Millikelvin magneto-optical studies of two-dimensional hole systems

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We present magnetophotoluminescence (PL) investigations of a range of very high-mobility low-density two-dimensional hole systems in GaAs-$Al_{1-x}Ga_xAs$ quantum wells, obtained using excitation both above and below the $Al_{1-x}Ga_xAs$ band gap. At low two-dimensional hole densities, we observe two peaks at zero magnetic field and an analysis of the temperature and excitation-power dependences of these suggests that they originate from the recombination of neutral and positively charged excitons. At higher densities, the peaks evolve smoothly into a structure related to the two-dimensional hole density of states. Their intensity dependences and their evolution in magnetic field support this description. In high magnetic fields at low densities, we observe a new PL line at lower energy whose behavior is similar to PL features reported recently as being an optical signature of the magnetically induced hole Wigner solid. However, examination of the effects of illumination on hole density leads us to conclude that our observations are not associated with the Wigner solid. In the higher-density regime, we observe minima in the PL intensity and shifts in the PL energy at integer and fractional Landau-level filling factors, and a more complicated PL structure at very low filling factors. [S0163-1829(96)05243-5]

I. INTRODUCTION

Optical techniques constitute a powerful probe of the microscopic properties of systems of reduced dimensionality in the limit of low temperature and high magnetic field. There have been extensive studies of two-dimensional electron systems (2DES) in this regime and the optical signatures of the fractional quantum Hall effect (FQHE) (Refs. 1–3) and the magnetically induced Wigner solid (WS) (Refs. 4–6) have been reported. The techniques have proved particularly useful in studies of the WS because the strong localization that accompanies the WS transition makes conventional transport measurements very difficult. In contrast, only a few such studies have been reported in two-dimensional hole systems (2DHS's).[7–13] This is because of the significantly shorter scattering time in conventionally grown hole systems and the consequent weakening of the interaction between carriers. However, developments in the growth of p-type modulation-doped heterostructures, by molecular-beam epitaxy, on [311] A-oriented substrates[14] have recently given rise to unprecedentedly high mobilities in 2DHS's, and momentum relaxation times comparable to those of the best 2DES have been reported.[15,16] These advances have offered the exciting prospect of examining the 2D hole WS. The advantages of extending studies of the WS to hole systems have been discussed fully in the literature before (see, for instance, Ref. 13).

Photoluminescence (PL) studies have been carried out on 2DHS's in single heterojunctions[7] and in quantum wells (QW) (Refs. 8–13) of various widths. In single heterojunctions, the PL from the 2DHS is a weak feature superimposed on a background of bulk-exciton PL peaks whose intensity is observed to reach a maximum at Landau-level filling factor $\nu=1$. The feature was assigned to an excitonic process that provides a probe of the heterointerface. The same group has also undertaken PL investigations of a 300-Å QW (Ref. 8) in which the 2DHS PL peak is raised in energy by about 2.5 meV by the extra confinement and is therefore easier to distinguish from the bulk PL. A single line A is observed, at zero magnetic field, which shows excitonic dispersion in magnetic field and a distinct intensity minimum at $\nu=1$ (the filling factor determined by transport measurements performed in the absence of illumination). A new line, B, about 0.7 meV above A, emerges at $\nu=\frac{1}{2}$. A gradual decrease in the intensity of A as the field is further increased was correlated with the appearance of an out-of-phase component in the magnetoresistance. This dephasing effect indicates that the 2DHG is becoming highly resistive, and has previously been associated with WS formation. Butov *et al.*[9] have examined the PL of a 200-Å QW and observe a single PL line at zero field with a stronger, more free-carrier-like dispersion in magnetic field. They correlate weak minima in the integrated PL intensity with longitudinal resistance minima at $\nu=1$ and 2, and observe a remarkably strong PL intensity feature at $\nu=\frac{1}{3}$. They also report a new PL line, which appears 0.6 meV below the first line at about $\nu=\frac{1}{3}$, at temperatures below 2 K. They observe a further new line some 4.5 meV below the main luminescence structure. They attribute both of these new lines to the formation of the 2D hole WS, an interpretation supported by subsequent time-resolved PL measurements.[10] Shields *et al.*[11] observe rather different structure in a 300-Å QW: at low densities a twin-peak struc-

TABLE I. Sample characteristics.

Sample	Spacer width (Å)	Transport characteristics prior to illumination p_s (cm^{-2})	mobility [$cm^2(Vs)^{-1}$]	Peak PL energies under illumination with green light (eV) E_1	E_2	ΔE	Peak PL energies under illumination with red light (eV) E_1	E_2	ΔE
A	800	5.6×10^{10}	8.0×10^{5}	1.5288	1.5297	0.0009	1.5279	1.5294	0.0015
B	600	8.6×10^{10}	4.8×10^{5}	1.5297	1.5307	0.0010	1.5285		
C	200	2.1×10^{11}	4.0×10^{5}	1.5308	1.5321	0.0013	1.5265		

ture is observed whose intensity and magnetic-field dependences lead to their interpretation as neutral and positively charged excitons.

In this paper, we present the results of PL measurements of 2DHS's in three 150-Å QW's having different spacer widths. Our results are presented in two sections. The first (Sec. III) establishes the identity of the PL structure seen at zero and low magnetic fields: neutral and charged excitons are observed in the low-density samples, free-carrier recombination in the highest density one. The second (Sec. IV) describes our observations at high magnetic fields and their interpretation. In the lower-density 2DHS's we observe a new PL line, similar to one of those seen by Butov *et al.*,[9] but in light of preliminary transport measurements, which show that the 2DHS is very strongly depleted under illumination, we do not associate this with the formation of a hole WS. In the highest-density sample, the integer and fractional quantum Hall effects are detected as minima in the PL intensity, and complicated PL structure emerges at filling factors below about 0.2.

II. EXPERIMENTAL AND SAMPLE DETAILS

The PL measurements were performed over a range of excitation intensities from 0.1 to 100 mW cm^{-2} using an argon-ion laser (emitting predominantly at 488 and 514 nm) for illumination above the $Al_{1-x}Ga_xAs$ band gap, or a Ti-sapphire laser (765 nm) to illuminate the samples below the $Al_{1-x}Ga_xAs$ band gap. These excitation sources will hereafter be referred to as green- and red-light sources, respectively. Optical fibers delivered the laser light and collected the PL signal which was analyzed using a single-grating spectrometer and a charge-coupled device array with a resolution of about 0.05 nm (0.1 meV). The samples were cooled either in a $^3He/^4He$ dilution refrigerator (base temperature 16 mK) or in a ^3He system (base temperature 300 mK) and subjected to magnetic fields up to 15 T, perpendicular to the plane of the 2DHS. Simultaneous transport measurements were carried out on the sample with the highest carrier density, using a geometry that ensured uniform illumination of the 2DHS between the voltage contacts. In the magneto-optical experiments utilizing red-light excitation, a range of photon energies was examined in order to avoid possible resonant excitation via empty high-order Landau levels.

The samples studied were one-side modulation-doped single QW's grown by molecular-beam epitaxy on (311)*A* semi-insulating GaAs substrates. The well widths were 150 Å and the widths of the undoped $Al_{1-x}Ga_xAs$ spacers separating the ionized acceptors from the 2DHS were 800, 600, and 200 Å for samples *A*, *B*, and *C*, respectively. The 2DHS densities p_s and the mobilities of the samples prior to illumination are summarized in Table I. Magnetotransport measurements demonstrate that in samples *A* and *B* the 2DHS is very strongly depleted even after temporary exposure to green light, and under continuous illumination we know that $p_s<10^{10}$ cm^{-2} in both samples, and consequently transport measurements become impossible. In contrast, red-light excitation has no effect on p_s. These observations are in agreement with the density-depletion model of Hayne *et al.*[17] which we can use to provide an estimate of p_s under green-light illumination assuming that the mechanism by which photoexcited holes replenish the depleted 2DHS is by tunneling through the $Al_{1-x}Ga_xAs$ spacer. Under this assumption, and using the excitation powers appropriate to the data of Fig. 1 (see below), we estimate that $p_s\sim4\times10^8$ cm^{-2} for sample *A* and $\sim1\times10^9$ cm^{-2} for sample *B*. For sample *C*, the depletion effect is much weaker, and the model yields an estimated p_s of 2×10^{10} cm^{-2} (in this case, we have used magnetotransport to measure p_s and the result, $p_s=4\times10^{10}$ cm^{-2}, suggests that the model of Ref. 17 provides reasonable lower-limit estimates).

III. PL RESULTS AT ZERO AND LOW MAGNETIC FIELDS

In this section we present the PL spectra taken at zero magnetic field and describe the dependences of these spectra on excitation power and temperature, and their evolution in magnetic fields up to 5 T. We then discuss the origin of the observed structure.

PL traces taken at 350 mK and zero magnetic field, for all three QW's, are shown in Fig. 1(a). Green-light excitation was used with incident light power densities lower than 10 mW cm^{-2}. The following observations may be made.

(i) Two transitions are present in all the traces, marked peak 1 (lower energy) and peak 2 (higher energy), whose positions and separation are given in Table I. Peak 2 becomes weaker relative to peak 1 as the spacer width decreases (and hence p_s increases). Peak 2 shows a ≈2 times stronger linear dependence on excitation power than peak 1 over the range of powers investigated.

(ii) As the spacer width decreases, increasing the steady-state value of p_s, the energies of both peaks increase and the energy separation between the peaks also increases (Table I). Under red-light excitation, the zero-field PL spectra for the three samples are shown in Fig. 1(b): peak 2 is absent from

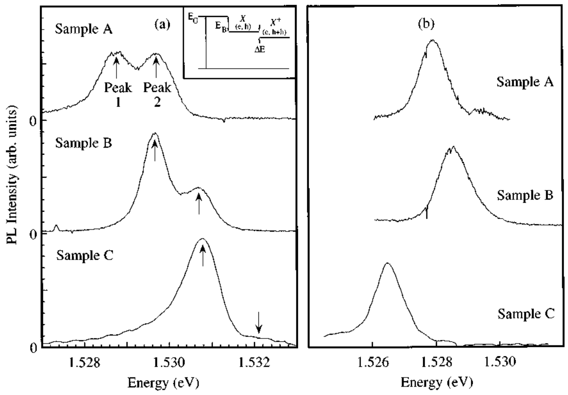

FIG. 1. (a) 350-mK PL spectra for the three QW samples under green-light excitation of less than 1 mW cm^{-2} for samples *A* and *B* and about 10 mW cm^{-2} for sample *C*. The inset is a schematic diagram of the energies of the PL emission energies for the two peaks observed. (b) PL spectra for the three samples, under red-light excitation. For samples *A* and *C*, the temperature was less than 100 mK; for sample *B* it was 350 mK. The excitation power densities were less than 50 mW cm^{-2}.

the spectra of samples *B* and *C* and weak even in that of sample *A*.

For samples *A* and *B*, the energies of the peaks shown in Fig. 1(a) were independent of excitation power. A quite different intensity dependence is observed in sample *C* (Fig. 2): as the power of green-light excitation is increased, the PL energy rises and the broad single peak narrows and forms a distinct twin-peak structure. In this sample, we were also

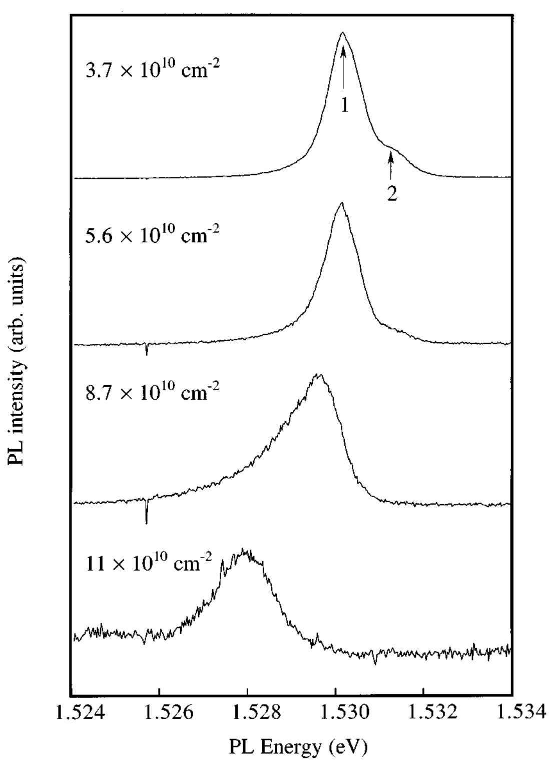

FIG. 2. 300-mK PL spectra for sample *C* over a range of p_s, obtained by green-light illumination of different powers (p_s increases as the power decreases). p_s was measured by simultaneous magnetotransport.

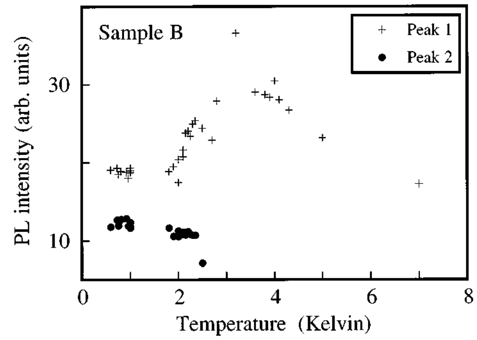

FIG. 3. The temperature dependences of the peak intensities of peaks 1 and 2, for sample *B*, using green-light excitation of ~0.3 mW cm^{-2}.

able to measure p_s from simultaneous magnetotransport, confirming that increasing intensity results in a reduction in p_s.

The temperature dependences of the intensities of the two luminescence peaks for sample *B* are shown in Fig. 3. Below about 1 K, both peak intensities are approximately independent of temperature. From 1 to 2.5 K, peak 2 weakens progressively and eventually disappears, while peak 1 strengthens. Then, above 3 K, peak 1 gradually weakens. The behavior in the intermediate-temperature regime suggests that the luminescence intensities are not simply determined by the thermal populations of the two levels—a more subtle explanation is required to account for the strengthening of the lower-energy line as the temperature rises.

In samples *A* and *B* [Fig. 4(a)], both peak energies vary as the square of the magnetic field at low fields, indicating that they are excitonic in origin. At higher fields, the dependences become linear but, interestingly, peak 2 retains its excitonic character up to higher fields than the peak 1, suggesting that the higher energy peak comes from a more strongly bound exciton. In sample *C* [Fig. 4(b)], the dominant peak, peak 1, has an almost linear field dependence for low levels of illumination, implying that recombination is between free carriers, becoming more quadratic as the illumination intensity increases. The peak intensities are also affected by magnetic field (not shown): for samples *A* and *B*, peak 1 weakens slightly with magnetic field while peak 2 strengthens. In contrast, both peaks strengthen for sample *C*.

Our interpretation of these data is as follows. In samples with low p_s (samples *A* and *B*, and sample *C* under strong green-light excitation), peaks 1 and 2 originate from positively charged and neutral excitons (X^+ and X), respectively. The energy levels involved are represented schematically in the inset to Fig. 1(a). A free electron-hole pair has energy E_G relative to the equilibrium situation, and the neutral exciton X has a binding energy E_B. When an additional hole becomes bound to form X^+, the total binding energy increases slightly, to $E_B+\Delta E$ (where ΔE is the binding energy of the second hole). Recombination of X results in a PL peak at energy E_G-E_B (peak 2), while that of X^+ leads to a PL energy of $E_G-E_B-\Delta E$ (peak 1).

The weakening of peak 2 relative to peak 1, as the spacer width is reduced (and hence p_s is increased) results from the greater abundance of X^+ in the presence of a greater number of excess holes, and this also accounts for the stronger de-

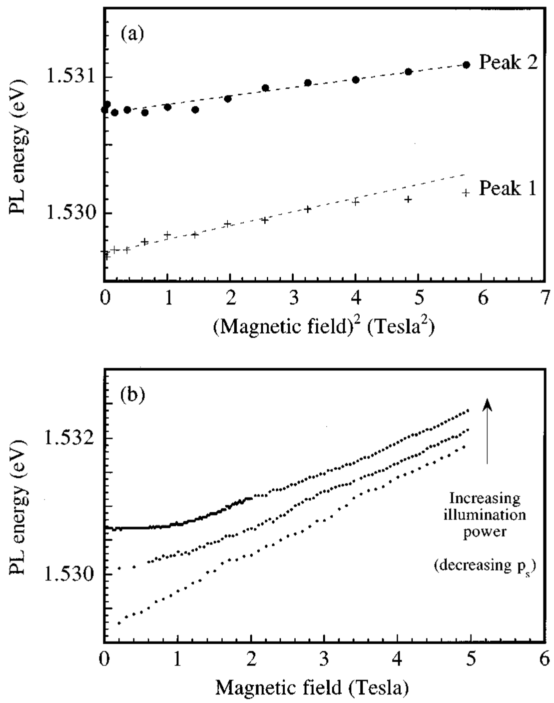

FIG. 4. (a) PL peak energy vs (magnetic field)^2 for sample *B* (the data for sample *A* are similar, but are omitted for clarity). The illumination conditions are the same as in Fig. 1(a). (b) PL peak energy vs magnetic field for sample *C*, showing the transition from free-carrier to excitonic behavior as the illumination intensity is increased. Estimated values of p_s are $<3\times10^{10}$ cm^{-2} (top trace); 6×10^{10} cm^{-2} (middle trace); and 1×10^{11} cm^{-2} (bottom trace).

pendence of peak 2 on excitation power. The energy separation of the peaks is also consistent with these assignments.[11]

As p_s is increased by reducing the spacer width [Fig. 1(a)], reducing the intensity of green-light excitation (Fig. 2) or going from green- to red-light excitation [Fig. 1(b)], the excitons become more weakly bound because of increased screening by the 2DHS, and eventually the recombination becomes free-carrier-like, taking the form of a broad PL feature whose shape is an approximate measure of the 2DHS density of states. This trend from excitonic to free-carrier recombination is most clearly seen in Fig. 4(b): in this case the trend is driven by excitation power: high excitation power leads to low p_s and hence to excitonic dispersion, while reduced excitation power gives larger p_s and free-carrier dispersion.

This interpretation is broadly in agreement with that of Shields *et al.*[11] and with observations of negatively charged excitons in modulation-doped QW's,[18–20] in resonant-tunneling structures[21] and in nominally undoped QW's.[22] However, some interesting differences are also apparent. Shields *et al.* report a gradual transfer of intensity from peak 1 to peak 2 as the temperature is raised from 1.8 to 20 K, caused by the thermal dissociation of X^+. We have shown that over a small range of temperatures around 3 K, peak 1 strengthens (Fig. 3). To understand this, we follow the argument of Phillips *et al.*:[22] at low temperatures, the carriers in the system are predominantly bound as excitons. Particularly in samples *A* and *B*, the 2DHS is so dilute that the formation of X^+ is relatively unlikely. As the temperature is raised, the equilibrium between excitons and free carriers is shifted toward the latter, and so X^+ formation becomes more likely. (The small excess of holes makes positively charged excitons more likely than negatively charged ones, and the observation of a strengthening of peak 1 as the 2DHS density increases supports this identification, although we cannot eliminate the possibility that both types of charged excitons are responsible for peak 1.)

The magnetic-field dependences of our excitonic features also differ in detail from those of Shields *et al.*: although in both cases the dispersion is clearly excitonic, with similar binding energies, Shields *et al.* report a significant enhancement of the binding energy of X^+ relative to X, resulting in an increased splitting between the peaks in magnetic field. In contrast [Fig. 4(a)], we observe that X^+ dissociates more easily in magnetic field: the low-field dispersion is stronger for peak 1 (indicative of a more weakly bound exciton), and becomes linear at lower fields. The gradual reduction in the intensity of peak 1 in magnetic field also suggests that X^+ is less stable than X in our samples. The origin of this slight difference between our observations and those of Shields *et al.* is not understood, although we believe it is related to the different QW well widths used.

We may now explain the relative sizes of the peak separations, ΔE, listed in Table I. The dependences of ΔE and of the individual peak energies on sample spacer width are governed by the changing shape of the QW and the consequent change in screening effects. First, consider the situation in which the 2DHS is completely depleted: the QW then contains no charge (except for an equal number of photoexcited carriers of each type, which have no effect on the electrostatics); furthermore, the Si acceptors in the doped $Al_{1-x}Ga_xAs$ region will have been neutralized by photoexcited holes.[17] Thus the whole structure is uncharged and so the QW is perfectly square—electrostatically equivalent to an undoped QW. Once this condition has been reached, the spacer width can have no effect on the PL energies. Since this is contrary to our observations (Table I), we conclude that the 2DHS is not completely depleted, in agreement with the kinetic model discussed elsewhere,[17] and indeed with our observation of positively-charged-exciton recombination.

As the 2DHS becomes populated, the QW becomes progressively more skewed and the tunneling barrier for photoexcited holes in the $Al_{1-x}Ga_xAs$ layer becomes larger. This change in 2DHS concentration increases the confining potential, enhancing the binding energy of the charged exciton.[23] At the same time the increasing concentration also increases the screening of the excitons, leading to a general decrease in the exciton binding energy. The interplay between these two processes determines the peak separation dependence on the spacer width (or, equivalently, on p_s). It follows from our observation of an increasing separation with p_s (Table I) that the first mechanism is stronger. This accounts for the observation that the energy separation between peaks 1 and 2 increases as the spacer width decreases [see Table I and Fig. 1(a)] and is further supported by the peak separation measured using red-light excitation of sample *A*: red-light excitation results in a higher 2DHS density than green-light excitation and, according to the argument above, should therefore give a larger peak separation—this is indeed what we observe (Table I).

In this section, we have established the origin of the PL

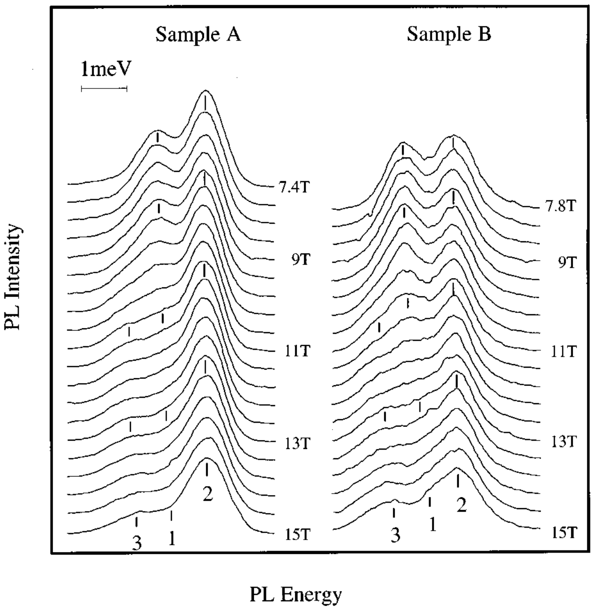

FIG. 5. High-magnetic-field traces for samples *A* and *B*. Illumination conditions are the same as in Fig. 1. A linear term 0.61 meV T^{-1} has been subtracted and successive field traces are shifted vertically downward with field for clarity.

observed at zero magnetic field: at low 2DHS densities, excitonic recombination is observed both from positively charged and neutral excitons, while at higher densities free-carrier recombination is observed. In the following section, we discuss the high-magnetic-field behavior of the PL in these two density regimes.

IV. PL RESULTS IN HIGH MAGNETIC FIELD

A. Experimental results for the low-density samples

When the magnetic field is increased, the dispersion of peaks 1 and 2 becomes almost linear, although some deviation from exact linear behavior occurs because of the dependence of the hole effective mass on magnetic field.[24] Although in our case the transitions are neutral and charged excitons, they are still expected to follow this trend.[18] There are no significant features in the PL integrated intensities at integer or fractional ν.

In Fig. 5, the evolution of the PL spectra at high magnetic field is presented for samples *A* and *B*. The illumination conditions are the same as for Fig. 1(a). The most striking feature of these data is that a new line, labeled peak 3, appears approximately 0.6 meV below peak 1, above about 7 T in sample *A* and 10 T in sample *B*. As the magnetic field increases, there is a gradual transfer of intensity from peak 1 to peak 3, and for both samples the overall integrated PL intensity starts to fall at the field at which peak 3 appears [Fig. 6(a)].

Figure 6(b) shows the temperature dependence of peak 3: its intensity rapidly weakens as the temperature is raised above about 0.4 K, disappearing completely by about 2.5 K. The decrease in integrated intensity exhibits the same behavior.

Our observation of a new low-energy PL peak emerging at high magnetic field is similar to that of Butov *et al.*[9] and

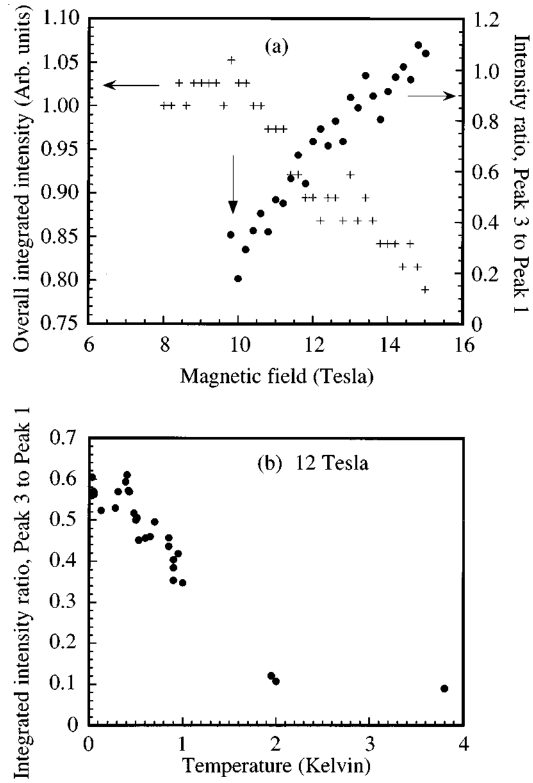

FIG. 6. Behavior of sample *B* at high magnetic fields: (a) shows the emergence of peak 3, and the accompanying fall in overall integrated PL intensity, above a threshold magnetic field of 10 T, indicated by the vertical arrow (the temperature is 50 mK); (b) shows the temperature dependence of peak 3 at a magnetic field of 12 T. Sample *A* behaves similarly (not shown), but has a threshold magnetic field of 7 T.

Kulik *et al.*,[10] which they interpret as being caused by WS formation. However, the depletion effect that we have observed in our samples results in a value of p_s, under the conditions of our PL experiments, sufficiently low in both samples to allow the formation of a WS at zero magnetic field (for a full discussion, see, for instance, Ref. 13). Thus we conclude that peak 3 is not associated with the transition to the 2D hole solid. In contrast, the sample of Butov *et al.* has a much larger value of p_s, as determined by their transport data, and so a magnetically induced WS transition is possible.

Although we do not have a conclusive interpretation of peak 3 at present, we note that the temperature dependence of this peak is very similar to that of peak 2, suggesting a common origin—perhaps peak 3 is a spin splitting of the 2D exciton, although the value of the splitting, 0.6 meV at 10 T, is about twice the predicted value for free excitons in 150-Å QW's.[25]

B. Experimental results for the high-density sample

We have established that in sample *C* the zero-field PL exhibits a gradual transition from recombination of free carriers to neutral/charged exciton recombination as p_s is reduced (either by going from red- to green-light excitation, or by increasing the green-light excitation intensity). In Figs. 7 and 8 we present the high-magnetic-field results for the high

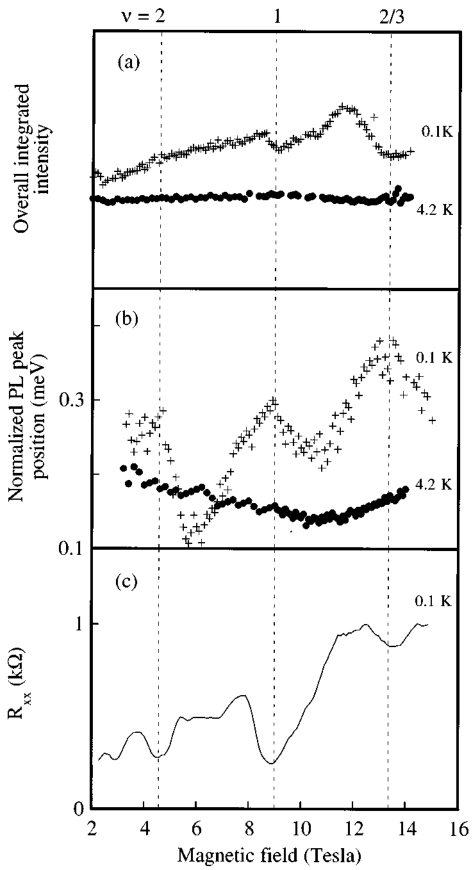

FIG. 7. (a) The integrated PL intensity, (b) the PL peak position (normalized by subtracting a straight line fit from the data), and (c) a simultaneous measurement of the longitudinal resistance R_{xx} for sample C, with $p_s = 2.1\times10^{11}$ cm^{-2}. The integer and fractional quantum Hall effects influence both the intensity and the peak position of the PL. Excitation was with red light.

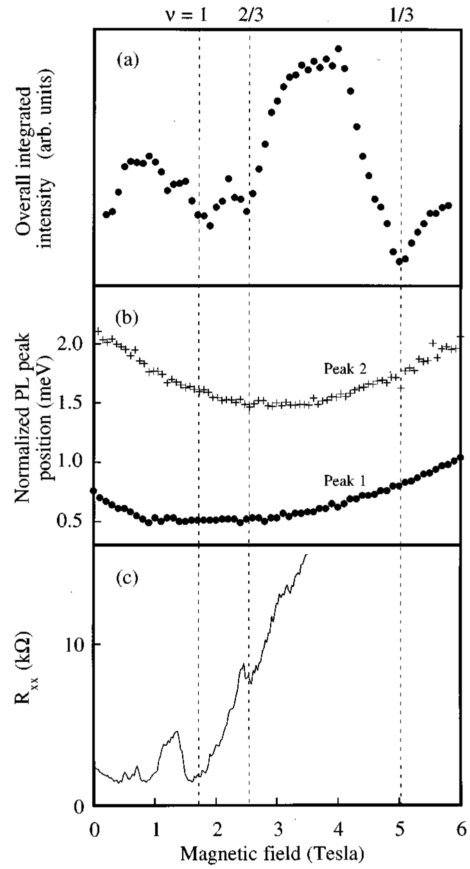

FIG. 8. (a) The integrated PL intensity, (b) the PL peak position (normalized by subtracting a linear field dependence from the data), and (c) a simultaneous measurement of the longitudinal resistance R_{xx} for sample C, with $p_s = 4\times10^{10}$ cm^{-2}. No modulations in peak position are observed, but there is still clear evidence of the integer and fractional quantum Hall effects in the integrated intensity. Excitation was with green light.

and low p_s limits, respectively, for this sample. In each case, the dependences of the integrated intensity and the PL peak position (with a linear dispersion subtracted) on magnetic field are shown, together with simultaneous magnetotransport data. In both cases, at low temperature there are distinct minima in the integrated intensities at integer and fractional ν that correlate well with the magnetotransport. These become progressively less distinct as the temperature is raised (representative 4.2 K data are given in Fig. 7). To explain this behavior, we follow the argument of Ref. 1 that the screening of the 2D holes from the photoexcited electrons is least effective when a Landau level is full, or when the holes are in an FQHE state, and in this case the holes and electrons become localized by the disorder, in different regions of the sample, with a consequent reduction in PL efficiency. It is particularly noteworthy that a clear minimum is observed in the integrated PL intensity at $\nu=\frac{1}{3}$ in Fig. 8(a), despite the fact that the resistivity has become too large to measure. This demonstrates the utility of the PL technique in the regime where insulating behavior makes transport measurements impossible.

There is a marked difference in the behavior of the PL peak positions in the high and low p_s regimes: at high p_s, the peak energy shows significant upward modulations at integer and fractional ν while at low p_s no such modulations are evident, either in peak 1 or peak 2. We can interpret this result in the following way: It has been established, both experimentally[1–3] and theoretically,[26,27] that the behavior of the PL energy at integer and fractional ν is strongly dependent on the strength of the electron-hole interaction: when the photoexcited carriers (in our case electrons) are well separated, in the growth direction, from the 2D carriers (holes), the interaction is weak and the PL energy exhibits downward-pointing cusps that are directly related to the energy gaps in the 2D density of states. As the separation is reduced, and the interaction becomes stronger, it is possible for upward modulations in the PL energy to occur, as we see in Fig. 7, because of an increase in the correlation self-energy of the 2D holes resulting from the perturbation caused by the photoexcited electrons. Finally, when the separation is reduced to zero (2DHS and photoexcited electrons in the same plane), no energy shifts occur. This last condition is the one describing our system at very low p_s (samples A and B) because in this case the QW is almost symmetrical. At higher p_s the QW becomes more skewed and the electrons and holes are slightly separated.

At fields above ~8 T, the low-p_s PL data for sample C start to exhibit structure (Fig. 9): first, a new line, peak 3, appears as a low-energy shoulder on peak 1, and then, at

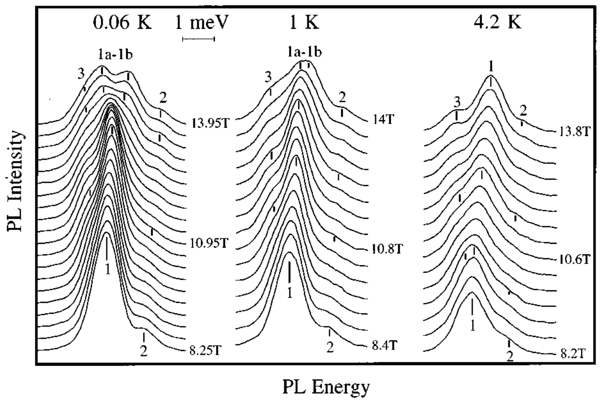

FIG. 9. Emergence of structure in the PL spectra at high magnetic fields in sample *C*. Under continuous green-light excitation, $p_s = 4\times10^{10}$ cm^{-2}.

higher fields, peak 1 splits. The lack of temperature dependence of peak 3 means that again we cannot invoke an explanation involving WS formation. In contrast, the splitting of peak 1 does have a strong temperature dependence, but occurs at too high a field to be associated with the WS transition.

We therefore conclude that none of our observations is related to the WS, despite some similarities between our results and those of Butov *et al.*[9] A possible explanation for this difference is that the sample of Butov *et al.* was a 200-Å QW while our well widths are 150 Å: The effect of WS formation on the PL is expected to weaken as the hole-electron interaction becomes stronger,[28] as it does as the QW becomes narrower, and consequently our experiments are likely to be less sensitive to the presence of the WS. However, given that significant similarities do exist between our data and those of Butov *et al.*, further investigations of the PL of these structures would be helpful in order to clarify the interpretation of the high-field structure.

V. CONCLUSIONS

We have presented a systematic study of the PL of 2DHS's in 150-Å QW's, ranging from extremely dilute systems to ones of moderate densities. In the dilute systems, we have interpreted the twin-peak PL structure observed at zero and low magnetic fields in terms of neutral and charged excitons. At higher magnetic fields, additional PL structure emerges, superficially similar to that previously attributed to formation of a WS state. However, the upper limit for p_s in our structures is too low to enable us to adopt a similar interpretation of our data.

As p_s is increased, the zero- and low-field PL structure evolves smoothly toward free-carrier-like behavior, characterized by a PL shape that approximately describes the 2DHS density of states and that disperses roughly linearly with magnetic field. In this regime, clear minima in the integrated PL intensity correlate with integer and fractional quantum Hall structure in simultaneous magnetotransport, and at the highest densities studied these are accompanied by upward shifts in the PL energy. Again, further PL structure emerges at high magnetic fields, and again the detailed behavior of this structure is not consistent with WS formation.

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