T corresponds to the strongly nonlinear

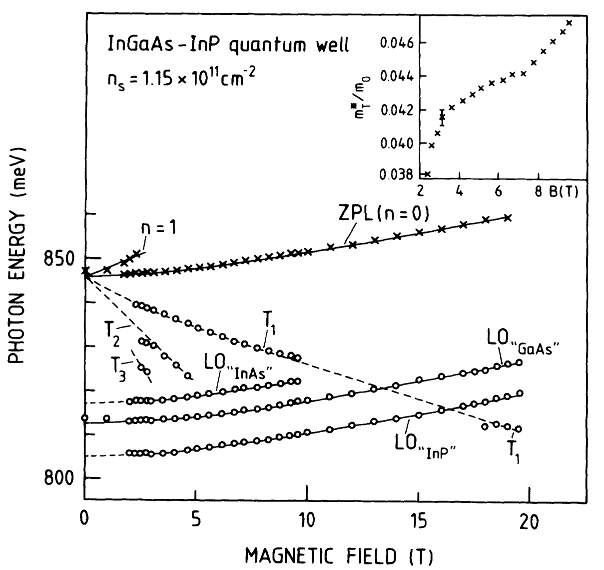

FIG. 1. Transition energies against magnetic field for sample A. T_1, T_2, and T_3 shake-up satellites and $In_xGa_{1-x}As$ quantum well and InP barrier LO-phonon satellites are observed. The splitting between T_1 and the ZPL is expressed as an apparent effective mass m_t^* in the inset, as a function of magnetic field. The deviation from the quantum-well band-edge effective mass of $0.049m_0$ arises due to coupling to $q\neq0$ magnetoplasmon excitations which occur at energies greater than the Landau-level separation $\hbar\omega_c$.

variation of the ZPL$-T_1$ splitting with field in Fig. 1 in this field region.

The T_1 satellite intensities decrease strongly with increasing magnetic field, from, for example, 0.4% of the ZPL at 3.6 T to 0.13% at 7.2 T [see Figs. 1(c) and 1(d) of Ref. 1]. This behavior, together with the importance of hole localization in enhancing the intensity of the shake-up satellites, can be understood from the following theoretical treatment. The simplest calculation of the shake-up effects due to a localized hole is Langreth's first-order treatment of the screened Coulomb interaction,[18] which has been adapted to a quasi-2D geometry by Hawrylak.[19] The result of this calculation is that the PL intensity $\bar{S}(\omega)$, due to shake-up, at energy $\hbar\omega$ below the principal PL line, is

$$\bar{S}(\omega)=\frac{1}{\pi^2\hbar}\frac{e^2}{4\pi\varepsilon_0}\int d^2\underline{q}\,|n(\underline{q})|^2\frac{1}{2q}\frac{f_{\rm eh}^2(q)}{f_{\rm ee}(q)}\frac{\theta(\omega)}{\omega^2}\times[-{\rm Im}\varepsilon^{-1}(q,\omega)]\,, \quad (1)$$

where the intensity of the principal PL line integrated with respect to ω is unity. $f_{\rm ee}(q)$, $f_{\rm eh}(q)$ are form factors for the electron-electron and electron-hole interactions for particles in the lowest subbands of the QW, and are given by[20]

$$f_{ij}(q)=\int_{-\infty}^{\infty}dz_1\int_{-\infty}^{\infty}dz_2|\psi_i(z_1)|^2|\psi_j(z_2)|^2\times\exp(-q|z_1-z_2|)\,, \quad (2)$$

where $\psi_i(z)$ and $\psi_j(z)$ are the wave functions for the lowest subbands of particles i and j. $\theta(\omega)$ is the Heaviside step function. $\varepsilon(q,\omega)$ is the dielectric function including both the static dielectric constant and the screening due to the two-dimensional electron gas (2DEG) in the magnetic field. The optic-phonon contribution to the dynamic screening is neglected, so that this theory includes only the electronic excitations of the 2DEG, and does not allow for the interaction of these excitations with phonons. $n(\rho)$ is the probability density for the localized hole in the plane of the QW, with $\rho=(x,y)$, and $n(\mathbf{q})=\int d^2\underline{\rho}\exp(-i\mathbf{q}\cdot\boldsymbol{\rho})n(\underline{\rho})$ is the Fourier transform of $n(\rho)$. A hole radius of 20 Å is deduced from the theory of LO-phonon satellites and the strength of the GaAs-like LO-phonon satellite reported in Ref. 1.

The overall strength of the shake-up satellites, compared to the principal PL line, is modified by refinements of the many-body theory[21] not included in Eq. (1) and because only some of the photocreated holes are strongly localized.[10,1] Only the localized holes contribute to $\bar{S}(\omega)$, whereas the principal PL line has contributions from all the holes. However, these more sophisticated treatments do not alter the form of the shake-up spectrum or its qualitative dependence on magnetic field, and so we shall briefly discuss these in terms of the relatively simple formula of Eq. (1).

In a magnetic field, the satellites T_n occur because $-{\rm Im}\varepsilon^{-1}(q,\omega)$ is sharply peaked at the magnetoplasmon frequencies, close to but greater than or equal to $n\omega_c$, for all q. At zero magnetic field, in contrast, $-{\rm Im}\varepsilon^{-1}(q,\omega)$ does not include sharp peaks when integrated over q, and so the shake-up spectrum forms a continuum.[1]

The intensity of T_n relative to the principal PL line is

$$I_n = \int_{n\omega_c}^{n\omega_c + E_0} d\omega\, \bar{S}(\omega) \tag{3}$$

where E_0 is sufficiently large that the integral includes the peak in $-\mathrm{Im}\varepsilon^{-1}(q,\omega)$ for all q. Different energies within the range of integration are not resolved in the PL experiment. Performing this integral on the ω-dependent factors of Eq. (1) and approximating $\omega \approx n\omega_c$ in the ω^{-2} factor in Eq. (1), gives

$$R_n(q) = \frac{1}{(n\omega_c)^2} \int_{n\omega_c}^{n\omega_c + E_0} d\omega [-\mathrm{Im}\varepsilon^{-1}(q,\omega)] \; . \tag{4}$$

$R_n(q)$ is a measure of the pole strength of $\varepsilon^{-1}(q,\omega)$ divided by $(n\omega_c)^2$, or, in physical terms, it is a factor which determines the strength of the hole-magnetoplasmon coupling. The intensity of T_n can thus be written

$$I_n = \frac{1}{\pi^2 \hbar} \frac{e^2}{4\pi\varepsilon_0} \int d^2\mathbf{q} |n(\mathbf{q})|^2 \frac{1}{2q} \frac{f_{\mathrm{eh}}^2(q)}{f_{\mathrm{ee}}(q)} R_n(q) \; . \tag{5}$$

The $|n(\mathbf{q})|^2$ term in Eq. (5), the Fourier transform of the hole probability density in real space, expresses the dependence of the shake-up satellite intensity on hole localization; strongly localized holes in real space, corresponding to large spread of the hole wave function in wave-vector space, lead to strong coupling to magnetoplasmon excitations and thus to strong shake-up satellites. This expression for the strength of the shake-up satellite is similar in form to that for the strength of the LO-phonon satellite due to a localized hole.[9] The formulas differ only because the strength of coupling to excitations (magnetoplasmons or LO phonons), as a function of q, is different for the two cases.

The properties of I_n as a function of magnetic field can be deduced from Eq. (5). $R_n(q)$ vanishes at $q=0$ and as $q \to \infty$, and peaks at $q \sim l_B^{-1}$ where $l_B = (\hbar/eB)^{1/2}$ is the magnetic length. This behavior of $R_n(q)$ dominates the q dependence of the integrand of Eq. (5): the hole radius is 20 Å, much smaller than l_B, and so $n(q) \sim 1$ for all q at which $R_n(q)$ is significant; also $f_{\mathrm{eh}}(q), f_{\mathrm{ee}}(q)$ are not reduced by much from their unity small-q limit because this would require l_B to be smaller than or comparable to $L/3$, where L is the well width.[22] We use a simple random-phase approximation (RPA) expression for $\varepsilon(q,\omega)$, which is adequate for the present sample at finite frequencies (i.e., for $n > 0$).[21] In the quantum limit, the form of ε, expressed as a function of ql_B and ω/ω_c, is independent of B, except for a $B^{-3/2}$ variation of the strength of the $n > 0$ poles of ε in the ω/ω_c plane, and a more complicated behavior of the $n=0$ pole. Applying this result in Eq. (5), one finds that, approximately, $I_n \propto B^{-2}$. Quantitative agreement with experiment is not expected, given the approximations mentioned above; however, the qualitative trend of a rapid decrease of I_n with B is in excellent agreement with experiment at low magnetic fields,[1] where the T_1 shake-up satellites were found to decrease strongly in intensity with increasing magnetic field, as mentioned earlier from 0.4% of the ZPL at 3.6 T to 0.13% at 7.2 T [see Figs. 1(c) and 1(d) of Ref. 1].

Spectra in the LO-phonon and T_1 satellite region at higher magnetic field are shown in Figs. 2(a), 2(b), and 2(c), at 8.5, 10, and 19 T, respectively. The decreasing trend of the T_1 intensity with field is much more rapid than B^{-2} between Figs. 2(a) and 2(b), with a factor of 2–3 decrease from 8.5 to 10 T, with the T_1 satellite only just visible at 10 T. At 8.5 T, the T_1 and GaAs LO-phonon satellites have 0.045% and 0.3%, respectively, of the intensity of the ZPL. Above 10 T the T_1 satellite is no longer visible until 18 T, when it reappears with a similar intensity to that observed at 10 T.

The extremely rapid decrease of I_1 from 8.5 to 10 T and beyond, together with the rough equality of I_1 at 10 and 18 T, contradict the approximate B^{-2} law predicted in the absence of optic phonons, and are attributed to resonant mixing between the relatively strong phonon satellites and the T_1 satellite. As seen in Fig. 1, the T_1 satellite crosses the phonon satellites in the 14–16-T region. Both forms of satellite arise from final-state excitations of the system; either a LO-phonon lattice excitation or an inter-Landau-level magnetoplasmon excitation is emitted during the recombination. In the 14–16-T region the two final states of the system are nearly degenerate. As

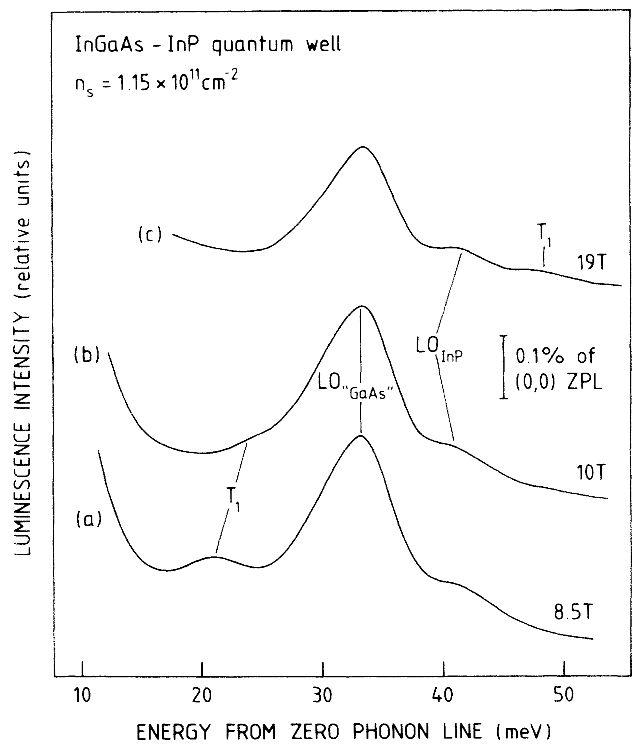

FIG. 2. LO-phonon and shake-up satellites relative to the intensity of the zero-phonon line for sample A at 8.5, 10 and 19 T in 2(a), (b), and (c), respectively. The T_1 shake-up satellite intensity decreases strongly in intensity up to 10 T. It is observed again at 19 T, with a similar intensity to that at 10 T due to resonant coupling with the GaAs-like LO-phonon satellites. 0.1% of the intensity of the zero-phonon line (ZPL) is marked by the vertical bar on the figure.

reported for $Al_xGa_{1-x}As$-$In_xGa_{1-x}As$-GaAs strained-layer quantum wells in Refs. 2 and 3, coupling between the two final states arises due to LO-phonon–magnetoplasmon mixing.[23,24] Resonant mixing between the T_1 and the much stronger LO-phonon satellites leads to the observation of the T_1 satellite in the $B=18-19.5$-T region. Further very clear evidence for the interaction between the magnetoplasmon shake-up and LO-phonon satellites is presented in Secs. III B and III C for the modulation-doped $In_xGa_{1-x}As$-InP QW's.

The value of m_t^* of $0.047m_0$ at 9.6 T is close to the band-edge effective mass $m_{\rm BE}^*$ of $0.049m_0$ measured for the modulation-doped quantum well of Sec. III B grown under very similar conditions to sample A. The deviation of the ZPL-T_1 energy splitting from $\hbar\omega_c=\hbar eB/m_{\rm BE}^*$ at $B<9$ T, and hence the small values of m_t^* in the inset to Fig. 1, arises since the shake-up process is a many-body magnetoplasmon excitation of the Fermi sea. As discussed in Ref. 1, following the theoretical treatment of Kallin and Halperin[25] and Macdonald,[26] the energy of the magnetoplasmon excitation is only equal to $\hbar\omega_c$ for in-plane wave vector $q=0$. The strongest coupling to magnetoplasmons occurs at $q\sim l_B^{-1}$, close to the maximum in the magnetoplasmon density of states (the magnetoroton maximum) which is expected to occur at $0.17\nu e^2/\varepsilon l_B$ above $\hbar\omega_c$, for filling factor $\nu=1$, where ε is the dielectric constant and $l_B=(\hbar leB)^{1/2}$ is the magnetic length. The factor ν/l_B varies at $B^{1/2}/B=B^{-1/2}$, and thus the deviation from $\hbar\omega_c$ is expected to decrease with increasing magnetic field. This is exactly the behavior observed in the Fig. 1 inset, where m_t^* increases markedly with increasing magnetic field. At $\nu=1$ (4.8 T), $m_t^*=0.0435m_0$ is calculated from the energy of the maximum of the magnetoplasmon density of states at $\hbar\omega_c+0.17\nu e^2/\varepsilon l_B$, in good agreement with the experimental value of $0.0430m_0$. The particularly strong variation of m_t^* from 2.3 to 4 T probably arises from the strong variation of the energy of the maximum of the magnetoplasmon density of states with filling factor in this region. Using the theory of Kallin and Halperin of Ref. 25, a value of m_t^* of $0.032m_0$ is predicted at $\nu=1$ (4.8 T), and $0.0435m_0$ at $\nu=2$ (2.4 T), in qualitative agreement with the variation of $0.038m_0$ to $0.043m_0$ obtained from the experiments.

The change of slope of the variation of m_t^* with B from 8 to 9.6 T, with m_t^* increasing to $0.047m_0$ at 9.6 T, may arise from repulsion of the T_1 satellite by the LO-phonon satellites, as T_1 approaches the interaction regime with the phonon satellites. It should be noted, however, that even at 19 T the value of m_t^* of $0.047m_0$ is still less than the value of $m_{\rm BE}^*$ of $0.049m_0$, as required by the magnetoplasmon interpretation of the shake-up satellites.

In physical terms, the breakdown of wave-vector conservation in the shake-up process, which permits efficient coupling to $q\neq0$ magnetoplasmon excitations, is enabled by the localization of the hole, whose wave function contains Fourier components at the required wave vectors. The strength of the shake-up process and of the phonon satellites is strongly enhanced by hole localization, which is probably due to alloy disorder in the $In_xGa_{1-x}As$ QW. The effects of disorder were also invoked by Pinczuk *et al.*[27] to explain the strong coupling to $q\neq0$ excitations in light scattering experiments in the quantum Hall regime. In Sec. III B, the effects of hole localization and alloy disorder are also discussed for a modulation-doped QW which shows a strong Fermi-energy-edge singularity in its PL spectrum.

B. Sample B, $n_s=9.2\times10^{11}$ cm^{-2}

The PL spectrum from sample B was first reported, to our knowledge, in Ref. 15. It consists of a broad band of width close to the electron Fermi energy of 45.0 meV, corresponding to $n_s=9.2\times10^{11}$cm^{-2}. Efficient recombination of electrons at the bottom of the band at $k=0$ up to the Fermi wave vector at 2.4×10^6 cm^{-1} is permitted by the strong hole localization in the $In_xGa_{1-x}As$ QW, mentioned in Sec. II. The hole localization probably occurs in alloy fluctuations in the $In_xGa_{1-x}As$ QW. The PL intensity is enhanced toward E_F due to the Fermi-energy-edge singularity[15,4,5,28] in this system with strong hole localization.

In magnetic field the spectrum breaks up into a series of Landau levels, as reported in Ref. 29. The transitions are labeled $(N_e,0)$ where $N_e=0$, 1, 2, 3, etc. is the electron Landau-level number, and the zero in the brackets labels the lowest localized hole state. Transitions between the $N_e>0$ electron Landau levels and the localized hole level are made allowed by the disorder in the system.[29] Only transitions from the lowest hole level are observed due to thermalization to this state at the sample temperature of 4.2 K.

Spectra from 3.1 to 9.6 T were reported in Ref. 29, and from 10 to 19 T are shown in Figs. 3(a) to 3(e). The variation of the transition energies with magnetic field is summarized in Fig. 4. With increasing magnetic field, successive electron Landau levels depopulate as the inter-Landau-level separation ($\hbar\omega_c=\hbar eB/m_{\rm BE}^*$) and the Landau-level degeneracy ($2eB/h$ including spin) increase with field. The carrier density in the QW of 9.2×10^{11} cm^{-2} is deduced from the fields (9.55 and 19.1 T) at which the $N_e=2$ and 1 Landau levels depopulate, at filling factors of $\nu=4$ and 2, respectively. No spin splittings are resolved at any magnetic field.[29] The splittings between the various $(N_e,0)$ transitions correspond to an electron effective mass of $0.049m_0$, as mentioned in Sec. III A. The shift rate of the (0,0) transition is equal to one half of the (1,0)-(0,0) splitting of $\hbar eB/m_{\rm BE}^*=\hbar\omega_c^{\rm electron}$, to within experimental error ($\pm2\%$). The (0,0) shift rate is therefore equal to $\frac{1}{2}\hbar\omega_c^{\rm electron}$. Thus the shift rate of the recombining hole level with field is negligibly small, consistent with the strongly localized nature of the hole state, as discussed above.

Two features are noteworthy in the variation of the $(N_e,0)$ transition energies with field. First we observe oscillations of the $(N_e,0)$ transition energy, for N_e filled, about the linear variation indicated by the full lines of Fig. 4.[30] These oscillations arise either from variations in the exchange and correlation energy with Landau-level filling factor (minima are observed at odd ν),[31] or possibly from oscillations in the self-consistent potential with filling factor.[32] Second, when the parent Landau level begins to depopulate, e.g., $N_e=2$ above $\nu=6$ (6.35 T), $N_e=1$ above $\nu=4$ (9.55 T), the energies of the transitions deviate below the straight line variation expected in an ideal single-particle picture. This effect was reported up to 9.6 T in Ref. 29, and attributed principally to the shift arising from the sweeping of the Fermi level through the broadened LL density of states with reducing filling factor. However, a contribution to the shift from the stronger excitonic effects expected for partially filled LL's (Ref. 33) cannot be excluded.

The main interest of the present paper is in the satellite transitions which are observed to lower energy below the (0,0) transition in Figs. 3 and 4. As for sample A, both LO-phonon satellites and T_n ($n=1$ and 2), shake-up satellites are observed. GaAs-like 33-meV satellites (0_L, 1_L, 2_L, . . .) replicate the well-resolved (N_e, 0) transitions, together with a two-phonon satellite 0_{2L} of (0,0). In addition, a 43-meV satellite of (1,0) is observed, labeled 1_A in Figs. 3 and 4. This satellite probably arises from the InP LO mode of the barrier. However, its strength, approximately equal to that of the 1_L GaAs LO-phonon satellite [see, e.g., Fig. 3(b) at 13 T, where both satellites are visible) is surprising. This is particularly so in view of the relative coupling strengths observed for the low-density 150-Å-wide QW sample of Fig. 2, where the GaAs-like mode is ~7 times stronger than the InP barrier phonon. A similar ratio of coupling strengths (GaAs:InP ~7:1) is also observed for low-doped QW's of the same width as sample B (100 Å). The relatively great strength of the 1_A mode in Fig. 3 does raise some doubt as to its identification as an InP LO satellite. However, the fact that its energy of 43 meV is exactly that of a LO phonon in InP makes its attribution to a barrier phonon very likely. That the 1_A line is a satellite of (1,0) is shown very clearly by inspection of Figs. 3(c) and 3(d). As the ($N_e=1$) level depopulates toward $\nu=2$ at 19.1 T, the (1,0) transition becomes progressively weaker, decreasing in intensity from 15 to 17 T by a factor of ~3. The 1_A satellite in turn decreases in intensity by 3.7 over the

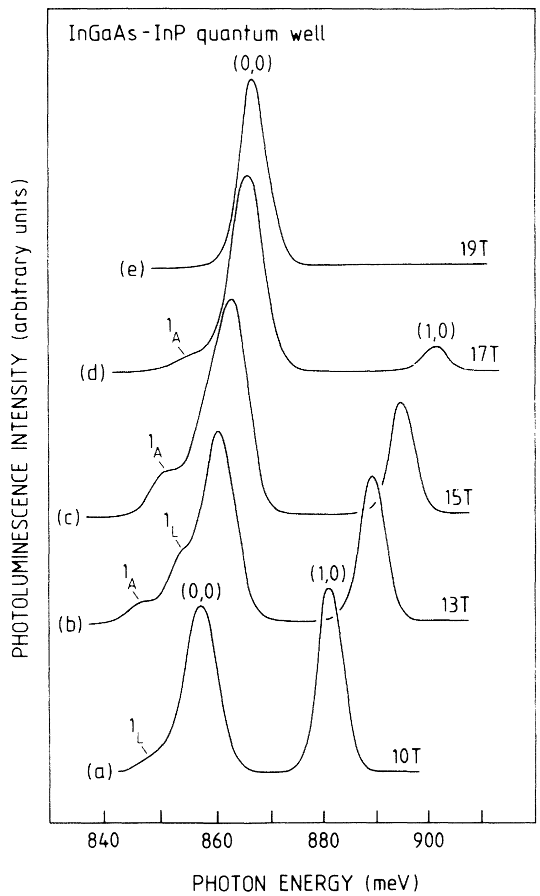

FIG. 3. PL spectra at 4.2 K as a function of magnetic field for sample B with $n_s=9.2\times10^{11}$ cm^{-2} at 10, 13, 15, 17, and 19 T in (a)–(e), respectively. The spectra at 17 and 19 T are divided in relative intensity by a factor of 1.4 relative to the spectra at lower field. At 10 T, both (0,0) and (1,0) transitions are observed. With increasing field (1,0) decreases in intensity until the quantum limit ($\nu\approx2$) is reached at 19 T, and only (0,0) is observed. Both 1_L and 1_A phonon satellites of (1,0) are seen, enhanced in intensity by resonant interaction with (0,0) in (b) and (c). When the (1,0) intensity is weak at 17 T due to $N_e=1$ depopulation, 1_A is also weak, showing clearly that it is a satellite of (1,0).

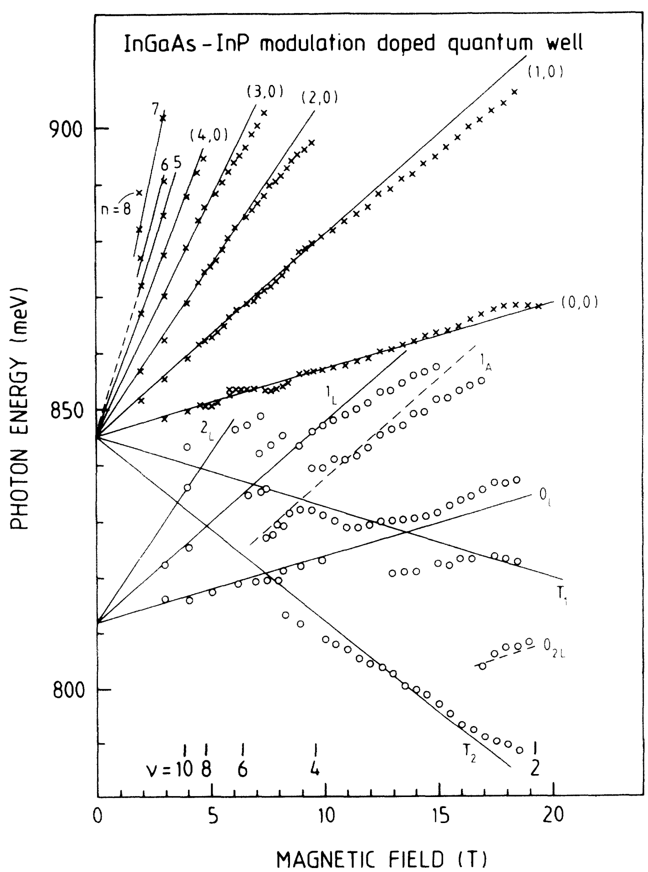

FIG. 4. Transition energies against magnetic field for sample B with $n_s=9.2\times10^{11}$ cm^{-2}. Landau-level filling factors are marked at the bottom of the diagram. Resonant anticrossings between the (0,0) transition and the 1_L and 1_A phonon satellites, and between the 0_L phonon satellite and the T_1 shake-up satellite are clearly visible.

same field range, and is unobservably weak at 19 T, when the $N_e = 1$ level is nearly depopulated [Fig. 3(e)], thus providing strong evidence that the 1_A transition is indeed a satellite of (1,0).

Clear evidence for resonant interaction between the T_1 shake-up satellite and the O_L phonon satellite is seen in Fig. 4 from 13 to 18 T in the 820–835-meV region. Representative satellite spectra plotted as a percentage of the intensity of the (0,0) transition are shown in Fig. 5. It is seen that the 0_L and T_1 satellites have 1–2 % of the intensity of (0,0), the relatively great strength of the satellites arising due to the strong hole localization in this sample. Marked anticrossing between the magnetoplasmon (shake-up) and LO-phonon lattice excitations is observed in Fig. 4 in the 13–18-T field region, with a splitting at resonance of 9 meV. This behavior is very similar to that reported for $Al_xGa_{1-x}As$-$In_xGa_{1-x}As$-GaAs modulation-doped structures in Ref. 3, where a splitting of the 1_L and T_1 modes at resonance of 8 meV was observed. The smaller effective mass in $In_{0.53}Ga_{0.47}As$ ($0.049m_0$) than in $In_{0.09}Ga_{0.91}As$ ($0.07m_0$) leads to larger inter-Landau-level separations, at a given magnetic field, with the result that the O_L-T_1 fundamental resonance is observed at 13–18 T, whereas for the strained-layer QW's of Ref. 3 the O_L-T_1 resonance would be expected outside the easily accessible field range, at $B > 21$ T. A small reduction in the fields of the O_L-T_1 interaction also occurs since the GaAs-like LO-phonon energy is 33 meV in the $In_{0.53}Ga_{0.47}As$-InP structures, as opposed to 36 meV in the $Al_xGa_{1-x}As$-$In_{0.09}Ga_{0.91}As$-GaAs samples.

Resonant interaction between the 2_L, 1_L, and 1_A satellites and the (0,0) transition is also observed. This is observed as a resonant repulsion of the satellites by (0,0) in Fig. 4.[34] In addition, there is a marked enhancement of the satellite intensities as they approach the energy of the (0,0) transition. The enhancements are clearly seen for 1_L and 1_A in Figs. 3(b) and 3(c) at 13 and 15 T, respectively. The enhancements of satellite intensity are shown more clearly in Fig. 6, where the intensities of the 1_L and 1_A satellites, relative to the parent (1,0) intensity, are plotted (the triangles and circles) as a function of the energy separation from (0,0). Plotting the 1_L, 1_A intensities relative to that of (1,0) provides a reliable correction for the decreasing $N_e = 1$ population through the magnetic-field region of relevance from 11 to 17 T.

A strong increase of the $1_L/(1,0)$ and $1_A/(1,0)$ ratios is observed as the satellites approach the energy of the (0,0) transition with increasing magnetic field. Away from resonance with (0,0), the phonon satellites of (1,0) have ~2% of the intensity of their parent recombination line. The ratios increase to 16 and 28%, respectively, before the lines are no longer observable at high field. 1_L is not observable above 14 T when it becomes unresolved from (0,0), whereas 1_A is not observable above 17 T due to depopulation of the $N_e = 1$ state.

The enhancements of 1_L and 1_A as they approach the energy of (0,0) are strongly reminiscent of the resonant

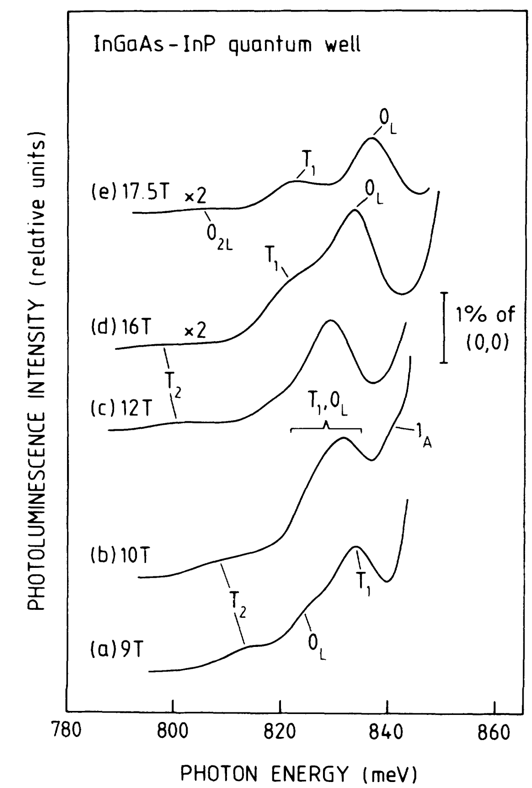

FIG. 5. Shake-up and LO-phonon satellites at magnetic fields of 9.6, 10, 12, 16, and 17.5 T in (a)–(e) for sample B. The vertical bar represents 1% of the intensity of the (0,0) transition.

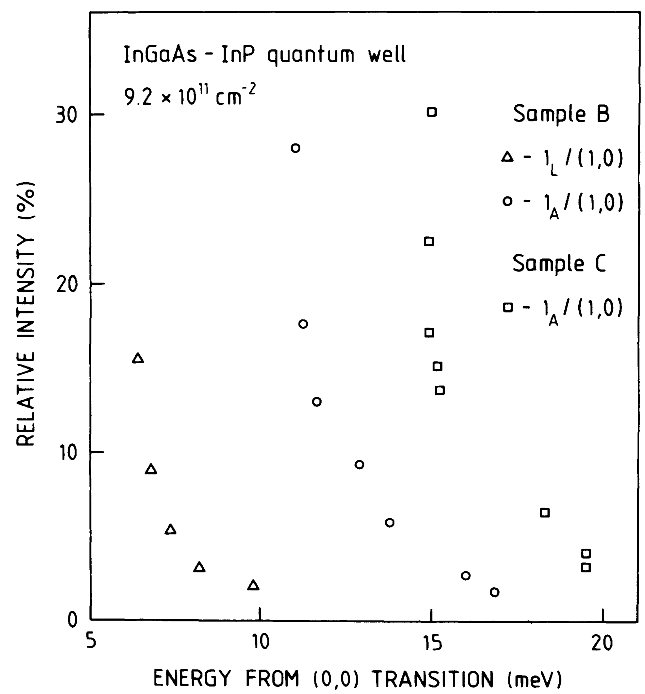

FIG. 6. Intensities of 1_L and 1_A phonon satellites (33- and 43-meV phonons, respectively) relative to the intensity of the (1,0) parent line as a function of the energy separation from (0,0). Triangles and circles represent 1_L and 1_A for sample B, and the squares 1_A for sample C.

enhancements of satellite intensity due to mixing with (0,0) which have been observed for $Al_{0.23}Ga_{0.77}As$-$In_{0.09}Ga_{0.91}As$-Gas modulation-doped QW's,[35] and which were ascribed to mixing of hole quasiparticles, by the Fröhlich interaction, in the (0,0) and N_L final states of the PL recombination. As for the T_1-O_L interactions described above, this resonance occurs in the final state of the recombination since, e.g., in Fig. 6 the 1_L and (0,0) transitions are only in near degeneracy after emission of the LO phonon in the 1_L transition.[35] In Ref. 35, the N_L-(0,0) interaction was observed as a resonant anticrossing and an exchange of intensities between the two recombination lines, as the magnetic field was swept through the resonance region.

For the samples studied in Ref. 35 the N_L lines which interacted with (0,0) were satellites of filled Landau levels, and so both transitions could be observed for magnetic fields on either side of the resonance value. In the present case, the 1_L and 1_A lines are satellites of the partially filled $N_e=1$ Landau level, and can be observed only at magnetic fields below the resonance value, because the $N_e=1$ level empties at a magnetic field lower than that required for resonance.

Within the resonant mixing model,[35] the behavior of Fig. 6 would imply a much stronger resonant interaction of 1_A with (0,0) than that of 1_L with (0,0); stronger resonant mixing would explain why the 43-meV satellite of (1,0) is so strong relative to the 33-meV satellite in sample B, whereas for sample A the 43-meV InP satellite of the (0,0) zero-phonon line is seven time weaker than the 33-meV GaAs satellite of the zero-phonon line. However, such a greater coupling strength for a 43-meV phonon relative to a 33-meV phonon is very difficult to explain within conventional models of the Fröhlich interaction.

A particularly striking feature of Fig. 6 is that the 1_A satellites have approximately equal intensity to the 1_L-GaAs satellites, at energy separations from (0,0) which are approximately 11 meV greater than those of 1_L. This energy is nearly equal to the energy difference between the 43 meV (1_A) and 33 meV (1_L) satellites, and implies that at a given magnetic field the two satellites have nearly equal intensity. This is seen, for example, by inspection of Fig. 3(b) at 13 T, and more clearly in Fig. 7 where $1_L/(1,0)$ and $1_A/(1,0)$ intensity ratios are plotted as a function of magnetic field. It is seen that the 1_L and 1_A intensity ratios increase in a very similar way with increasing magnetic field.

The behavior of 1_L is at least qualitatively consistent with the resonant polaron coupling model of Ref. 35. It is the 1_A line which is particularly anomalous; it is enhanced in strength at an unexpectedly large energy separation from (0,0), and is approximately equal in strength to 1_L over a range of magnetic fields. The observations mentioned in the preceding paragraph suggest that the magnetic field, or a property which is strongly magnetic field dependent, also contributes to the strong enhancements of satellite intensity between 12 and 16 T. The filling of the $N_e=1$ Landau level varies very strongly over this field range. The $N_e=1$ LL is full at $\nu=4$ at 9.55 T and empty at $\nu=2$ at 19.1 T. The resonant polaron coupling[35] is expected to be proportional to the number of hole scattering states which is proportional to $(\nu-2)$, which decreases with increasing magnetic field. This factor is proportional to the (1,0) intensity by which the data of Fig. 7 are divided before plotting. Figure 7 suggests in addition a separate factor, proportional to the number of electron-scattering states [proportional to $(4-\nu)$, the number of unoccupied electron states] which increases with increasing magnetic field. However, the dependence on the number of electron-scattering states does not appear to have a simple explanation within the theory of resonant polaron coupling since processes involving empty states in the $N_e=1$ Landau level are not expected to contribute to the resonant interaction at low temperature.[35]

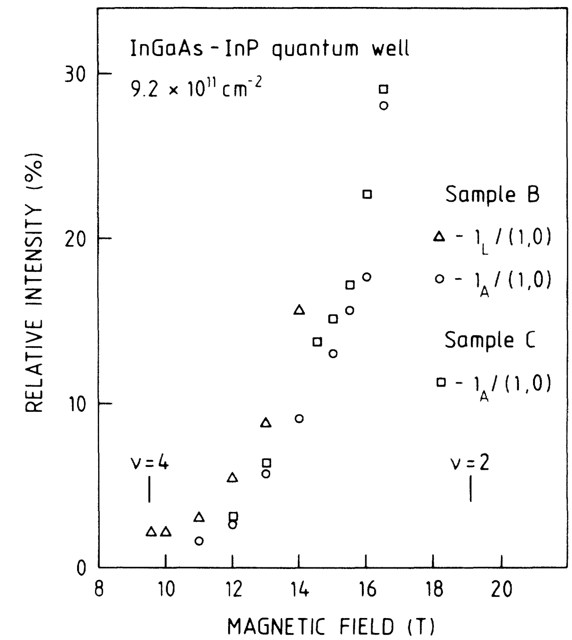

FIG. 7. The $1_L/(1,0)$ and $1_A/(1,0)$ intensity ratios of Fig. 6, but plotted as function of magnetic field, and hence Landau-level filling factor. As for Fig. 6, triangles and circles represent $1_L/(1,0)$ and $1_A/(1,0)$ for sample B, and the squares $1_A/(1,0)$ for sample C. The $N_e=1$ parent Landau level is full at $\nu=4$ at 9.55 T, and empty at $\nu=2$ at 19.1 T. The fields at which $\nu=4$ and 2 are the same for the two samples. The good agreement between the three ratios when plotted as a function of field suggests that the Landau-level filling plays an important role in determining the magnitude of the enhancement of satellite intensity.

To summarize this point, the reason for the strong enhancements of 1_L and 1_A intensities as they approach (0,0) remains unclear. A full theory for the interaction between the phonon satellite of a nearly empty Landau level and the transition arising from the filled $N_e=0$ level is needed before definitive statements can be made. Nevertheless, the nearly equal intensities of the 33- and 43-meV satellites of (1,0) observed at a given magnetic field suggest that the filling of the parent $N_e=1$ Landau level plays an important role in determining the coupling strength to the (0,0) transition. Similar results for the $1_A/(1,0)$ ratio as a function of magnetic field are also shown in Fig. 7 for sample C (the squares), and are seen to be in good agreement with the sample B results. This is consistent with the suggested importance of LL filling in determining the satellite intensities, since the carrier density, and hence LL filling with field, is very similar for this sample.

C. Sample C, $n_s = 9.2\times10^{11}$ cm^{-2}

Sample C has very similar carrier density to sample B, but much lower disorder, and hence hole localization, in the QW. Its PL spectrum at $B=0$ is shown in Fig. 8(a). It peaks in intensity at 866 meV and then decreases in intensity toward the electron Fermi energy at E_F. Its PL spectrum is very similar to that reported for the $Al_xGa_{1-x}As$-$In_xGa_{1-x}As$-GaAs QW's of Refs. 2 and 3, and is typical for a QW with low disorder containing a high density of free carriers. The low-energy peak at 866 meV corresponds to allowed $\Delta k=0$ electron-hole recombination, and then decreases in intensity toward $k_F=2.4\times10^6$ cm^{-1} as the transitions become increasingly forbidden due to the requirements of wave-vector conservation. It is only in the case of strong hole localization in real space, corresponding to a hole wave function containing large Fourier components of the order of k_F, that recombination at k_F is probable. This is the situation for sample B. For sample C, the PL intensity decreases strongly toward E_F, consistent with weak hole localization in this case.

In magnetic field the spectrum breaks up into a series of $(N_e,0)$ Landau-level transitions, as shown in Figs. 8(b), 8(c), and 8(d) at 9.6, 14, and 18 T, respectively. Both phonon and shake-up satellites are observed in Figs. 8(b) and 8(c), and are shown in more detail in Fig. 9. The variation of the transition energies of all the observed transitions as a function of magnetic field is shown in Fig. 10. Landau-level filling factors are marked on Fig. 10, determined from Landau-level depopulation as described for sample B in Sec. III B.

The behavior of the $(N_e,0)$ Landau-level transitions in

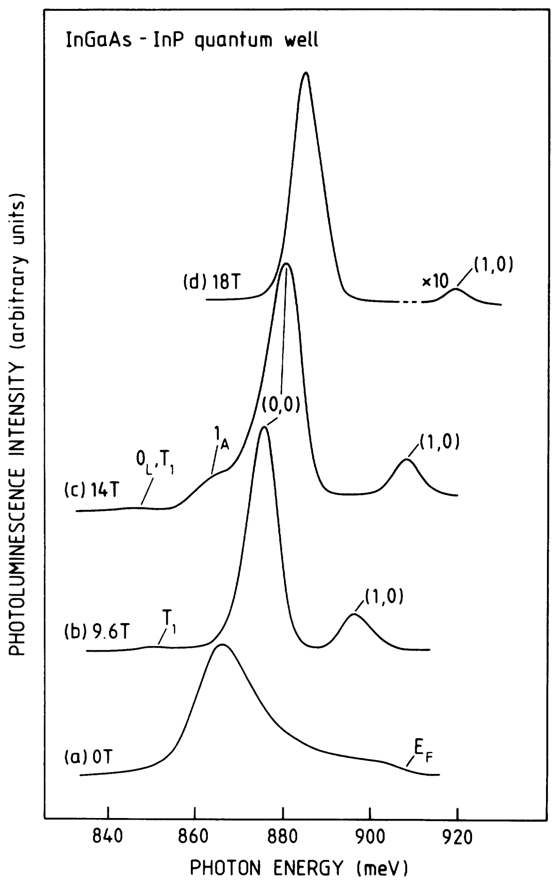

FIG. 8. PL spectra at $B=0$, 9.6, 14, and 18 T in (a), (b), (c), and (d) for sample C at 4.2 K. The PL spectrum in this sample of low disorder peaks on the low-energy side, as opposed to that for sample B which shows a strong Fermi-energy edge singularity at E_F. Consistent with the low disorder, the $\Delta N\neq0$ Landau-level transitions are weak compared to the allowed (0,0) transitions. 1_A and 0_L phonon satellites, and T_1 shake-up satellites are visible to lower energy in (b) and (c).

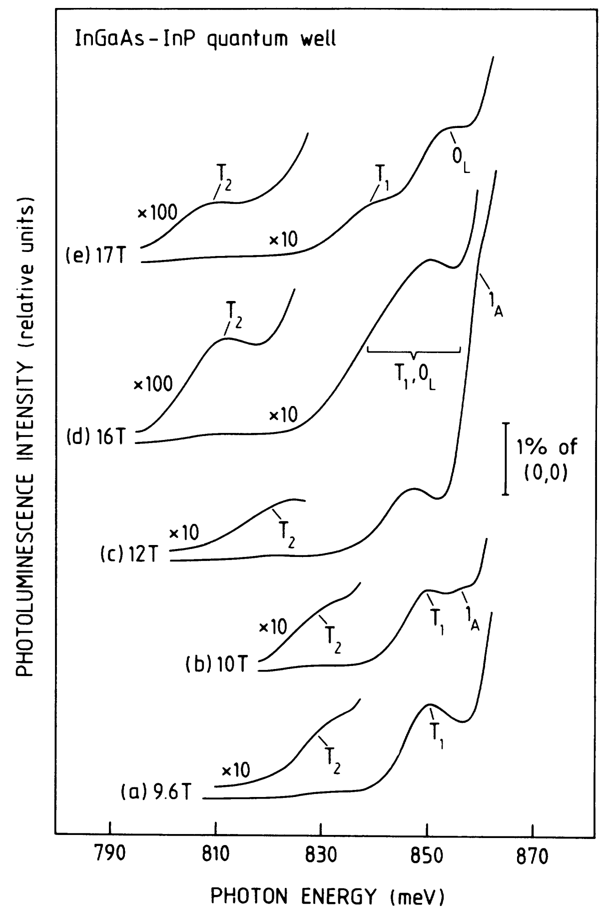

FIG. 9. Expanded spectra in the satellite region for sample C at magnetic fields of 9.6, 10, 12, 16, and 17 T in (a)–(e), respectively. The vertical bar represents 1% of the intensity of the (0,0) transition. It should be noted that the spectra at 16 and 17 T are roughly an order of magnitude weaker than those at lower field.

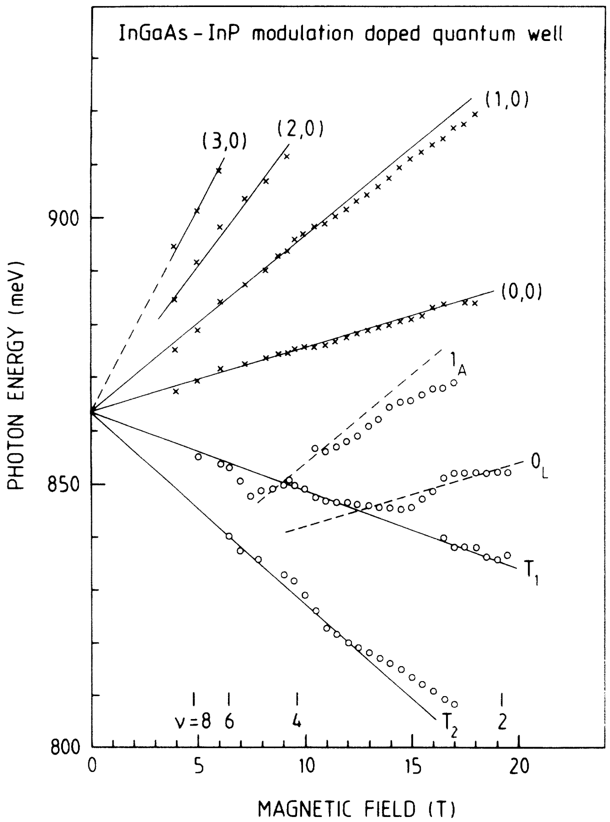

FIG. 10. Transition energies against magnetic field for sample C. Splitting of the PL spectrum into $(N_e,0)$ Landau-level transitions is observed. To lower-energy 1_A satellites, enhanced by resonant interaction with (0,0), T_1 and T_2 shake-up satellites, and 0_L phonon satellites are observed. By comparison with sample B in Fig. 4, GaAs-like LO-phonon satellites are much less prominent, 1_L being absent, and 0_L probably only observed by resonant mixing with T_1 at high field.

magnetic field is similar to that reported in Fig. 4 for sample B. The Landau-level splittings at a given magnetic field are ~15% less than for sample B, and correspond to an electron effective mass of $m^*_{\rm BE}=0.057m_0$. The reasons for this higher effective mass ($0.057m_0$ compared to $0.049m_0$) are not understood since the transition energies, and hence alloy compositions in the two samples, are very similar. As for sample B in Fig. 4, the (0,0) transitions in Fig. 10 show oscillations in energy as a function of filling factor, and deviation of the (1,0) energy below a linear variation when the $N_e=1$ level is partially filled.

The shift rate of the (0,0) transition with field is 0.56 of the (1,0)-(0,0) splitting $\hbar eB/m^*_{\rm BE}$, as opposed to 0.50 of the (1,0)-(0,0) splitting for sample B. The greater shift rate of the (0,0) transition is indicative of a finite shift rate of the recombining hole level with field for sample C(this was zero for sample B), consistent with the weaker hole localization for sample C. An apparent hole effective mass of $0.48m_0$ for the localized hole state is deduced from the observed (0,0) shift rate with field. No evidence for hole LL splittings is observed, due to thermalization to the $N_h=0$ level at the sample temperature of 4.2 K.

The most interesting difference in the spectra compared to those of sample B is found in the satellite region and is that the GaAs LO-phonon satellites are observed to be much weaker than for sample B. For this reason and also because the inhomogeneous broadening of the PL is larger in sample C than in sample B, the 1_L phonon satellites are never resolved, and 0_L is only seen in the region of interaction with T_1 above 14 T. The intensities of 0_L relative to (0,0) at 17 T for the two samples are 0.5% (sample B) and 0.05% (sample C), respectively. As discussed in Secs. III A and III B and in Refs. 1, 8, and 9, the strength of the phonon coupling is related to the degree of hole localization and hence disorder in the system. As already deduced from the form of the $B=0$ PL spectra, sample C has much weaker disorder and hole localization than sample B, and thus the weaker phonon coupling is not unexpected.

Most strikingly, however, in the interaction regime with (0,0), the 1_A satellite of (1,0) is observed with very similar intensity relative to its parent (1,0) transition to that in sample B.[36] It shows a very similar repulsion from (0,0) (see 10–17-T region in Fig. 10, compared with the same field range in Fig. 4), although its energy separation from (0,0) at any given magnetic field is about 5 meV greater than in sample B. The greater energy separation arises since the (0,0) to (1,0) separation is smaller in sample C due to the larger value of $m^*_{\rm BE}$ ($0.057m_0$ compared to $0.049m_0$). As a result the 43-meV satellite of (1,0) will be at a greater energy from (0,0). The intensity ratio of the 1_A satellite to that of its parent line (1,0) is plotted as a function of its energy separation from (0,0) in Fig. 6 (the squares), and as a function of magnetic field in Fig. 7. As discussed in Sec. III B, the good agreement between the intensity ratios for the 1_L, 1_A satellites investigations in sample B, and for 1_A in sample C, when plotted as a function of magnetic field, suggests that Landau-level filling plays an important role in determining the strength of the enhancement of the $N_e=1$ satellites.

One consequence of the relative weakness of the GaAs-like LO-phonon satellites in sample C is that the shake-up satellites are observed more clearly, particularly in the 10–13 T anticrossing region. The strengths of the T_1 satellites of Figs. 9(a) and 5(a), at 9.6 and 9 T, respectively, are comparable [0.6 and 1.2% of (0,0)], respectively. In the case of sample C, T_1 may gain intensity by mixing with 1_A, and for sample B by mixing with 0_L also. The fan diagrams of Figs. 4 and 10 and the spectrum of Fig. 9(b) show that the T_1, 1_A, and 0_L lines are closely interacting in the field region around 10 T. With increasing field for sample C, the T_1 and T_2 satellites become much weaker. At 17 T, the T_1 satellite has only 0.03% of the intensity of (0,0), with 0_L having a similarly low intensity.

By contrast, for sample B, the 1_L and 0_L LO-phonon satellites are relatively strong over the whole field range (see Figs. 3 and 5) due to the strong hole localization in this sample. At high field the T_1 satellites are probably observed strongly in sample B due to resonant mixing with the phonon satellites. T_1 has 0.25% of the intensity of (0,0) at 17 T due to mixing with 0_L, compared to 0.03% in sample C where 0_L is very weak.

IV. CONCLUSIONS

A photoluminescence study of $In_{0.53}Ga_{0.47}As$-InP quantum wells in high magnetic fields up to 20 T has been reported. Results for three samples, one containing 1.5×10^{11} cm^{-2} free electrons, and the other two containing 9.2×10^{11} cm^{-2} electrons, have been presented. One of the high-density samples has strong disorder and strong hole localization, and the other weak disorder and weak hole localization. These carrier densities in all the samples studied are sufficiently high that many-body interactions play a very important role in determining the form of the observed magneto-PL spectra.

In quantizing magnetic field, a number of low-energy satellites of the principal Landau-level transitions are seen, arising from different final-state excitations of the system. In the recombination process both lattice (LO-phonon) or Fermi-sea (inter-Landau-level shake-up) excitations can be emitted, and lead to the low-energy satellites observed in the magneto-PL spectra. When the energies of the two final states in which either LO-phonon or shake-up excitations are emitted, become close in energy, clear resonance anticrossing between the satellites is observed. Such mixing between the LO-phonon and shake-up excitations is observed for all three samples investigated.

The strength of the coupling to both types of excitation is enhanced by the degree of localization of the photocreated hole which participates in the recombination. This is shown particularly clearly in the comparison of the satellite spectra for the two heavily doped samples, one with strong and one with weak hole localization. At high magnetic field, the satellite spectra are at least an order of magnitude stronger for the sample with strong hole localization. In the heavily doped sample with weak disorder, the phonon satellites of the lowest-energy Landau-level transition are very weak, and are only observed in the field region of resonant mixing with the principal shake-up satellite.

Resonant anticrossing between the phonon satellites of the $N_e=1$ Landau level and the lowest-energy (0,0) transition is observed for the two heavily doped samples. Strong enhancements of intensity of the satellites are observed through this field range. The enhancements are of similar magnitude for the GaAs-like 33-meV phonon satellites of the quantum well and for the 43-meV phonons of the InP barrier material at a given magnetic field. This behavior is surprising since the 43-meV barrier satellites are 10 meV further away in energy from (0,0) than the 33-meV well satellites. Although this behavior is not fully understood, it is suggested that Landau-level filling which depends only on magnetic field, as well as the energy separation from the interacting (0,0) level, plays an important role in determining the resonant enhancements of the $N_e=1$ phonon satellite intensities.

Interactions between the T_n satellites and LO-phonon satellites, and perhaps the origin of the 1_A satellite, could be examined in a theory that gives a unified treatment of the electron-phonon and electron-electron interactions: such a method has been used, for example, to study coupled plasmon-phonon modes in quantum wells.[23,24] In contrast, our simple theory of the shake-up satellites presented in Sec. III A ignores the electron-phonon interaction, and so can only be applied to the shake-up satellites at low B in the low-density sample: at low B, the T_1 energy is well below the LO-phonon energies, and so interactions of this shake-up satellite with the LO-phonon satellites of the same principal PL line are expected to be weak. Furthermore, in the low-density sample, in contrast to the high-density samples, no complications arise from the interaction of T_1 with the phonon satellites N_L of higher Landau levels. A theory of the high-density samples, or of the low-density sample at high magnetic fields, will require the unified treatment of electron-electron and electron-phonon interactions mentioned above.

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