Optical Investigations of the Integer and Fractional Quantum Hall Effects: Energy Plateaus, Intensity Minima, and Line Splitting in Band-Gap Emission

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Plateaus in the electron-hole recombination energy and minima in the peak intensity at integer and fractional filling factors occur in the luminescence from ultrahigh-mobility GaAs single quantum wells. At Landau and spin gaps the regions of plateaus and intensity minima broaden as the temperature is reduced, in consort with the transport Hall resistance. A sharp intensity minimum and peak shift is seen at $\nu=\frac{2}{3}$, while higher-field fractions are characterized by a splitting in the luminescence. The optical anomalies are directly related to the position of the Fermi energy in localized transport states.

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A gap in the extended-state spectrum at the Fermi energy is the origin of both the integer and fractional quantum Hall effects. In the former the gap is caused by the magnetic Landau or spin quantization of the energy levels, while in the latter a gap is created by a condensation of the electrons into a many-body Laughlin ground state.[1] When the Fermi energy (E_F) resides in a localized-state region in such a gap, the response of the two-dimensional electron gas is strongly modified. For example, the electrons cannot screen the potentials due to remote ionized impurities,[2] causing a broadening in the density of electronic states. This reduced electron polarizability has a strong effect on optical processes as well. In the magnetic quantum limit it appears to be related to the alteration of the local potential of a photoexcited hole by the response of the electron gas.[3]

Optical recombination of electrons and holes in the fractional quantum Hall effect (FQHE) regime has been observed in Si metal-oxide-semiconductor field-effect transistors[4] and GaAs/AlGaAs quantum wells.[3] The former experiments have been interpreted as evidence of a quasiparticle gap, while the latter observe changes in the screening behavior of the electrons in the FQHE. In the integer quantum Hall effect (IQHE) regime, previous studies[5] have seen nonlinearities in the emission energy ($E_{\rm PL}$) as a function of magnetic field (B). In contrast,[5] we observe near linear behavior[6] of the energy versus field at $T \gtrsim 2.8$ K, showing no transition to the predicted magnetoexciton insulator,[7] and indicating that luminescence plateaus observed in other studies may arise from the poorer mobility of the samples (10 to 100 times smaller). Theoretical calculations[8] of the screening response at Landau gaps show that $E_{\rm PL}$ should exhibit upward cusps at even filling factors, due to the weaker screening of the hole potential by the 2D electrons. However, the relative importance of screening and vertex corrections (the exciton effect) on optical processes in magnetic fields is still an open question,[7,9] as is the influence of localized transport states.

In this work on higher-mobility ($\mu \gtrsim 2\times10^6$ cm^2/V s) single quantum wells, we observe striking plateaus in the recombination energy accompanied by minima in the peak intensity at integral filling factors. The *widths* of the plateaus and minima are correlated to the quantized Hall ρ_{xy} plateau widths. Optical measurements were performed while observing fractional Hall plateaus in ρ_{xy} and deep minima in ρ_{xx} at $\nu=\frac{2}{7}, \frac{1}{3}, \frac{2}{5}, \frac{3}{7}, \frac{4}{7}, \frac{3}{5}$, and $\frac{2}{3}$. As the temperature is reduced, and FQHE states are resolved, a luminescence intensity minimum and peak shift develops precisely at $\nu=\frac{2}{3}$. At higher fields a splitting of the main luminescence peak is seen in the region of $\nu=\frac{1}{3}$ and $\frac{2}{5}$.

The experiment consists of simultaneous measurement of the transport resistivity components and photoluminescence spectra from one-side-doped GaAs/AlGaAs single quantum wells [250-Å well width, $\mu=(2-5)\times10^6$ cm^2/V s, $n_s=(1.0-2.9)\times10^{11}$ cm^{-2}]. Electron temperature was monitored by transport, and heating was prevented by keeping the excitation intensity below $I<5\times10^{-4}$ W/cm^2. To avoid B-field-dependent intensity variations of the emission created by changes in absorption (due to higher Landau levels tuning through the excitation energy), different laser energies between 1550 and 1650 meV, as well as filtered sources (10–40-nm bandwidth), were employed.

Plateaus in the recombination energy and minima in the intensity at the filling factors $\nu=1,2$ are revealed in the series of spectra plotted as a function of B in Fig. 1.

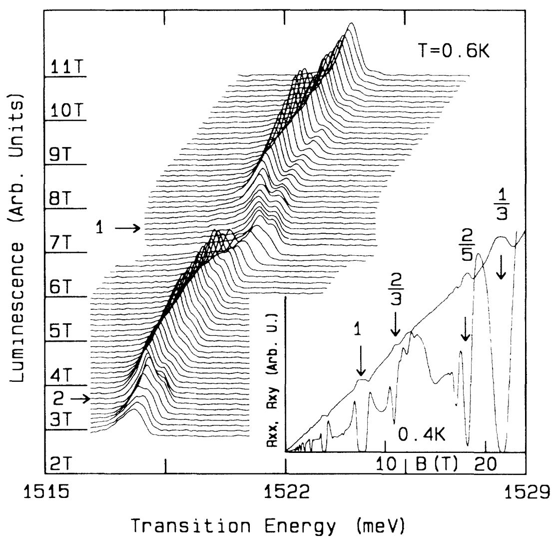

FIG. 1. Emission spectra of a sample (A) with $\mu = 3.2\times10^6$ cm^2/Vs and $n_s = 1.83\times10^{11}$ cm^{-2} at $T = 0.56$ K excited by a 1580-meV laser source ($p = 1.2\times10^{-4}$ W/cm^2). The B field is shown by following the spectral base line to the scale at the left-hand side. Inset: Typical R_{xx} and R_{xy} traces during illumination with $p = 8\times10^{-5}$ W/cm^2.

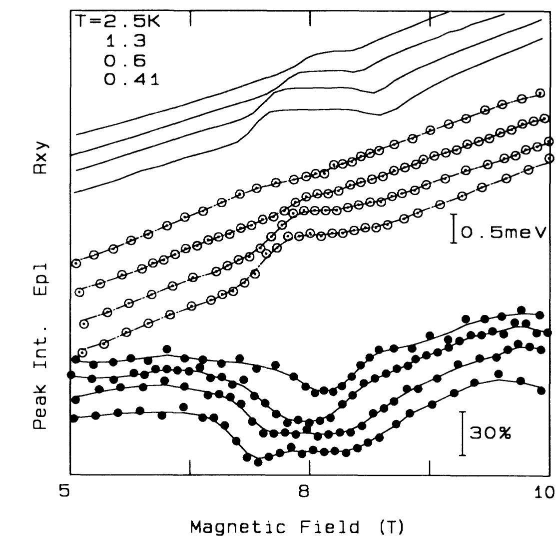

FIG. 2. Transition energy E_{PL} (circled dots), peak intensity (solid dots), and Hall resistance R_{xy} (solid lines) at $\nu = 1$ for sample A excited with $p = 8\times10^{-5}$ W/cm^2, 10-nm-bandwidth source centered at 780 nm at $T = 2.5$, 1.3, 0.6, and 0.41 K. The E_{PL} curves are offset by $+0.5$ meV each, and the peak intensity and R_{xy} curves by arbitrary constant values.

Two peaks are readily apparent above 4 T, and we confine our discussion to the lower-energy transition which polarization analysis shows is due to recombination of holes in the uppermost valence level with electrons in the lowest spin-split electron Landau level.[10]

The energy plateaus and intensity minima increase in width in B with decreasing temperature in the same manner as the width of the quantized Hall plateau in ρ_{xy} and zero-resistance state in ρ_{xx}. This direct correlation between the position of the Fermi level with respect to the localized and extended transport states and the optical anomalies in recombination has not been seen before.[3,5,11] Figure 2 presents a detailed study at the spin gap ($\nu = 1$). Since the peak width does not vary appreciably through the filling-factor minima, the minima in peak intensity also reflect minima in total integrated intensity. While in some samples the pinning of E_{PL} is not complete and appears more as a change in slope, the intensity minima are comparatively robust; they exist independent of excitation source and sample carrier density, appearing whenever E_F is in localized states. At each temperature from 2.5 K to 410 mK, the approximate B-field widths of the optical plateaus and intensity minima are within 30% of the corresponding Hall plateau (Fig. 2). The extent of quantized ρ_{xy} delineates the region in B over which E_F lies in a region of localized states. As the temperature is reduced, fewer extended states are within k_BT of E_F, causing the plateau width of ρ_{xy} to increase. The correspondence between the transport Hall plateau, intensity minima, and recombination-energy plateau widths observed upon cooling the 2D electrons associates the optical and transport phenomena with a common origin—the precise position of the Fermi energy in localized transport states.[12]

Theoretical calculations of the influence of screening on electron-hole recombination do not account well for the data.[8] The main many-body contributions to the single-particle electron and hole energies are the screened-exchange and the Coulomb-hole self-energy terms. For electrons, the exchange interaction is reduced by screening while the Coulomb-hole term is enlarged, and the two terms nearly cancel. For holes, so few exist ($< 10^{-5}n_s$) that the exchange term is irrelevant, leaving only the Coulomb-hole term. This correlation hole for the hole describes the additional electron density in the vicinity of the hole. The screening oscillates as E_F passes from the Landau-level centers to the gaps, causing the hole self-energy and thus E_{PL} to oscillate. The calculations use a phenomenological model of the density of states but do not include the effects of carrier localization, and the integer and fractional Hall effects are beyond their scope.[8]

The present data show that the passage of E_F into localized states at the edge of the ρ_{xy} plateau creates an abrupt change in the response of the electrons to the presence of the hole. In the absence of correlation effects, the oscillator strength should actually increase when the polarizability is reduced, since weaker screening causes a larger vertex correction (excitonic binding), yielding both greater electron-hole overlap and redshift in E_{PL}. This is complicated at integral and fractional gaps, since the dearth of states at E_F promotes the importance of *interlevel* over *intralevel* excitations, increasing the coupling to higher Landau levels. For the transition energy, the vertex correction is offset by the Coulomb-hole (correlation-hole) self-energy term—the polarization clouds of a closely spaced electron-hole pair cancel.[9] Hence with E_F in the gap region, the loss of electron screening may overcome any enhancement of electron-hole binding and cause the observed blueshift.

The data indicate that correlation effects may be greater than vertex corrections. Near $\nu=1$ the upper electron spin state has a much lower occupancy, which increases the vertex correction and reduces the electron self-energy exchange term. Yet the emission from both spin states exhibit the same shift at $\nu=1$ (Fig. 1), indicating that the correlation hole of the hole is the primary mechanism. It seems clear that a complete picture can only emerge with the proper inclusion of localization into the current theories.

We turn now to optics in the FQHE. Figure 3(a) shows simultaneous development of the minima in peak intensity and ρ_{xx} at $\nu=\frac{2}{3}$ for temperatures $T\leq 1.3$ K.[13] The reduction in luminescence peak intensity at fractional filling factors strengthens as the temperature is lowered, but ceases further action for temperatures well below the activation energy ($\sim$0.8 K for $\nu=\frac{2}{3}$ and 3 K for $\nu=\frac{1}{3}$). Figure 3(b) details the luminescence in the region of $\nu=\frac{2}{3}$, where the kinetic energy term ($\frac{1}{2}\hbar\omega_c$) has been subtracted from the transition energy. The peak position shifts abruptly just at $\nu=\frac{2}{3}$ by $\sim$0.1 meV, and is accompanied by a $\sim$20% increase in width. The line is too broad to distinguish between a simple shift and the appearance of a higher-energy component. Significantly, the peak narrows and returns to the kinetic-energy line on either side of the $\frac{2}{3}$ minima. The shift weakens to $\Delta E^{2/3}\sim 0.04$ meV at 0.77 K and ceases entirely above 1.4 K, concurrent with the disappearance of the ρ_{xx} minima. This clear evidence of the fractional quantum Hall effect in optics has been observed in four different samples.

In the high-field region about the FQHE states $\nu=\frac{2}{5}$ and $\frac{1}{3}$ a clear splitting ($\Delta E^{1/3}\approx 0.3$ meV) of the luminescence is seen (Fig. 4). At $T=1.3$ K (Fig. 4, left-hand side), the splitting is observed only about $\nu=\frac{1}{3}$, concurrent with a weak minima in ρ_{xx} *solely at that fraction.* The splitting exists only at temperatures low enough that fractional states are seen, and consists of components that exchange oscillator strength as a function of B. Difficulty in controlling the carrier density under illumination in the high fields ($B\geq 14$ T) at low temperatures ($T\leq 1$ K) sometimes causes the transport measurement to be incommensurate with the optical data. As the temperature is reduced, the higher-energy peak contains a greater percentage of the total oscillator strength, and extends over a larger range in B, similar to

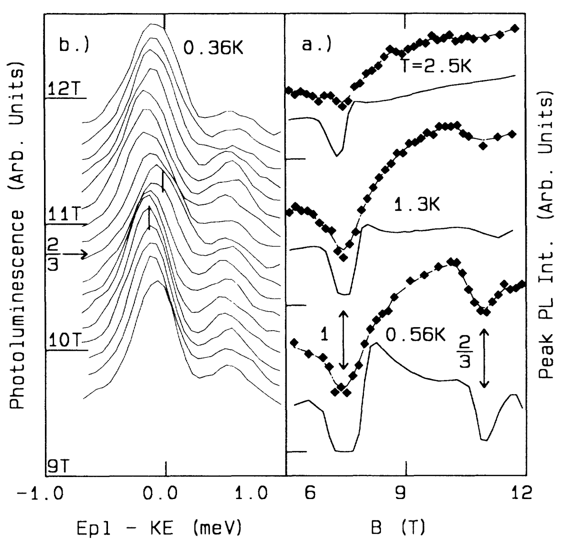

FIG. 3. (a) Peak intensity and R_{xx} in a sample (B) with $\mu=3.6\times10^{6}$ cm^2/V s and $n_s=1.81\times10^{11}$ cm^{-2} illuminated with a 40-nm-width source centered at 770 nm. (b) Luminescence spectra at fields about $\nu=\frac{2}{3}$ in a sample (C) with $\mu=3.3\times10^{6}$ cm^2/V s and $n_s=1.80\times10^{11}$ cm^{-2} at $T=0.36$ K. The kinetic-energy term ($\frac{1}{2}\hbar\omega_c$) has been subtracted to show clearly the peak shift which occurs *just* at $\frac{2}{3}$. The energy shift is $\Delta E_{\rm PL}^{2/3}\sim 0.1$ meV$\sim$1 K, and the activation energy measured from transport under illumination is $E_a^{2/3}=1.1\pm0.1$ K.

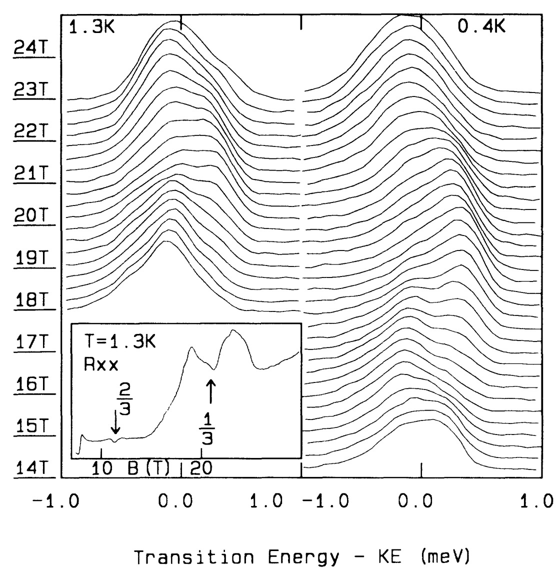

FIG. 4. Spectra of sample A at $\nu=\frac{2}{5}$ and $\frac{1}{3}$ with $\frac{1}{2}\hbar\omega_c$ subtracted as in Fig. 3(b). The left-hand side shows spectra at $T=1.3$ K, where the splitting is observed only about a narrow range at $\nu=\frac{1}{3}$ concurrent with a minima in ρ_{xx} solely at $\frac{1}{3}$. The right-hand side plots spectra at $T=0.4$ K, where the high-energy component is both more dominant and extends over a larger field range. Inset: R_{xx} vs B at $T=1.3$ K taken simultaneously with spectra.

our earlier work on low-mobility materials.[3] Also appearing at $T \leq 0.5$ K are additional splittings of weaker character in the region of $\nu = \frac{2}{5}$ (Fig. 4, right-hand side).

The optical signature of the FQHE in the high-field region is characterized by a line splitting with an energy spacing of ~ 0.3 meV and an emergence of the high-energy component which was seen in many samples. The transport activation energy is $E_a^{1/3} = 3.1 \pm 0.2$ K (0.27 meV), yielding a quasiparticle gap of ~ 6.2 K. Note that both the splitting and $E_a^{1/3}$ are about a factor of 3 greater than the shift and $E_a^{2/3}$ observed at $\nu = \frac{2}{3}$. In some samples the splitting was confined to a very narrow field region ($\Delta B = 0.5$ T) with the high-energy component dominant at higher fields.

The optical data in the integer regime show that the screening of the hole is important in determining the emission energy, and we are therefore reluctant, in the absence of a complete theory, to assign the peak shifts at $\nu = \frac{2}{3}$ and the splitting at $\nu = \frac{1}{3}$ directly to any quasiparticle gap. In addition, the splitting in the high-field region is unchanged over a significant range in field, whereas one would expect the quasiparticle energy gap ($^3\Delta$) to reach a maximum at a specific filling factor ν_c and diminish on either side. It is likely that the shift at $\nu = \frac{2}{3}$ exists over a narrow field range because there are no other FQHE states of similar strength nearby, while both the $\frac{2}{5}$ and $\frac{2}{7}$ states in the neighborhood of $\nu = \frac{1}{3}$ have measured activation energies exceeding 1 K, leading to a much broader range in B over which the high-energy component is observed. Since the luminescence probes the states of the 2D electrons which respond to the hole over a distance of a few screening lengths,[14] small changes in the local environment of the hole between different FQHE ground states may have a negligible effect on the emission in the high-field region.

These measurements show a direct correlation between the position of the Fermi energy in IQHE and FQHE gaps and the optical recombination energies and intensities. The energy shifts and intensity minima at integral filling factors indicate physical phenomena beyond the abrupt change in screening of the hole potential by the 2D electrons and make evident that localization effects play a fundamental role. At $\nu = \frac{2}{3}$ there is a minimum in the recombination intensity and a shift in the peak energy, and we surmise that the quasiparticles are involved in screening the hole potential over some suitable distance. In the regime of the fractions $\nu = \frac{2}{5}$ and $\frac{1}{3}$, evidence of a splitting coupled to the fractional quantum Hall state is presented.

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[12]Previously observed blueshifts in luminescence (Ref. 3) and absorption [e.g., B. B. Goldberg, *et al.*, Phys. Rev. Lett. **63**, 1102 (1989)] at $\nu = 1$ can only now be recognized as due to localized transport states. Well-to-well density fluctuations and preponderance of localized states in low-mobility samples could manifest as a splitting and emergence of new, blueshifted lines.

[13]For some samples the position of the higher-field fractions are shifted to lower magnetic fields at low temperatures because of a carrier depletion due to the effect of illumination. Since the simultaneous transport measures the local density under the conditions of illumination, this is not a severe problem in the low-field region.

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