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Longitudinal-optical phonon and shake-up excitations in the recombination spectra of semiconductor quantum wells

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The observation of both LO-phonon and inter-Landau-level magnetoplasmon shake-up excitations in the magnetophotoluminescence spectra of quantum wells containing high densities of free carriers is reported. The inter-Landau-level magnetoplasmon excitations occur at energies greater than the bare Landau-level separations, in agreement with the predictions of many-body theory. Clear evidence for LO-phonon–magnetoplasmon coupled-mode behavior is observed.

The recombination of a high-density electron gas with photocreated minority carrier holes can lead to a number of different final-state excitations of the system. For example, in semiconductor quantum wells (QW's) with which this paper is concerned, longitudinal-optical- (LO) phonon lattice excitations[1–3] and Fermi-sea particle-hole pair shake-up excitations[4] have both been reported in the last few years.[1,2,4] For metals, both phonon and shake-up excitations have been discussed to explain the observation of asymmetric line shapes in x-ray photoemission spectra, in addition to the observation of collective-mode plasmon satellites.[5] For bulk semiconductors the observation of a plasmon satellite in photoluminescence (PL) spectra has also been suggested.[6]

The present work reports the observation of both LO-phonon satellite and shake-up satellite recombination in the magneto-PL spectra of $Al_yGa_{1-y}As$-$In_xGa_{1-x}As$-GaAs modulation-doped QW's. In magnetic field the conduction- and valence-band densities of states are quantized into discrete Landau levels (LL's). The use of magnetic field is critical for the observation of the LO-phonon and shake-up excitations in high-density systems since the otherwise broad PL spectrum then breaks up into discrete peaks. As a result both the lattice and Fermi-sea processes give rise to a series of discrete peaks to lower energy, thus permitting spectroscopic study of the various excitations.

It has been shown previously that the strength of both the LO-phonon[1,2] and shake-up satellites[4] increases with the localization of the photocreated holes in the system. The hole localization is determined by the disorder in the structure. The present samples are of high perfection with relatively weak disorder. Nevertheless both the lattice LO-phonon and Fermi-sea shake-up excitations are observed weakly in the spectra. Clear effects of interaction between the shake-up and LO-phonon satellites are observed as the magnetic field is varied.

The experiments were carried out at 4.2 K on a series of modulation-doped, pseudomorphic strained-layer $Al_yGa_{1-y}As$-$In_xGa_{1-x}As$-GaAs QW's ($y \approx 0.23$, $x \approx 0.10$) with electron densities in the range $(7–10) \times 10^{11}$ cm^{-2}.[7,8] Attention is concentrated on a particular sample with $n_s = 7.2 \times 10^{11}$ cm^{-2}, and well width 150 Å. PL was excited by 25 mW/cm^2 of 633-nm radiation from a He-Ne laser.

The PL spectrum from the sample with $n_s = 7.2 \times 10^{11}$ cm^{-2} at $B = 0$ is shown in Fig. 1(a). It shows a peak at 1.417 eV together with a long tail to higher energy. The electron Fermi energy E_F (25.4 meV) is marked on the spectrum, corresponding to $n_s = 7.2(\pm 0.2) \times 10^{11}$ cm^{-2} for an electron effective mass of $0.068m_0$.[7] The PL intensity falls off very rapidly from its peak at 1.417 eV with only a very weak feature at E_F. This is characteristic of a QW of low disorder with electron-hole recombination being fully allowed only for vertical transitions close to $k = 0$.[9,10] Transitions from electrons in states up to $k_F \approx 2 \times 10^6$ cm^{-1} are observable due to the residual disorder which breaks translational symmetry and permits weakly $\Delta k \neq 0$ transitions; the finite temperature of the photocreated holes (20–25 K) also permits $k \neq 0$ transitions.[11]

In Figs. 1(b) and 1(c) at 4.1 and 9.4 T, respectively, the PL spectrum breaks up into a series of LL transitions, labeled (N_e, N_h) arising from recombination between electrons and holes in LL's of index N_e and N_h, respectively. The dominant transition (0,0) arises from electrons and holes in the lowest-energy states. Both Landau quantum-number-allowed ($N_e - N_h = 0$) and nominally forbidden $N_e - N_h = +1, +2$ transitions are observed to higher energy. Transitions such as (1,1),(2,2) arise due to the weak thermal population of $N_h = 1,2$ levels.[11] The $(N_e, 0)$ ($N_e > 0$) transitions are allowed by the weak disorder for the same reasons that $\Delta k \neq 0$ transitions are allowed at $B = 0$.[12,13]

The transition energies are plotted in Fig. 2 as a function of magnetic field. The energy spacing between the $(N_e, 0)$ peaks is given by the electron cyclotron energy $\hbar\omega_c = \hbar eB/m_e^*$, with $m_e^* = 0.068m_0$.[7,13] The splitting between (1,0) and (1,1), (2,0), and (2,1) is given by the hole LL splitting with $m_h^* = 0.15m_0$, as expected in a strained-layer $In_xGa_{1-x}As$ QW with $x \approx 0.1$.[13] LL filling

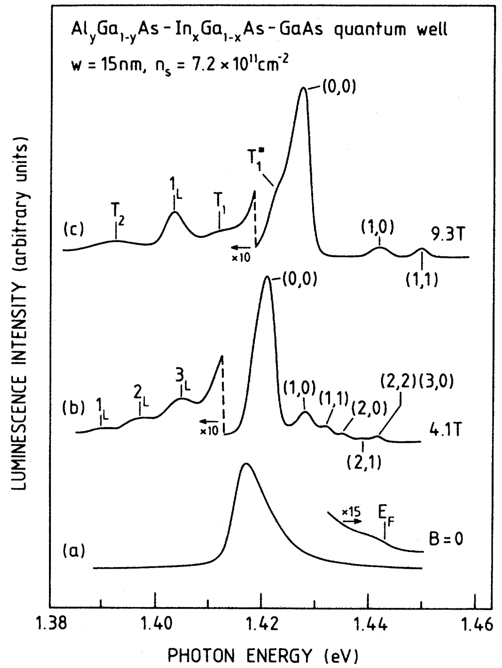

FIG. 1. PL spectra at 4.2 K for quantum well with $n_s = 7.2 \times 10^{11}$ cm^{-2}, at $B = 0$, 4.1, and 9.3 T. For $B = 0$ (a) a broad PL band arising from recombination of electrons in states from $E = 0$ up to E_F is observed. In finite B (b) and (c) the spectrum breaks up into Landau-level transitions labeled (N_e,N_h). To lower energy LO-phonon satellite (N_L) and shake-up excitations (T_n) are observed.

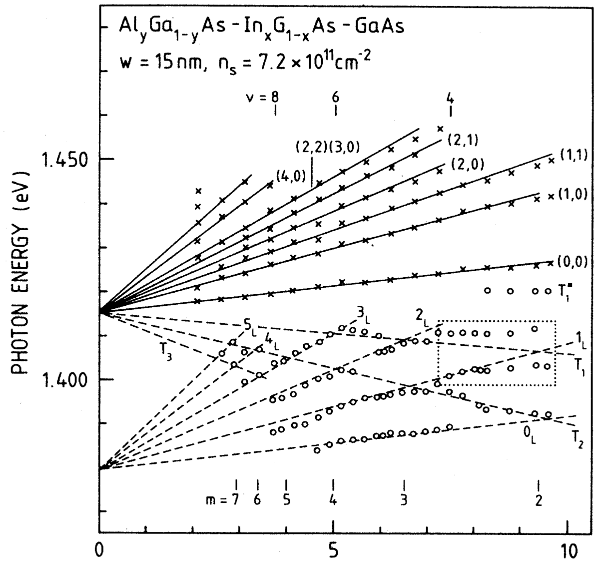

FIG. 2. PL transition energies against magnetic field for sample of Fig. 1. Transitions between electron and hole Landau levels (N_e,N_h) are indicated by crosses (full lines). To lower energy (open circles, dashed lines) LO-phonon satellites (N_L) and shake-up satellites (T_n) of the $(N_e,0)$ transitions are observed. Resonant coupling between the T_1 and 1_L satellites is seen in the boxed region between 7 and 10 T. Landau-level filling factor (ν) and magnetophonon resonance (m) indices are indicated.

factors (ν), including spin, are indicted on the figure.[14] No spin splittings are resolved.

To lower energy below the principal (0,0) transitions, a series of satellite lines N_L ($N_L = 0,1,2,\dots$) and T_n ($n = 1,2,\dots$), etc. is visible in Figs. 1(b) and 1(c) and in the fan chart of Fig. 2. The $(N_e,0)$ LL fan is replicated at 36 meV lower energy by the N_L satelites, in which a GaAs-like LO-phonon vibrational excitation of the QW material is emitted in the $(N_e,0)$ recombination. The allowed (N_e,N_h) recombination lines with $N_e = N_h$ ($N_e,N_h \geq 1$) show no evidence for LO-phonon satellite replication. For the present sample with E_F(25.4 meV) < $\hbar\omega_{LO}$(36 meV) the parent LL's of the N_L satellites depopulate before the N_L satellites are resonant with (0,0). As a result the resonant polaron anticrossing between the (0,0) and N_L final states, discussed in Ref. 7, is not seen.

The T_N satellites by contrast arise from the emission of Fermi-sea shake-up excitations. In the $(N_e,0)$ electron-hole recombination process an inter-LL magnetoplasmon excitation of the Fermi sea occurs in which an additional electron is promoted to a partly filled or empty LL. Since a Fermi-sea excitation is created in the shake-up, the T_n satellites occur to lower energy below $(N_e,0)$. Neglecting many-body interactions, the T_n peaks are expected at energies $\Delta N_e \hbar\omega_c^e$ below the $(N_e,0)$ recombination lines, where ΔN_e is the increase in Landau quantum number of the electron which is promoted to higher energy.

In contrast to the previously reported observation[4] of shake-up processes in a sample with low n_s where only the $N_e = 0$ LL was populated, a given T_n satellite in Figs. 1 and 2 can arise from a variety of inter-LL excitation processes. In Ref. 4, it was shown that the strength of the shake-up satellites falls off roughly linearly with the energy of the inter-LL excitation; a $\Delta N_e = 1$ excitation is significantly stronger than a $\Delta N_e = 2$ process. Thus the T_1 peak occurring fairly close to $\hbar\omega_c^e$ below (0,0) is very likely a $\Delta N_e = 1$ shake-up satellite of (0,0) [rather than a $\Delta N_e = 2$ satellite of (1,0)]. Since the $N_e = 1$ level is filled up to $\nu = 4$ at 7.4 T, the shake-up can only occur by inter-LL excitation between $N_e = 1$ and $N_e = 2$ (between $\nu = 6$ and 4), and between correspondingly higher LL's at lower magnetic field. The T_2 satellite is probably a $\Delta N_e = 2$ satellite of (0,0) with second electron promotion from $N_e = 0$–2, 1–3, or 2–4 depending on the LL filling factors.

Closer inspection of the energy separation of the T_1 satellite from (0,0) in Fig. 2 shows that it occurs at an energy ~ 1.25 times greater than the (0,0),(1,0) splitting of $\hbar\omega_c$. Such behavior is expected since in the correct many-body, magnetoplasmon description of inter-LL transitions the excitation energy is only equal to $\hbar\omega_c$ for magnetoplasmon wave vector $q = 0$.[15–17] The maximum in the magnetoplasmon density of states occurs for $q \sim 1/l_0$, where l_0 is the magntic length $(\hbar/eB)^{1/2}$, at energies $\sim 20\%$ greater than $\hbar\omega_c$ (at 7 T in GaAs).[18] Coupling to states at $q \sim 1/l_0$ (1.1×10^6 cm^{-1} at 7 T) is allowed by the weak disorder in the system,[4,17] and by the magnetoplasmon–LO-phonon coupling at the $T_n - N_L$ satellite resonances discussed later. By contrast with the

(0,0)-T_1 splitting, the T_2-T_1 separation is much closer to the (1,0)-(0,0)($\hbar\omega_c$) separation (see Fig. 2). This is expected from the theory of Ref. 15, where it is shown that the density-of-states maximum for $\Delta N_e = 2$ excitations is shifted above $2\hbar\omega_c$ by roughly the same energy as $\Delta N_e = 1$ is shifted above $\hbar\omega_c$, with the result that the T_2-T_1 separation is expected to be close to $\hbar\omega_c$, as observed. The shoulder on the low-energy side of (0,0) labeled T_1^*, occurring $\sim 1.30\hbar\omega_c$ below (1,0) [Figs. 1(c) and 2], is very likely a $\Delta N_e = 1$ satellite of (1,0), gaining intensity by resonant interaction with (0,0).

Expanded spectra in the satellite region at closely spaced magnetic fields are shown in Fig. 3, and in Fig. 4 the variation with field of the intensities of the N_L satellites, as a percentage of the intensity of the (0,0) zero-phonon line, is shown. Clear interaction between the N_L and T_n satellites is observed. In the absence of many-body effects with the inter-LL excitation energies equal to multiples of $\hbar\omega_c$, resonances between the N_L and T_n satellites will occur at magnetic fields given by the "magnetophonon" resonance (MPR) condition $m\hbar\omega_c = \hbar\omega_{\mathrm{LO}}$, where m (>0) is an integer.[19] Since the (0,0)-T_1 spacing is $\approx 1.25\hbar\omega_c$, the resonances are expected at

$$(m + 0.25)\hbar\omega_c = \hbar\omega_{\mathrm{LO}} \; . \qquad (1)$$

Magnetic fields corresponding to this modified MPR condition, for $m = 2$–7 are marked on Figs. 2 and 4.[20] At resonance the N_L and T_n excitations correspond to LO-phonon–magnetoplasmon coupled modes.[21,22] Resonant anticrossing between T_1 and 1_L is seen very clearly in Fig. 2 at the onset of the $m = 2$ resonance (the dotted, boxed region), with splitting between the two modes at resonance of 8 meV. It is worth noting that a splitting at resonance for LO-phonon–magnetoplasmon coupled modes of ~ 6 meV, reasonably close to our experimental findings, was calculated in Ref. 22 for an $\mathrm{In}_x\mathrm{Ga}_{1-x}\mathrm{As}$ heterojunction although at the lower n_s of 4×10^{11} cm^{-2}.

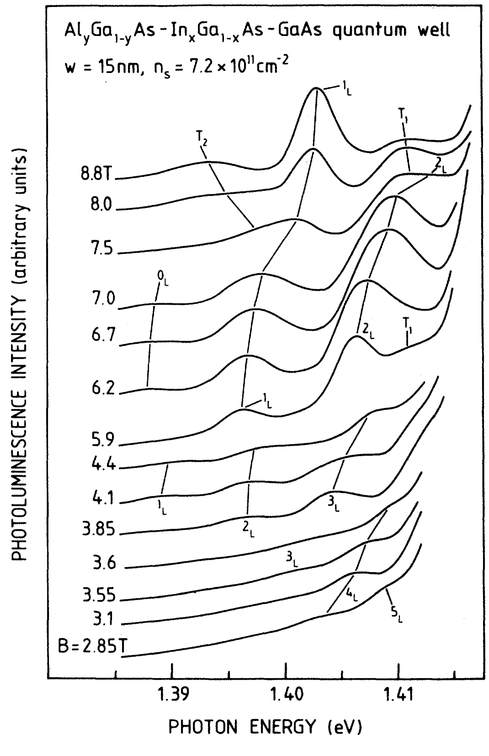

FIG. 3. Expanded spectra in the N_L, T_n satellite region between 2.85 and 8.8 T. The resonance enhancements of, for example, 4_L at 3.1 T, 3_L at 3.85 T, 2_L at 6.7–7.5 T, and 1_L from 7.5 to 8.8 T are clearly visible.

The variation of intensities of the N_L satellites with B is plotted in Fig. 4 as a percentage of the (0,0) intensity. A series of oscillations of satellite intensity is seen, with maxima occurring to a good approximation at fields given by Eq. (1) ($m = 7$ to 3), corresponding to the crossing points of N_L and T_n in Fig. 2. Several points should be noted. At fields beyond which the parent LL of an N_L satellite begins to empty (e.g., fields greater than $\nu = 6$ for the $N_e = 2$ parent LL of the N_L satellite), the N_L satellite intensities are expected to be reduced by the N_e depopulation with B. In field ranges where such depopulation effects are strong, dashed rather than solid lines are drawn through the experimental points of Fig. 4. Furthermore, it is only for fields above 5 T for T_1 and 7 T for T_2 that the T_n lines are resolved as separate features from N_L; at lower fields the intensities plotted, close to resonance, arise from unresolved T_n, N_L satellites.

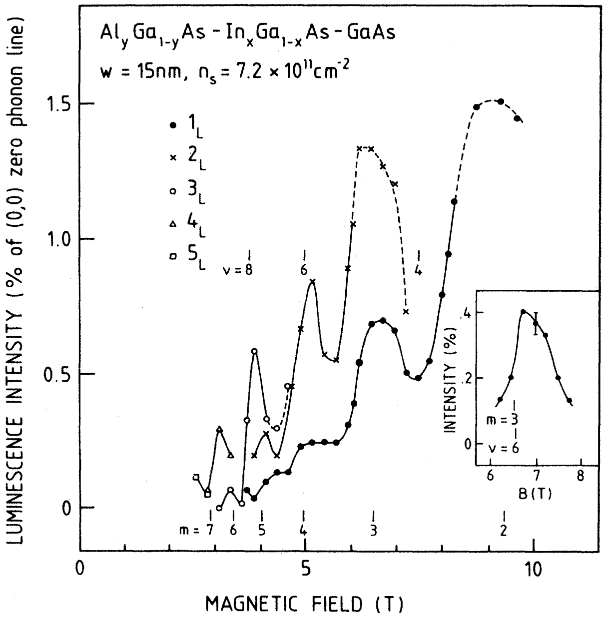

FIG. 4. Integrated intensities of the N_L satellite lines vs magnetic field for sample with $n_s = 7.2 \times 10^{11}$ cm^{-2}, as a percentage of the intensity of the (0,0) zero-phonon line. The lines drawn through the experimental points are guides to the eye. The lines are drawn dashed in magnetic-field regions where the N_L intensity is strongly reduced by Landau-level depopulation (e.g., 2_L beyond $\nu = 6$). For $B < 5$ T, T_n lines are not resolved from N_L. Good correlation of the intensity maxima with fields corresponding to N_L, T_n crossing (integer m values) is seen. The inset shows the variation of 1_L intensity with B in the region of $m = 3$ for the sample with $n_s = 9.5 \times 10^{11}$ cm^{-2}.

We suggest that the oscillations of satellite intensity arise from the mixing of the otherwise unperturbed LL's by the electron–LO-phonon interaction at the MPR condition. The mixing will give rise to increased inter-LL scattering at resonance.[23] This in turn will lead to enhanced shake-up satellite intensities, and hence magnetoplasmon–LO-phonon coupled-mode intensities, at fields close to integer m values, in agreement with the results of Fig. 4.

Variations in satellite intensity due to oscillations in screening with LL filling factor can be excluded as an explanation for the findings of Fig. 4. Very similar variations in N_L, T_n intensity with B have been found in a sample of the same design as that discussed in Figs. 1–4, but having 30% higher n_s ($n_s = 9.5 \times 10^{11}$ cm^{-2}). The LL's will hence depopulate at ~30% higher fields than those for the lower n_s sample. The variation of the 1_L intensity with B for this sample is shown in the inset to Fig. 4. Once again a peak in intensity close to an integer m value is observed, supporting the attribution of the intensity oscillations to T_n, N_L resonant interaction.

In conclusion, both LO-phonon and inter-Landau-level shake-up excitations have been reported in the magneto-PL spectra of QW's with high carrier density. Both $\Delta N_e = 1$ and $\Delta N_e = 2$ shake-up satellites were observed at energies close to the predictions of many-body theory for magnetoplasmon excitations in a high-density system. Clear evidence for LO-phonon–magnetoplasmon coupled mode behavior was observed. Very recently, Butov *et al.*[24] have reported experimental results which bear a number of similarities to those in the present paper. Most notably a clear observation of magnetoplasmon–LO-phonon coupled mode satellites in magnetoluminescence spectra is reported by these workers.

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