Optical Detection of the Integer and Fractional Quantum Hall Effects in GaAs

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(Received 26 February 1990)

We report a definitive optical detection, using band-gap photoluminescence, of the integer and fractional quantum Hall effects in GaAs by a comprehensive study of integer states from $\nu=1$ to 10 and the $\nu=\frac{2}{3}$ hierarchy out to the $\frac{5}{9}$ daughter state, in an ultrahigh-mobility single heterojunction at 120 mK.

PACS numbers: 73.20.Dx, 73.40.Kp, 78.65.Fa

The integer and fractional quantum Hall effects[1,2] (IQHE and FQHE) occur in two-dimensional electron systems in a perpendicular magnetic field when the Landau-level filling factor ν is an integer or fraction p/q (where p is integer, q is odd integer in the $l=0$ level). They are characterized in transport by plateaus in the Hall resistivity ρ_{xy} at quantized values $h/\nu e^2$, with a corresponding zero or minimum in the longitudinal resistivity ρ_{xx}. The IQHE is observed at relatively high temperatures ($\lesssim 50$ K) and can be described in a single-particle framework. For the FQHE, electron-electron interactions play a crucial role: It is believed to result from condensation of electrons into an incompressible liquid[3] with an energy gap ~ 1 K to excited states. Elementary excitations of the electron liquid are fractionally charged quasielectrons and quasiholes ($e^* = \pm e/q$ at p/q filling),[3-5] which recondense to form successive daughter states in a hierarchical scheme[4] that are only clearly observed at mK temperatures, although it should be noted that recent theory[6] treats FQHE states as the IQHE of composite fermionic objects. While there is a report[7] of a spectroscopic measurement of the FQHE quasiparticle gap at $\nu=\frac{7}{3}$ and $\frac{8}{3}$ in a Si structure at 1.5 K, optical experiments that probe the QHE in GaAs have remained a major challenge.[8,9] An important advance was made by the observation of anomalies in the energy of photoluminescence near $\nu=\frac{2}{3}$ and 1 from a GaAs multiple quantum well at 0.4 K.[10] In this Letter we report a definitive detection of both the integer and fractional QHE in GaAs by measurements of intrinsic band-gap photoluminescence from electrons in $n=0$ and 1 subbands of the two-dimensional electron gas (2DEG) confined at a single heterojunction at 120 mK.

The modulation-doped $GaAs/Ga_{0.68}Al_{0.32}As$ heterojunction (1600-Å spacer) is shown schematically in the inset to Fig. 1: The electron density is 9.7×10^{10} cm^{-2} and the mobility is 9×10^6 cm^{2}V^{-1}s^{-1}. The GaAs layer (5000 Å) is very weakly n type ($\sim 10^{14}$ cm^{-3}), producing flat bands that give sharp luminescence lines. A GaAs/GaAlAs superlattice (SL) buffer acts to prevent carbon acceptors reaching the 2DEG. The unetched sample (with electrical contacts at the edges) was mounted in the dilute phase of a dilution refrigerator at 25 mK. Optical fibers delivered light from a dye laser at wavelength 740 nm (i.e., below the GaAlAs band gap) with an intensity $<10^{-4}$ W cm^{-2}, and transmitted luminescence to a spectrograph–charge-coupled-device detector with a spectral resolution of 0.05 meV. A sample temperature of 40 mK was achieved with the laser off; this increased to 120 mK under continuous illumination, as determined by comparison with transport measurements at elevated refrigerator temperatures with the laser off. Temperature rise and the presence of photoex-

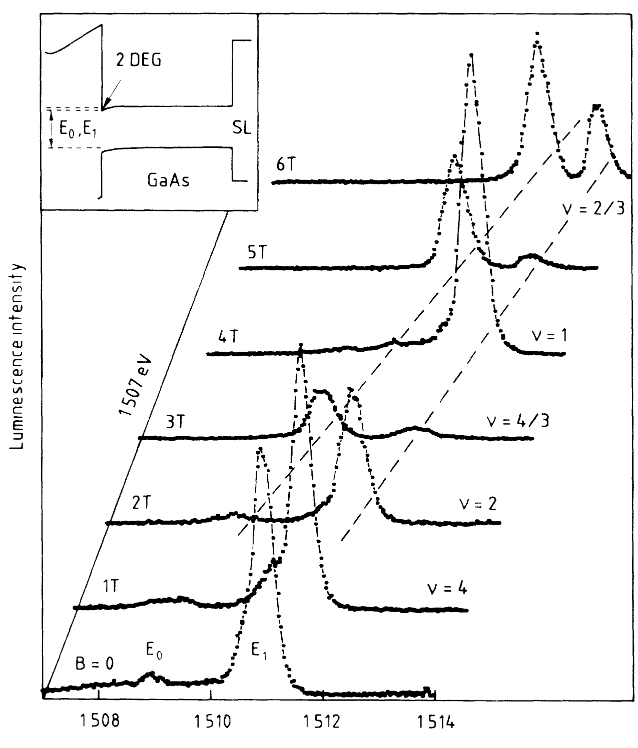

FIG. 1. Selected photoluminescence spectra at 120 mK in the field range $B=0$–6 T. Inset: Sample structure (see text) and E_0, E_1 energies.

cited holes both modify the depth of FQHE ρ_{xx} minima, but neither significantly affects the low-temperature transport characteristics of the 2DEG.

Luminescence spectra obtained at 120 mK are shown in Fig. 1 for several fields. They show two lines E_0 and E_1, whose zero-field energies are 1.5089 and 1.5109 eV. We assign these lines to recombination of electrons in the $n=0$ and 1 subbands of the confining potential. The much higher intensity of E_1 compared to E_0 at zero field is due to the greater penetration of $n=1$ electron wave functions into the GaAs layer where there is overlap with photoexcited hole wave functions. On increasing the magnetic field, both lines shift to higher energy as expected for electron-hole $l_e=0 \rightarrow l_h=0$ recombination (dashed lines in Fig. 1 are a guide to the eye), although a weak nonlinear variation of energy with field at low fields is suggestive of excitonic character. The E_0-E_1 peak-to-peak separation of 2.0 meV is less than the Fermi energy (3.5 meV); however, the ρ_{xx} data presented below show no evidence of any significant population in the upper subband, which further supports the possibility of excitonic character. The remarkable field-induced modulation of the *intensities* of both lines evident in Fig. 1 is highly correlated with changes in the electron ground state.

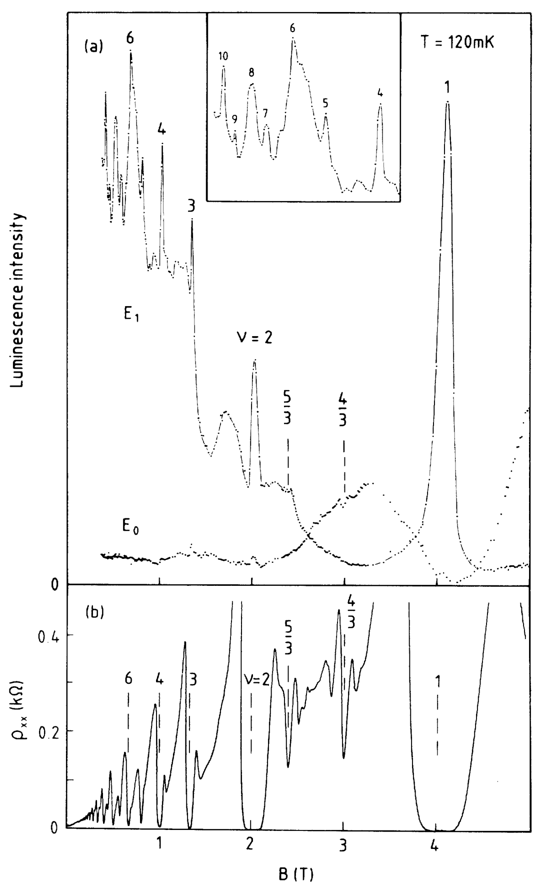

FIG. 2. (a) Intensities of the E_0 and E_1 luminescence lines at 120 mK as a function of magnetic field for $\nu \geq 1$. Inset: Region $\nu=10$ to 4 on an expanded scale. (b) Simultaneous ρ_{xx} data.

Low field ($\nu \geq 1$).—The peak intensities of E_0 and E_1 at 120 mK are shown in Fig. 2(a), together with ρ_{xx} data [Fig. 2(b)] taken simultaneously. The ρ_{xx} data show well-developed minima at integer filling $\nu=1$ to 10 and at fractional states $\frac{4}{3}$, $\frac{5}{3}$ [with weak minima at $\frac{7}{5}$, $\frac{8}{5}$, $\frac{9}{7}$, and $\frac{11}{7}$ (not labeled)]. The E_1 luminescence line has sharp intensity maxima at integer ν, stronger at ν even than at ν odd (with the exception of $\nu=1$). Underlying this behavior there is a general decrease in E_1 intensity with increasing field, with steplike drops at $\nu=5$, 3, and $\frac{5}{3}$. The E_1 intensity recovers at fields intermediate between $\nu=3$ and 4, and more strongly between $\nu=2$ and 3. In contrast, the E_0 intensity is weak and shows little variation for fields up to $\nu=2$. For $\nu<2$ the E_0 intensity first increases to a broad maximum, with a small but distinct dip at $\nu=\frac{4}{3}$, and then decreases to a small value at $\nu=1$. At this occupancy E_1 is dramatically enhanced by ~ 35 above base line; in fact, the peak occurs at 4.08 T, whereas the field for $\nu=1$ filling deduced from sharp FQHE ρ_{xx} structure is 4.0 T.

Although many additional factors will have to be considered, the field dependence of the E_0 intensity can be interpreted qualitatively in terms of screening. An electron can scatter between states in a partly filled Landau level in the $n=0$ subband to screen the potential of a photoexcited hole, thereby increasing the $n=0$ electron-hole wave-function overlap; in a completely filled level, screening is suppressed. Since the $l_e=0$ level is full for $\nu>2$, the E_0 signal which arises from $l_e=0 \rightarrow l_h=0$ recombination might be expected to be small in this range, as observed. For $1<\nu<2$ the $l_e=0$ level is partly filled and screening becomes active, consistent with the observed increase in E_0 intensity. At $\nu=1$, screening is strongly suppressed and the E_0 intensity falls very close to zero; the electronic g factor is exceptionally enhanced (by factors ~ 30 in similar samples) due to unscreened electron-electron interactions. For $\nu<1$ the E_0 intensity again recovers. Of particular interest, screening is also expected to be reduced in FQHE ground states, with a direct effect on the E_0 intensity; the small dip at $\nu=\frac{4}{3}$ (Fig. 2) and minima at fractional filling in the region $\nu<1$ discussed below (Fig. 3) provide additional support for this mechanism.

A number of factors also influence the E_1 intensity, including screening and occupancy. Excitonic character of the E_1 line will be weakened due to screening by $n=0$ electrons, and E_1 will therefore be enhanced at integral and fractional filling. The E_1 intensity is also dependent on the photoexcited population of the $n=1$ subband, which in turn depends on the density of vacant $n=0$ states. Furthermore, the matrix element for intersubband scattering by acoustic-phonon emission falls sharply when the energy of the emitted phonon becomes $\lesssim 1$

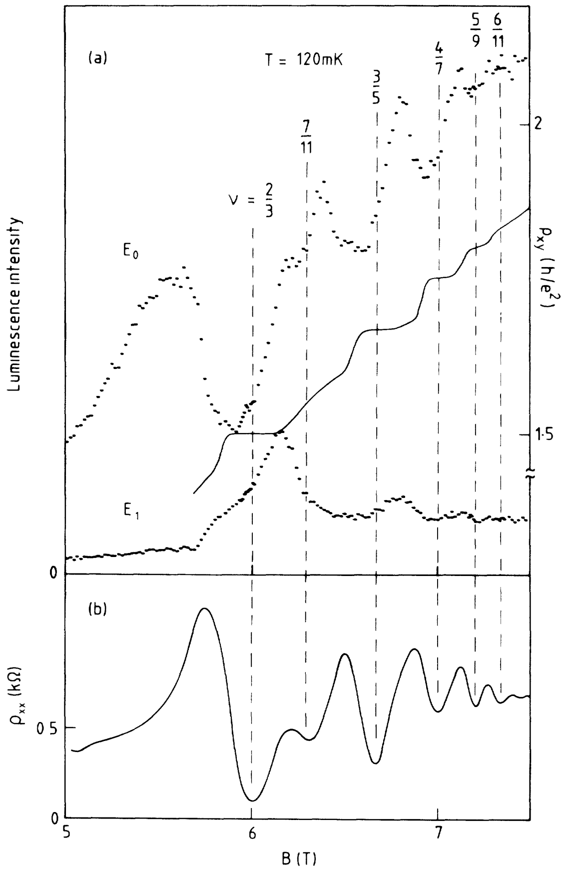

FIG. 3. (a) Intensities of the E_0 and E_1 luminescence lines at 120 mK for $\nu < 1$. (b) Simultaneous ρ_{xx} data. Also shown in (a) is a ρ_{xy} trace from a Hall bar sample at a similar temperature in the absence of laser illumination.

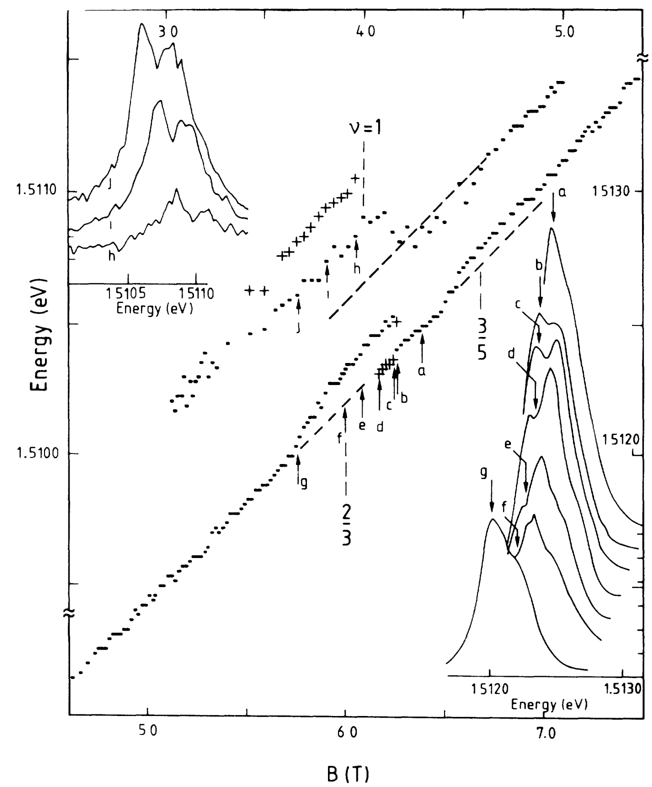

FIG. 4. Magnetic-field dependence of the energy of the E_0 luminescence line. Bottom and right-hand axes refer to the lower section of the figure (spanning the $\nu=\frac{2}{3}$ hierarchy), while top and left-hand axes refer to its low-field continuation (to the $\nu=1$ region). Lower and upper insets: Spectra showing E_0 doublet structures resolved at $\nu=\frac{2}{3}$ and 1. The weaker component is marked as +.

meV, holding up photoexcited electrons in E_1.[11] This occurs when the Fermi energy approaches the $n=1$ subband.

High field ($\nu < 1$).—E_0 and E_1 intensities presented in Fig. 3(a) are compared with ρ_{xx} data [Fig. 3(b)] taken simultaneously. Also shown are ρ_{xy} measurements of a Hall bar sample from the same wafer and with the same electron density, at a similar temperature but in the absence of laser illumination. The ρ_{xx} measurements identify FQHE states at $\nu=\frac{2}{3}$, $\frac{7}{11}$, $\frac{3}{5}$, $\frac{4}{7}$, $\frac{5}{9}$, and $\frac{6}{11}$. The resolution and structure in ρ_{xx} out to $\nu=\frac{5}{9}$ are mirrored in remarkable detail in the E_0 intensity. Significantly, the optical data in Figs. 2 and 3 were repeated with *no current* flowing in the sample and closely similar results were obtained. These results provide *definitive* evidence for optical detection of the FQHE. Whereas the E_0 intensity shows minima at the above fractions, the E_1 intensity develops maxima (as for the IQHE). The strength of these features decreases through the $\frac{2}{3}$ hierarchical sequence. The optical and transport structure are not in precise field alignment (see dashed lines in Fig. 3). E_1 maxima occur at fields above $\nu=p/q$ filling, whereas E_0 minima occur at lower fields. This is suggestive of localization effects, and the E_0 minima (E_1 maxima) correlate fairly well with the low- (high-) field extent of the ρ_{xy} plateaus shown. However, for $\nu=1$ in the IQHE, both the broad E_0 minimum and sharp E_1 maximum are close to the center of the ρ_{xx} minimum.

The field dependence of the E_0 energy in the $\nu=1$, $\frac{2}{3}$, and $\frac{3}{5}$ regions is shown in Fig. 4. The behavior around $\nu=\frac{2}{3}$, shown in the lower section of the figure, is striking. At $B=6.25$ T ($\nu=0.64$) a doublet structure is resolved, as shown in the lower inset (position *b*) with a splitting of 0.16 meV (1.8 K). The lower component of the doublet lies on a line extrapolated from lower field (arrows in the inset mark energies corresponding to this line). With decreasing field the higher-energy component becomes the more intense, and the relative strength of the lower component rapidly diminishes (Fig. 4, lower inset, *a–e*). The peak of the luminescence remains above the extrapolated line for a range of fields spanning $\nu=\frac{2}{3}$ (lower inset, *c–f*) before shifting down to the line at $B=5.75$ T ($\nu=0.7$), although a weak upper component is still discernible at this (lower inset,

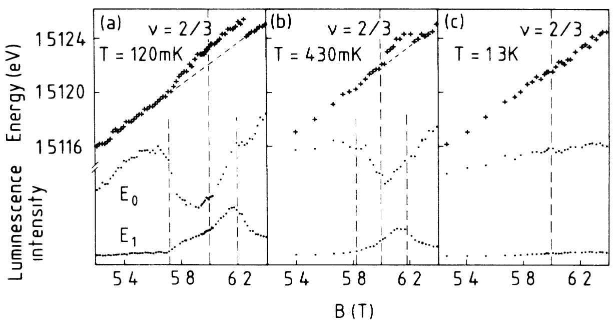

FIG. 5. Temperature dependence of the E_0 energy and the E_0,E_1 intensities near $\nu=\frac{2}{3}$ at (a) $T=120$ mK, (b) $T=430$ mK, and (c) $T=1.3$ K. The vertical broken lines adjacent to $\nu=\frac{2}{3}$ mark the extreme extent of the $\frac{2}{3}$ ρ_{xx} minimum.

g) and lower fields. A similar effect is seen around $\nu=\frac{3}{5}$, although it is less distinct. At $\nu=1$ the luminescence peak is shifted upwards in energy by 0.2 meV (2.4 K) and an upper component becomes resolved again (see upper inset, spectra h, i, and j), a further 0.2 meV higher in energy. The doublet structure is not well resolved at lower fields, but the shift to high energy is maintained. In contrast, the energy of E_1 is linear in field throughout this entire range (not shown).

Kukushkin and Timofeev[7] first observed energy shifts of +0.34 meV (4 K) and −0.26 meV (3 K) above and below $\nu=\frac{7}{3}$ (in filling factor) in a Si structure; these shifts were interpreted to be $3\epsilon_e$ and $3\epsilon_h$, where ϵ_e and ϵ_h are the quasielectron and quasihole creation energies, which agreed quantitatively with measurements of the transport gap $\Delta=\epsilon_e+\epsilon_h$. In the luminescence spectrum of a GaAs multiple quantum well Heiman *et al.*[10] observed a shift of 0.7 meV (8.1 K) at $\nu\approx\frac{2}{3}$ which could not be identified as a quasiparticle energy. Our observed doublet separation of 0.16 meV (1.8 K) at $\nu\approx\frac{2}{3}$ is smaller than the transport gap $\Delta_{2/3}=4.6$ K. Furthermore a doublet structure, albeit not clearly resolved, extends to fields significantly below $\nu=\frac{2}{3}$, and a doublet is also resolved at and below $\nu=1$ with a similar energy separation. It is clear that the doublet splitting at $\nu=\frac{2}{3}$ is not simply related to the quasiparticle gap and our observations require a quantitative theory of photoluminescence in both the IQHE and FQHE regimes.

In Fig. 5 we present a combined plot comparing the E_0 energy and the E_0,E_1 intensities around $\nu=\frac{2}{3}$ at three temperatures 120 mK, 430 mK, and 1.3 K. Vertical lines also mark the extreme limits of the ρ_{xx} $\frac{2}{3}$ minimum. This comparison provides convincing evidence that the optical anomalies are associated with the $\frac{2}{3}$ ground state: The intensity of E_0 decreases sharply at the low-field limit, whereas the intensity of E_1 decreases sharply at the high-field limit (the latter is close to the entry point into the $\frac{7}{11}$ ground state). At 120 mK the correlation of the transport data, luminescence intensities, and the E_0 shift is excellent. At 430 mK the field region in question has narrowed. At 1.3 K all indications of the $\frac{2}{3}$ state have vanished from both the optical and transport data.

In summary, we have made a definitive observation of the FQHE and IQHE by optical spectroscopy of an ultrahigh-mobility GaAs/GaAlAs single heterojunction at mK temperatures. Photoluminescence intensity modulations correlate strikingly with the integer and fractional QHE in GaAs, whereas energy anomalies cannot be assigned to FQHE quasiparticle gaps. This work presents a considerable theoretical challenge, and opens the way for optical spectroscopy of the Wigner solid.

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