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# Time-resolved photoluminescence of a two-dimensional hole system in the extreme quantum limit

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We report time-resolved and continuous-wave magnetoluminescence measurements on a two-dimensional hole system in a $GaAs/Al_xGa_{1-x}As$ quantum well. The dominant spectral emission line in the absence of magnetic field and at high Landau-level filling factor $\nu$ has a short recombination lifetime, characteristic of extended hole states. Two additional lines appearing at $\nu \lesssim \frac{1}{3}$ have long lifetimes, signaling the recombination of localized holes. The fraction of localized holes abruptly increases below $\nu = \frac{1}{3}$.

Recently, magneto-optical studies of the correlated states of $GaAs/Al_xGa_{1-x}As$ two-dimensional electron systems (2DES's) in the extreme magnetic quantum limit (Landau-level filling factor $\nu < 1$) have attracted considerable interest.[1–8] Recombination of electrons with free holes and with holes bound to acceptors has been investigated. These studies report the detection of both the fractional quantum Hall (FQH) state and a localized state of the 2DES which was interpreted as a Wigner solid. The condensation of 2D electrons into FQH liquid states at particular fractional fillings causes a shift of the photoluminescence (PL) line position and a variation of the PL intensity.[1–5] At very low fillings ($\nu \lesssim \frac{1}{5}$) new emission lines are observed in the PL spectra and are interpreted as manifestations of the electron solid.[4,5]

In addition to investigations of the quasiequilibrium characteristics of 2DES's in continuous-wave (cw) photoluminescence experiments, time-resolved measurements have been carried out on quantum wells (QW's) and heterojunctions.[6–8] For electron recombination with itinerant holes, PL lines with considerably different decay times were observed at low filling factors; the lines with long lifetimes were related to the recombination of localized electrons in the Wigner solid regime.[6,7] In time-resolved measurements of electron recombination with holes bound to acceptors, a local electron configuration consistent with the Wigner solid triangular lattice model was deduced.[8]

Recent improvements in sample quality have also allowed studies of $GaAs/Al_xGa_{1-x}As$ 2D *hole* systems (2DHS's) in the extreme quantum limit. In contrast to the 2DES's, however, only a few cw photoluminescence experiments on 2DHS's have been reported up to now.[9–11] In a study of a 2DHS confined in a 200 Å $GaAs/Al_xGa_{1-x}As$ QW,[9] new PL lines were observed near and below $\nu = \frac{1}{3}$. In analogy to the PL measurements on 2DES's, these lines were tentatively attributed to the recombination of localized holes. In the present paper we report time-resolved PL measurements on a 2DHS in the extreme quantum limit. The results allow us to distinguish between the recombination of localized and extended hole states, and confirm the PL line assignments made in Ref. 9.

$GaAs/Al_{0.3}Ga_{0.7}As$ QW structures with well widths of 200 Å were grown by molecular beam epitaxy on undoped GaAs (311)*A* substrates and modulation doped with Si, which is incorporated as an acceptor on the (311)*A* surface. We etched a Hall bridge mesa on the samples, alloyed contacts to the 2DHS, and performed simultaneous magnetotransport and PL measurements. Care was exercised to ensure that the laser excitation spot illuminated the entire active region of the Hall bridge. When cooled in the dark, the hole density and mobility (determined from diagonal resistivity $\rho_{xx}$ oscillations and the Hall resistivity) were $p \simeq 2.1 \times 10^{11}$ cm$^{-2}$ and $\mu \simeq 6 \times 10^5$ cm$^2$/V s for sample I, and $p \simeq 1.3 \times 10^{11}$ cm$^{-2}$ and $\mu \simeq 7 \times 10^5$ cm$^2$/V s for sample II. Photoexcitation caused a reduction in the hole density. Once this lower density was reached, it remained fixed independent of the photoexcitation power.

Sample I was mounted in the mixing chamber of a $^3$He/$^4$He dilution refrigerator with a base temperature of $\simeq 40$ mK. Under illumination, the temperature of the mixing chamber, $T_{bath}$, rises to $\simeq 60$ mK. In the time-resolved PL measurements, photoexcitation consisted of pulses from a dye laser (wavelength $\approx 600$ nm) with a 1 ps duration, average power density of $10^{-5}$–$10^{-4}$ W/cm$^2$, and a repetition frequency of 4 MHz. The PL signal was detected by a time-correlated photon counting system with a time resolution of 270 ps. For photoexcitation in the cw PL measurements we used a He-Ne laser (wavelength $\approx 633$ nm) with a power density of $10^{-5}$–$10^{-4}$ W/cm$^2$. The PL signal was detected by a charge coupled device camera.

The cw PL spectra of the 2DHS (sample I) at $T_{bath} \approx 60$ mK and magnetic fields $B = 6$–$16$ T are shown in Fig. 1 in steps of 0.2 T. The measured density during and after the illumination is $p \simeq 6.2 \times 10^{10}$ cm$^{-2}$. At low magnetic fields ($B < 8$ T) only one emission line ($A$) with linewidth $\approx 0.7$ meV dominates the spectra. At high magnetic fields ($B \gtrsim 8$ T, $\nu \lesssim \frac{1}{3}$) two new lines $S$ and $X$ appear in the spectra at $\sim$ 0.6 and $\sim$ 3.8 meV below line $A$, respectively. The data of Fig. 1 are essentially the same as those of Ref. 9 except that at the much lower temperature of the present experiments the intensity of line $A$ is quite weak at low $\nu$. As in Ref. 9, to separate the $S$ and $A$ lines, the spectra were approximated by

 

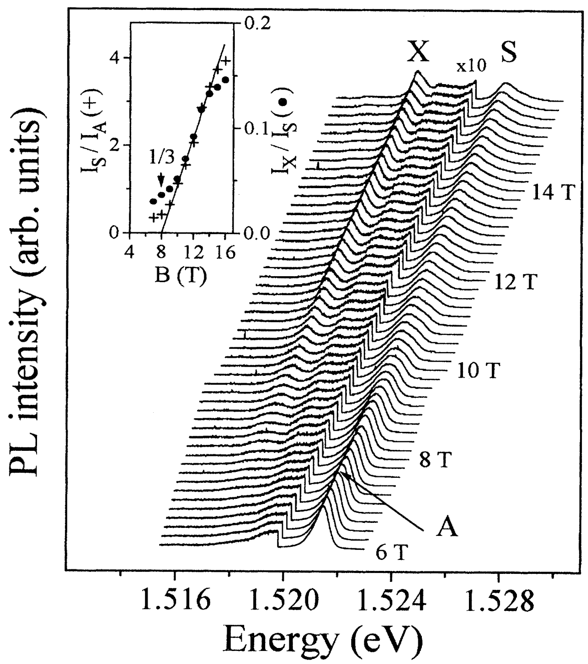


FIG. 1. cw photoluminescence spectra of sample I, with density (under photoexcitation) $p \simeq 6.2 \times 10^{10}$ cm$^{-2}$, at $T_{\text{bath}} = 60$ mK and for magnetic fields $B = 0-16$ T in 0.2 T steps. The low energy parts of the spectra are multiplied by a factor of 10 to show the appearance of line $X$. Inset shows the ratios of the line intensities.

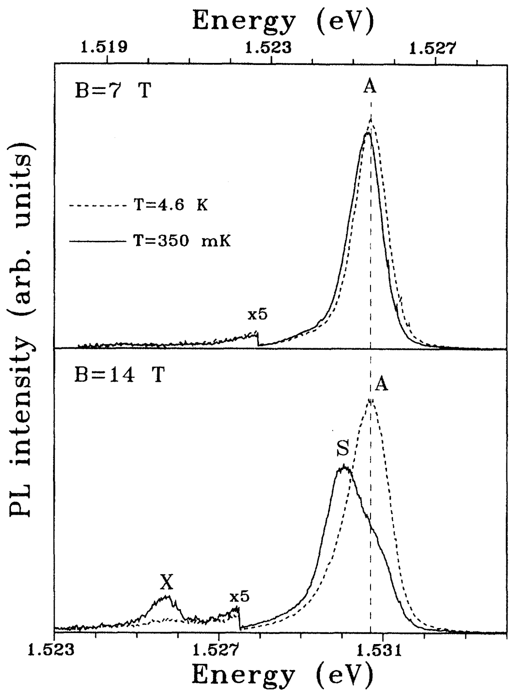


FIG. 2. cw photoluminescence spectra of sample II, with density (under photoexcitation) $p \simeq 7.1 \times 10^{10}$ cm$^{-2}$, at $T = 350$ mK and 4.6 K. Upper (lower) part of the figure shows the spectra at $B = 7$ T (14 T).

two Gaussians. With increasing magnetic field or decreasing temperature, the intensities of the $S$ and $X$ lines increase, while the intensity of line $A$ decreases (Figs. 1 and 2). Finally, between lines $X$ and $S$ we observe an additional weak line whose intensity is nearly independent of magnetic field and temperature. The presence of this line, although not emphasized, is also apparent in the data of Ref. 9 (see Fig. 3 of Ref. 9).[12]

To verify that all these lines originate from the recombination of 2D holes in the QW with photoexcited electrons, we measured the PL spectra for the bulk GaAs substrate[13] in our structures by moving the laser excitation spot off of the Hall bar mesa. Such spectra show PL lines whose $B = 0$ energy positions (1512.5 meV and 1515.2 meV) as well as $B$ dependence are consistent with emission from the bulk free and bound excitons.[14] On the other hand, the positions of the $X$, $S$, and $A$ lines are different from these bulk lines and, moreover, are sensitive to changes in the confinement potential. For example, reducing the 2D hole density in a given sample results in a downshift of the positions of lines $X$, $S$, and $A$.[9,15]

Based on the observations summarized in the previous two paragraphs, Butov *et al.*[9] assigned line $A$ to the recombination of extended hole states and lines $S$ and $X$ to the recombination of the localized holes with the photoexcited electrons. It was also proposed that line $X$ corresponds to the recombination of a complex composed of two localized holes and one electron. Before presenting the time-resolved data, which are consistent with these assignments, we will briefly summarize the results of other recent cw PL studies of GaAs/Al$_x$Ga$_{1-x}$As 2DHS's and compare them to ours. In a PL study of a 2DHS (with similar density $p \simeq 6 \times 10^{10}$ cm$^{-2}$) confined in a 150 Å wide QW, a new low energy PL line was reported at high magnetic fields ($\nu \lesssim \frac{1}{3}$).[11] The qualitative characteristics of this line are similar to that of line $S$ in our structure. However no analog of the $X$ line was observed. The observation of the $X$ line in the wider QW used in our study is consistent with the assignment of this line to the emission from an exciton-plus-hole complex:[9] the carrier lifetime is longer in a wider QW thus favoring the complex formation. In a PL study of a more dilute 2DHS ($p \simeq 2.7 \times 10^{10}$ cm$^{-2}$) confined in a 300 Å wide QW, a line at $\approx 2$ meV below the main PL line was observed.[10] However, in view of the presence of a thick GaAs layer in their structure, this line was associated with the bulk free excitons.[13]

Our time-resolved PL spectra are shown in Fig. 3 for $B = 7$ and 16 T. These data reveal the characteristic features of the PL spectra time evolution for $\nu > \frac{1}{3}$ and $\nu < \frac{1}{3}$. The spectra were integrated within the time intervals denoted by 1,2,3, . . . and separated by dotted lines in the upper insets of Fig. 3; these insets present the spectrally integrated decay curves. All the PL spectra shown in Fig. 3 are normalized to have equal integrated intensities. At $B = 7$ T, line $A$ dominates the PL spectra. Both its energy position and line shape are nearly unchanged with time and are close to those in the cw spectrum. This observation points to the rapid cooling rate of the photoexcited electrons. We believe that the ther-

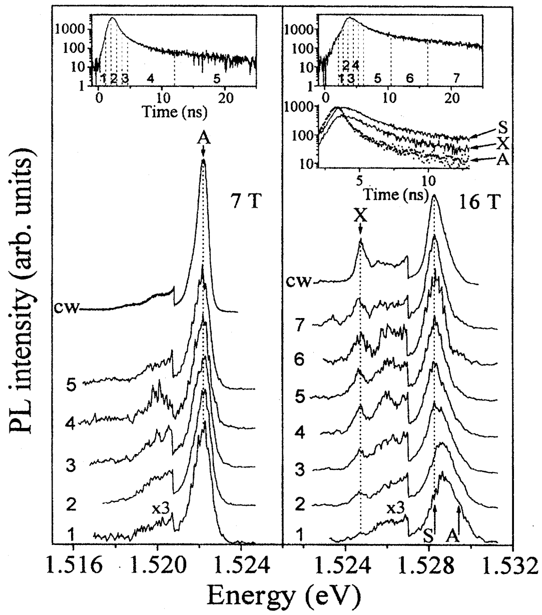


FIG. 3. Time-resolved PL spectra of sample I at $B=7$ and 16 T. The spectra are integrated within the time intervals denoted by 1,2,3, . . . and separated by dotted lines in the upper insets of the figure; these inserts present the spectrally integrated decay curves. All the spectra are normalized to have equal integrated intensities. cw PL spectra are also shown. Lower inset on the right presents the PL decay curves at the energies of lines $S$, $X$, and $A$.

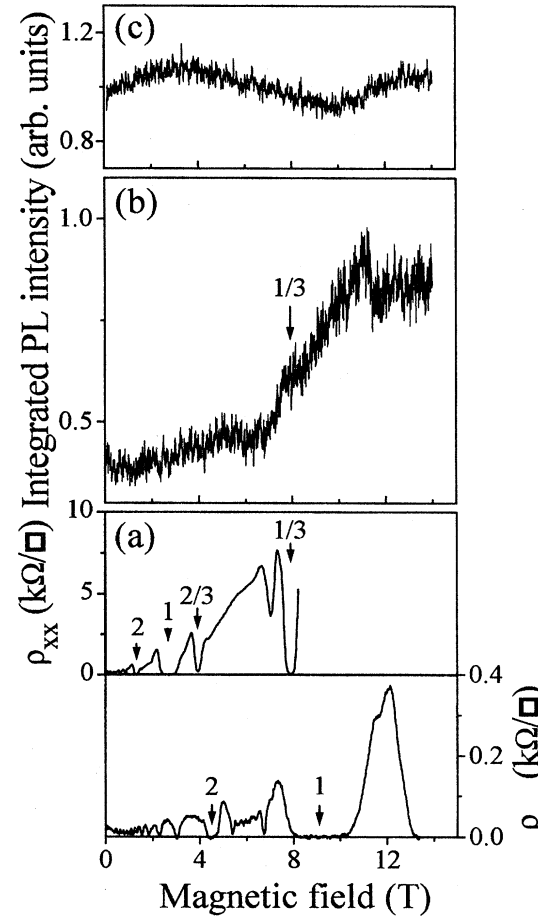


FIG. 4. Magnetic field dependence of (a) the resistivity $\rho_{xx}$ after cooling in the dark (lower trace) and under photoexcitation (upper trace); (b) PL intensity integrated over energy and over the time interval $t=5-30$ ns; (c) PL intensity integrated over energy and over all time. The data in (b) are normalized to the total intensity shown in (c), and thus represent the relative fraction of the long-time recombination.

malized photoexcited electrons with density $\sim 10^8$ cm$^{-2}$ (corresponding to our excitation density) are localized.[16]

We observe a more complicated time evolution of the PL spectrum at $B=16$ T compared to the 7 T data. At time $t\approx 2$ ns (curve 1) a broad PL line is seen in the high energy part of the spectrum (throughout the paper we take the time origin $t=0$ to correspond to the beginning of the laser pulse). The relative intensity of the high energy edge of this broad line, which corresponds to the $A$ line position,[9] decreases with time and, for $t\gtrsim 6$ ns, we observe a symmetric line with a linewidth of $\approx 1$ meV (curves 5–7) whose energy position coincides with that of line $S$ in the cw spectrum. The measured PL decay curves at the energies of lines $S$, $X$, and $A$ are presented in the lower inset of Fig. 3. The decay times of the $S$ and $X$ lines are equal, and much longer than that of line $A$. At 16 T the initial decay times are $\tau_{S,X}\approx 2$ ns and $\tau_A\approx 0.5$ ns. We observe a short decay time for line $A$ in the whole range ($B=0-16$ T) of magnetic fields studied (compare the 7 T and 16 T decay curves of the $A$ line in Fig. 3). The $S$ and $X$ lines, on the other hand, have long decay times in the entire field range where they are observed ($\nu\lesssim\frac{1}{3}$).

Emission kinetics provides an opportunity to distinguish between the recombination of extended and localized hole states. For extended hole states the average overlap between the localized electron and hole wave functions (in the plane) is larger than that for localized hole states, implying a shorter recombination lifetime for the former.[8,17] The short lifetime of line $A$ strongly suggests that it corresponds to extended hole recombination. The $S$ and $X$ lines with a long decay time, on the other hand, correspond to localized hole recombination.

The different recombination decay times of the extended and localized states can be used to temporally separate their emissions. Because of their short decay time, the extended states essentially contribute to the integrated intensity only at the initial stage of the recombination process, while at long times the localized states dominate the recombination. Thus the relative fraction of the localized hole states can be deduced from the integrated intensity of the long-time recombination. The magnetic field dependence of the latter is presented in Fig. 4(b) which shows the PL intensity integrated over energy and over the time interval $t=5-30$ ns. The data are normalized to the total PL intensity, integrated over energy and over all time, itself shown in Fig. 4(c). At low magnetic fields $B\lesssim 7$ T the fraction of the hole states with long decay time depends only weakly on $B$ while at $B\gtrsim 7$ T it abruptly increases [Fig. 4(b)]. The changes of the decay time are mainly caused by changes of the rate of radiative recombination as the energy and time integrated PL intensity is nearly independent of $B$ [Fig. 4(c)].

The time-resolved PL data reveal that the number of localized holes increases abruptly above a magnetic field which corresponds to $\nu \simeq \frac{1}{3}$. The cw data are in agreement with this observation (Fig. 1). Assuming that the $I_S/I_A$ ratio is approximately proportional to the area covered by the localized states, we note in the inset of Fig. 1 that this ratio starts to grow at $B \gtrsim 8$ T ($\nu \lesssim \frac{1}{3}$). The ratio $I_X/I_S$ also grows above $\approx 8$ T. This is consistent with the conjecture[9] that the $X$ line corresponds to the recombination of a complex composed of two localized holes and one electron: with increasing $B$, the probability of complex formation is enhanced because the area covered by localized states grows and, in addition, because the empty space between holes grows as well (reduction of the screening of the complex by holes).

The magnetic-field-induced localization of 2D holes can be caused either by random potential fluctuations or by the formation of a pinned hole Wigner solid. Our experiment does not allow us to distinguish between these two possibilities. The filling factor $\nu = \frac{1}{3}$ below which we observe an abrupt growth of the sample area covered by localized holes is consistent with the filling factor around which an insulating phase is observed in magnetotransport experiments;[18,19] it is also close to the theoretically expected critical $\nu$ for the formation of a 2D hole Wigner solid state.[20]

In conclusion, we have performed time-resolved and cw PL experiments on a high quality 2DHS in the extreme quantum limit. On the basis of different decay kinetics, the recombination of extended and localized states is identified. The fraction of localized hole states is found to increase markedly at $\nu \approx \frac{1}{3}$, consistent with the results of transport experiments.[18]

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