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Magneto-optical probe of the two-dimensional hole-system low-temperature ground states

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Band-gap magnetophotoluminescence (PL) has been used to study a high-quality, low-density p-type GaAs-$Al_xGa_{1-x}As$ single quantum well at millikelvin temperatures. Two PL lines associated with recombination in the quantum well are observed. The lower-energy line, present over the entire field range, displays intensity minima at integer quantum Hall states and a marked intensity falloff to a minimum value as the Landau-level filling factor is reduced to $\nu=\frac{1}{3}$. The higher-energy line emerges in the extreme quantum regime $\nu<1$, and shows an intensity maximum at $\nu=\frac{1}{3}$. These intensity features are quenched with increased temperature. The results show remarkable similarities with optical studies of two-dimensional electron systems.

Band-gap magnetophotoluminescence (PL) is now well established as a sensitive probe of the low-temperature, high-magnetic-field ground states of the two-dimensional electron system (2DES), formed in n-type GaAs-$Al_xGa_{1-x}As$ single heterojunctions (SHJ's) and single quantum wells[1–6] (SQW's). In contrast, optical studies of the two-dimensional hole system (2DHS) formed in p-type structures are only just being addressed,[7,8] following the identification of strong fractional quantum Hall effect (FQHE) states[9,10] and an insulating phase that has been associated with Wigner crystallization[10,11] (hole solid) in electrical-transport measurements of high-quality p-type GaAs SHJ's.

In optical studies of 2DES's, the 2D electron-to-free-valence-hole (e-h) recombination gives rise to a sharp PL line present over the entire magnetic-field range that exhibits strong intensity modulations correlated with quantum Hall effect [integer (IQHE) and FQHE] ground states.[1–6] A feature common to many studies is the emergence of additional PL lines in magnetic field. In our recent study of a low-density, flat-band n-type SHJ,[4] a new line emerges for $\nu<1$, intermediate in energy between the ground and first excited 2D subband recombination, which gives way to two lines in the magnetically induced Wigner solid (MIWS) regime $\nu<\frac{1}{5}$. The temperature and field dependencies of this PL structure were analyzed to map a phase diagram, which agreed well with the electron liquid-solid phase boundary obtained by a variety of techniques.[4,5] The appearance of a PL line to higher energy than the main PL emission for $\nu<1$ is also a common feature of intrinsic recombination in n-type SQW's.[3,6] A quite different signature is observed in n-type SHJ's involving recombination with holes spatially localized on a layer of deliberately introduced impurities (beryllium acceptors) $\sim$200 Å below the heterointerface [electron to neutral acceptor (e-A^0) recombination]: in addition to steps in the recombination energy associated with FQHE energy gaps, a PL line emerges for $\nu<0.28$ to *lower* energy than the main emission, interpreted as recombination of electrons in a MIWS phase.[12] These observations have generated considerable theoretical interest.[13]

In a previous paper,[7] we presented a detailed PL study of a high-quality, low-density p-type SHJ at 75 mK. While one sharp spectral line was interpreted as recombination at the heterointerface showing an intensity anomaly that correlated with the $\nu=1$ QHE, the results were complicated by bulk emission. A general conclusion was that progress towards observing definitive PL signatures of QHE states and the MIWS phase requires characterized flat-band SHJ's or for attention to shift to high-quality SQW structures, in which problems associated with strong band bending are avoided. A very recent study of band-gap recombination in a narrow p-type SQW (200-Å well width) reports, in addition to one PL line present over the entire field range, the emergence of two extra lines for $\nu\leq\frac{1}{3}$ *lower* in energy to the main emission.[8] The appearance of the new lines is interpreted as being consistent with the magnetic-field-induced localization of 2D holes, possibly a pinned Wigner solid state.[8] However, this observation is more reminiscent of the PL signature associated with extrinsic e-A^0 recombination reported for n-type SHJ's than intrinsic e-h recombination, which suggests different optical signatures in band-gap PL for n- and p-type samples. In this paper we report a PL investigation of a 300-Å-wide p-type SQW that draws a significantly different conclusion; our results demonstrate remarkably similar data for 2DES and 2DHS spectroscopy, despite the complexity of the GaAs valence band.

PL measurements at an excitation wavelength of 737 nm have been carried out on the low-density, high-mobility p-type modulation-doped SQW sample $T128$ ($n=2.7\times10^{10}$ cm^{-2} and $\mu\sim1\times10^6$ $cm^2/V\,s$ after laser illumination) grown on the (311)A GaAs surface using silicon as the acceptor dopant.[14] The sample was mounted strain-free in the dilute phase of a dilution refrigerator inserted into a superconducting magnet system. Full experimental details are given in Refs. 4 and 7.

InZn Ohmic contacts were annealed into the corners of the 2×2-mm^2 sample and the electrical-transport data, obtained by conventional low-frequency four-terminal lock-in techniques, revealed structure at IQHE states $\nu=4,3,2,1$ and

$\nu=\frac{2}{3},\frac{1}{3}$ FQHE states, although the contact geometry caused some admixture of ρ_{xx} and ρ_{xy} components. Absolute quantization of Hall plateaus was perturbed by the admixture but the plateau values scale correctly and unambiguously for these assignments. Representative QHE transport structure observed in our low-density p-type samples with this contact configuration (and for Hall bar samples) has been set out elsewhere[7] (for SHJ sample $A325$, see below). Significantly, in SQW sample $T128$ ρ_{xx} increases substantially for $\nu<\frac{1}{3}$ and an out-of-phase ($\theta=90°$) component in ρ_{xx} sets in beyond $\nu\sim\frac{1}{2}$, diverging asymptotically at $\nu=\frac{1}{3}$, which, in n-type material, has been correlated with the onset of a MIWS phase.[4] This is consistent with the identification of an insulating phase in high-quality p-type SHJ's close to $\nu=\frac{1}{3}$ associated with the formation of a hole solid.[10,11]

A 300-Å-wide well was selected to reduce deleterious effects on the intrinsic optical spectroscopy associated with the interface. To demonstrate that the quantum-well signal can be distinguished from bulk recombination with this well width, a comparison of PL spectra in the low-filling-factor region of interest $\nu\leqslant 1$, obtained for p-type SHJ $A325$ ($n=6\times10^{10}$ cm^{-2}) and SQW $T128$ at the same magnetic field (9 T) is presented in Fig. 1. Figure 1(a) shows the 75-mK, 1.75-μW spectrum of SHJ $A325$; full details are presented in Ref. 7. In brief, the peak labeled X is assigned to GaAs bulk free-exciton recombination, confirmed by its absolute energy at zero field (1.5151 eV), its energy trajectory with magnetic field, and by photoluminescence excitation studies—the X trajectory is shown over the full field range in Ref. 7 (labeled as "peak 2"). The A^0,X emission corresponds to recombination of acceptor-bound excitons and A^0,X-D to acceptor-defect bound excitons. The arrowed peak exhibited features correlated with the $\nu=1$ QHE reminiscent of 2D *excited* subband recombination (E_1 line) in n-type structures [Fig. 1(a) inset].[7] However, in n-type SHJ's with an optimized flat-band structure, ground-subband recombination (E_0 line) provides the important probe of the QHE regime; this was not observed in our p-type SHJ.

Our focus consequently shifted to p-type SQW samples and PL data for SQW $T128$ are shown in Figs. 1(b) and 1(c); structure associated with recombination in the quantum well is labeled QW. Figure 1(b) was obtained at 4.2 K with an enhanced excitation power of 100 μW, Fig. 1(c) shows the 80-mK, 5-μW spectrum. Under high-illumination conditions [Fig. 1(b)], several bulk features resulting from recombination in the GaAs buffer layer below the quantum well are brought up and the bulk free-exciton peak X dominates the spectrum. Under our normal millikelvin illumination conditions of 5 μW [Fig. 1(c)], PL structure associated with recombination in the quantum well is resolved together, at this high magnetic field, with a weakened free-exciton signal $\sim$2 meV lower in energy. Care must be taken when assigning the PL structure lying at energies below the main quantum-well emission owing to the many bulk PL lines present in this region; note, for example, the PL structure between the QW and X emissions brought up at high laser power in Fig. 1(b) that is also seen in Fig. 1(a).

The magnetic-field dependencies of the SQW PL peak-energy positions and intensities at 80 mK are shown in Fig. 2. Figure 3 presents a comparison of 80-mK and 4.2-K intensity data in the regions around $\nu=1$ ($\sim$1.1 T) and $\nu=\frac{1}{3}$ (3.5 T). Figure 4 shows the temperature dependence of the raw PL spectra at $\nu=1$ and $\frac{1}{3}$.

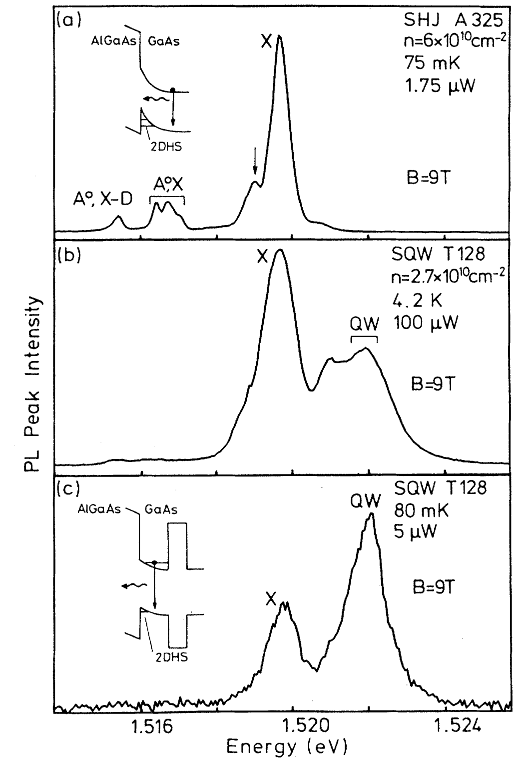

FIG. 1. Comparison of 9-T PL spectra for p-type SHJ $A325$ and p-type SQW $T128$: (a) SHJ at 75 mK (1.75-μW excitation power), (b) SQW at 4.2 K (100 μW), and (c) SQW at 80 mK (5 μW). PL associated with recombination in the quantum well is labeled QW; all lines to lower energy than QW emission can be attributed to bulk recombination. Insets show schematic band profiles and recombination channels specifically associated with the 2DHS.

PL emission associated with recombination in the quantum well is characterized by two spectral lines labeled A and B (Fig. 2). The A line is present over the entire field range studied whereas the B line is not observed for low fields, emerging in the extreme quantum regime $\sim$0.7 meV *higher* in energy than the A emission [Fig. 2(a)]. The bulk free-exciton X is observed for fields beyond 5 T $\sim$1.7 meV to lower energy than the A emission; the energy trajectory of this line exactly overlays that of the bulk free exciton in p-type SHJ $A325$.[7] The bulk exciton X can be observed in our SQW sample at low field ($<$5 T) with increased excitation power. The slopes of the PL energy trajectories increase with field, demonstrating the excitonic nature of the emission and show no significant anomalies at QHE states. As with e-h studies of n-type samples,[1–6] the optical signature of QHE ground states is carried by the PL intensity data.

In the IQHE regime at 80 mK, the A-line intensity shows a sharp minimum at the $\nu=1$ QHE state [Figs. 2(b) and 3(a)]. The PL intensity minimum correlates with the width of the ρ_{xy} $\nu=1$ QHE plateau shown in Fig. 2(b). The association of this PL feature with the $\nu=1$ QHE is reinforced by its temperature dependence, which is an essential check; at 4.2 K the A-line intensity minimum is quenched [Fig. 3(a)] and a detailed study confirms that this occurs over the same tem-

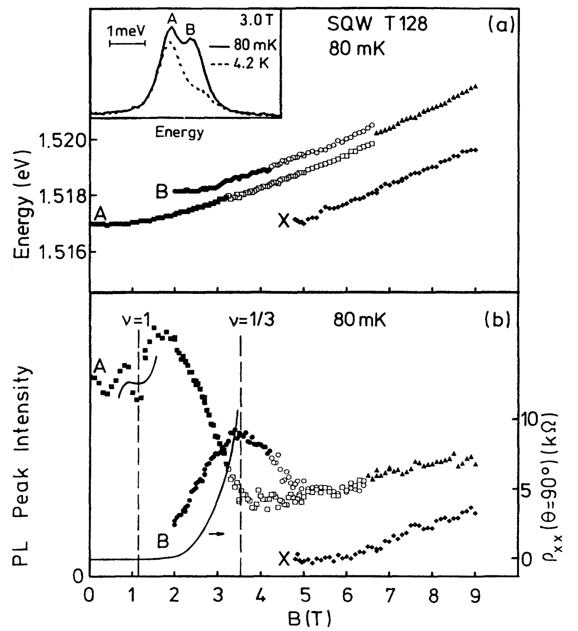

FIG. 2. (a) Field dependence of PL peak energy data for the SQW at 80 mK (5-μW excitation power). (b) Corresponding PL peak intensity data at 80 mK together with the ρ_{xy} plateau at $\nu=1$ (arbitrary units and offset for clarity) and onset of a ρ_{xx} ($\theta=90°$) out-of-phase component for $\nu<1$ (right axis). Beyond 7 T the doublet is not resolved and so the midpoint of the spectrum is plotted. Open symbols indicate that the positions of A and B components were confirmed by an overlay of 80-mK spectra with 4.2-K spectra in which A,B components were more clearly resolved. Inset: 3.0-T spectrum at 80 mK (full line) and 4.2 K (dashed line) using identical excitation power (10 μW).

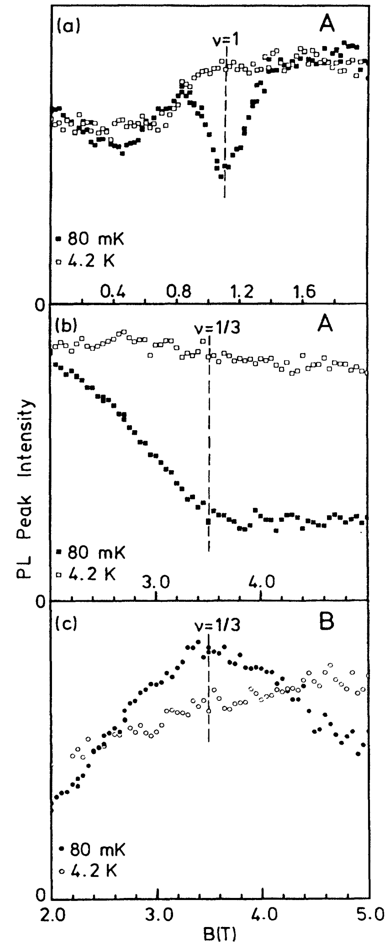

FIG. 3. Comparison of 80-mK, 5-μW (closed symbols) and 4.2-K, 10-μW (open symbols) A,B PL peak intensities around (a) $\nu=1$ and (b) and (c) $\nu=\frac{1}{3}$. The A-line intensity minimum at $\nu=1$, the collapse of A intensity to a minimum value as the filling factor is reduced to $\nu=\frac{1}{3}$, and the corresponding B-line intensity maximum at $\nu=\frac{1}{3}$ are quenched with increased temperature.

perature range as the quenching of the $\nu=1$ transport features. Owing to the lower overall spectral intensity at elevated temperatures, the 4.2-K data in Figs. 3 and 4 were obtained under illumination conditions of 10 μW (compared to 5 μW for the 80-mK data), which additionally normalizes the 4.2-K and 80-mK A-line intensities at $B=0$ T. The quenching of the $\nu=1$ A-line intensity minimum in Fig. 3(a) can also be seen in the raw PL data in Fig. 4(a).

The inset to Fig. 2(a) compares the 3.0-T PL spectrum at 80 mK and 4.2 K, both obtained with 10-μW excitation power. At 80 mK the quantum-well emission is characterized by a well-resolved A,B doublet at this field with no bulk emission evident. This comparison shows that whereas the A component is relatively unaffected at increased temperatures, the intensity of the higher-energy B component is strongly reduced. This behavior is also a striking feature in n-type samples[4,5] and argues against the assignment of the B line to higher 2D subband emission.

For $\nu<1$ at 80 mK, the A-line intensity drops markedly to a minimum value as the filling factor is reduced to $\nu=\frac{1}{3}$, concomitant with the emergence and strengthening of the B line; at $\nu=\frac{1}{3}$, the emergent B line has an intensity maximum [Fig. 2(b)]. At high temperatures, this intensity signature is quenched and there are no features discernible in the 4.2-K spectral intensity associated with the $\nu=\frac{1}{3}$ ground state in either line. This can also be seen in the raw PL data at $\nu=\frac{1}{3}$ shown in Fig. 4(b); the B-line intensity maximum at $\nu=\frac{1}{3}$ is quenched and the A-line intensity is restored to a dominant value with increased temperature.

An important observation is that the magneto-PL of p-type SQW $T128$ reinforces the overall picture of e-h recombination in both n-type SHJ's and SQW's.[1–6] The main features in common are (i) the observation of an A,B doublet structure over a broad magnetic-field range in which the B component, $\sim\frac{1}{2}$ meV to *higher* energy, emerges in the region $\nu<1$, (ii) A,B components have a contrasting temperature dependence, (iii) the A line present over the entire field range exhibits intensity minima at QHE states whereas the B line has intensity maxima, and (iv) the A,B energy trajectories exhibit an excitonic character with no significant energy shifts at QHE states. The recent study[8] of a 200-Å p-type SQW shows features similar to those reported here, but important differences exist.

We attribute the A-line emission to recombination of 2D holes in the ground subband of the quantum well with photoexcited electrons. The intensity minimum at $\nu=1$ can be explained by correlation and screening effects and is a well-

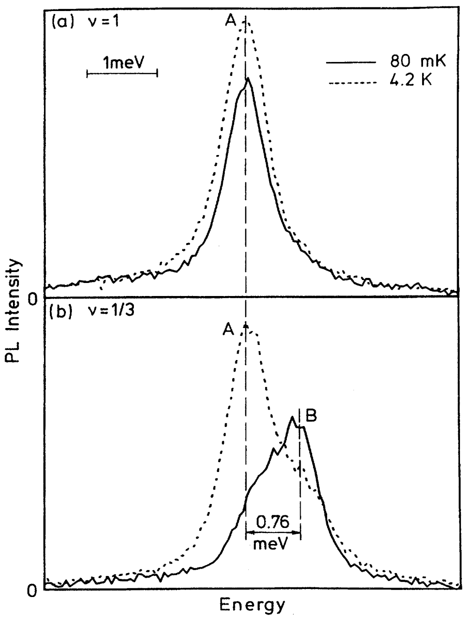

FIG. 4. Comparison of the 80-mK and 4.2-K raw PL spectra at (a) $\nu=1$ and (b) $\nu=\frac{1}{3}$.

established optical signature of QHE ground states.[1–6] The quenching of the A-line minima with increased temperature correlates with the destruction of QHE states as evidenced by transport data. Weak features in the A-line intensity, which are quenched with increased temperature, can also be observed close to $\nu=2$ and 4 in Fig. 3(a). The observation of intensity minima in the main PL line at $\nu=2$, 1, and $\frac{1}{3}$ in the p-type SQW of Ref. 8 is in agreement with our data.

The B line has much in common with studies in n-type SHJ samples in which a new line is also observed to emerge in the FQHE regime 0.5 meV above the ground subband emission.[4,5] In both cases, these emergent lines extrapolate back to zero intensity at $\nu=1$ and are additional to the first excited 2D subband emission. In Ref. 5, we attributed this line to the recombination of excitons close to the interface distinct from the 2DES recombination channel. In SHJ samples, such excitons are created in the bulk GaAs buffer layer and diffuse quickly towards the heterointerface, where the exciton ground-state electronic wave function can be thought of as some linear combination of quantum-well and continuum states. Provided the lifetime of this interface exciton is long enough for recombination to occur before the electron is incorporated into the 2DES ground subband, the emission will be distinct from subband recombination. Such a mechanism is not inconsistent with B emission in our SQW sample, as it is plausible that an interface exciton is created within the wide well. The different behavior of the B line in our SQW and the n-type SHJ samples upon entering the MIWS phase (see below) may be related to details of the exciton proximity to the 2D layer.

The B-line intensity maximum at $\nu=\frac{1}{3}$ can be explained as an indirect result of reduction in A emission.[4,5] The emergence of two lines to *lower* energy than the A line for $\nu\leq\frac{1}{5}$ reported in Ref. 8, discussed in relation to a MIWS phase, is not observed in our sample nor in intrinsic recombination in n-type SHJ's and SQW's. This significant difference is not understood but could indicate that well width is important.

The emergence of the B line and collapse of the A line at millikelvin temperatures correlates with the onset of ρ_{xx} dephasing, which increases asymptotically at $\nu=\frac{1}{5}$ [Fig. 2(b)]. Dephasing of ρ_{xx} has been related to the formation of a MIWS phase, anticipated close to $\nu=\frac{1}{3}$ in a 2DHS.[10,11] For $\nu<\frac{1}{5}$ our PL spectrum remains relatively unchanged with field and the A,B-line intensities become equal. Results reported in Refs. 4 and 5 for an n-type SHJ, showed that the emergent B line attributed to interface exciton recombination gave way to two new lines in the MIWS regime ($\nu<\frac{1}{5}$ for a 2DES). The two lines were associated with the recombination of interface excitons that become either localized (in x-y) by the formation of an electron lattice at the heterointerface or that remain unlocalized. This behavior is not resolved in our p-type SQW, which could be related to the spatial offset of the single-electron interface exciton from the 2D plane. Results for n-type SQW's also show no clear emergence of prominent additional structure at the anticipated MIWS boundary.[3,6]

Note added. Recently, we became aware of further PL results for narrow (150 Å) p-type SQW's.[15] The data show a PL signature similar to that attributed to the MIWS phase in beryllium δ-doped n-type SHJ's but the Ref. 15 authors point out that other explanations are possible.

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