Optical Anomalies of the Two-Dimensional Electron Gas in the Extreme Magnetic Quantum Limit

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(Received 12 November 1987)

Band-gap optical recombination from the two-dimensional electron gas in GaAs-(Al,Ga)As quantum wells was measured in the regime of the fractional quantum Hall effect. New intrinsic emission lines emerge at the Landau-level filling factor $\nu \lesssim 1$ and at $\nu < 0.8$. The anomaly near $\nu = 1$ is associated with changes in population of the lowest spin-split Landau level. The spectral doublet observed near $\nu = \frac{2}{3}$ has a striking temperature dependence below $T = 2$ K similar to the magnetoresistance ρ_{xx} associated with the many-body quantum fluid.

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

Observations of the fractional quantum Hall effect (FQHE)[1,2] are understood as evidence of condensation of the two-dimensional (2D) electron gas into an incompressible fluid with quasiparticle excitations having fractional charges.[2-4] The FQHE is observed in magnetoresistance experiments as plateaus in the Hall resistance and minima in the diagonal resistivity at fractional values of the Landau-level filling factor having an odd denominator. Magneto-optics experiments in the FQHE regime could reveal physics of the many-body condensate that is not accessible in magnetotransport. Results have been reported for silicon metal-insulator-semiconductor transistors, at $\nu = \frac{7}{3}$ and $\frac{8}{3}$ and $T = 1.5$ K,[5] and in modulation-doped GaAs-(Al,Ga)As quantum wells at $\nu \simeq \frac{2}{3}$ and $T \simeq 0.5$ K.[6]

This Letter presents results of optical spectroscopy of the 2D electron gas in magnetic fields of $B \leq 30$ T and temperatures $T \geq 0.4$ K. In this extreme magnetic quantum limit all the electrons are in the lowest spin-split Landau level. The experiments were carried out on high-mobility GaAs quantum wells by measurements of the intrinsic optical emission due to recombination of electrons in the 2D electron gas with holes in the valence Landau level. We observe two remarkable anomalies in the optical emission. The first occurs at $\nu \lesssim 1$, where a new recombination line emerges at a slightly higher energy than the intrinsic line and becomes dominant with increasing magnetic field. The second anomaly occurs for filling factors $\nu < 0.8$ when another new high-energy emission line appears. At $\nu \simeq \frac{2}{3}$ the low-temperature optical recombination takes the form of a well-defined doublet. The temperature dependences of these anomalies are very different. The one at $\nu \simeq 1$ has little variation for $T < 2.5$ K, *while the doublet at $\nu<0.8$ changes rapidly in the measured temperature range $0.4<T<2.5$.* The temperature dependence of the optical emission at $\nu \simeq \frac{2}{3}$ is similar to that of the diagonal magnetoresistivity ρ_{xx} in the observed FQHE.

Simultaneous optical and transport measurements were carried out on n-type modulation-doped GaAs-(Al_xGa_{1-x})As multiple quantum wells grown by molecular-beam epitaxy. These structures have 20–30 periods of 17.5- or 20-nm-thick GaAs wells and 50–55-nm-wide $Al_{0.3}Ga_{0.7}As$ barriers. Three samples showed well-defined magnetoresistance minima at $\nu = \frac{2}{3}$. They have densities of 1.8, 3.5, and 3.9×10^{11} cm^{-2} with respective mobilities of 1.3×10^5, 2.0×10^5, and 2.3×10^5 cm^2/(V sec). A fiber-optic apparatus,[7] modified by the

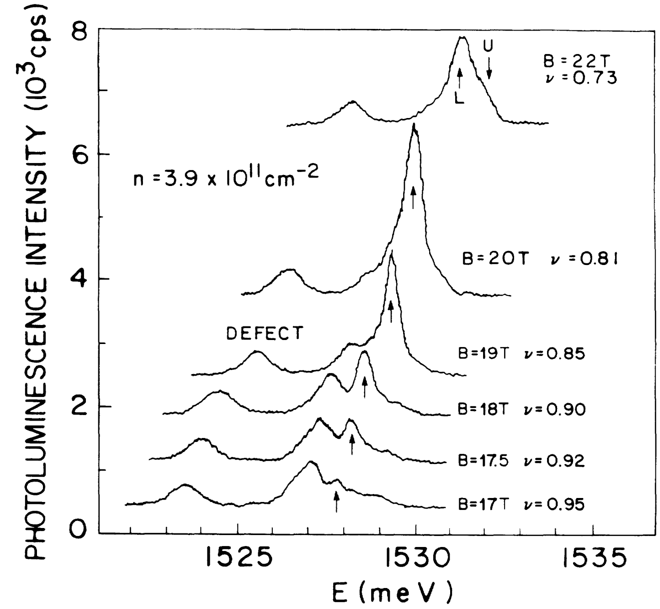

FIG. 1. Photoluminescence spectra of the 2D electron gas in GaAs-(Al,Ga)As quantum wells. The arrows indicate the new peak appearing for $\nu < 1$. The second anomaly is identified by the new feature labeled *U*.

use of a single 600-μm-diam silica fiber, was used to transmit the excitation light and to return the photoluminescence (PL) from the sample. The apparatus was placed within a ^{3}He cryostat in which temperatures as low as 0.4 K could be achieved in a high-field ($B \lesssim 30$ T) dc hybrid (superconductor and Bitter solenoid) magnet. The power of the incident light was kept below 10^{-3} W/cm^2 with no effect on the magnetotransport results, indicating no significant changes in temperature and density of the 2D electron gas.

Figure 1 shows spectra taken in the magnetic quantum limit $\nu < 1$, which occurs at $B = 16.3$ T. We ascribe the features at higher energies to recombination of an electron in the 2D electron gas with a photoexcited hole in the highest valence Landau level since *they occur close to the onset of absorption observed in the PL excitation spectrum.*[8] The weaker peak appearing at $\simeq 3$ meV below has a sizeable Stokes energy shift from the absorption and is assigned to recombination at a defect.[9]

For increasing B a new intrinsic line rapidly emerges when $\nu < 1$, denoted by arrows. It is absent at $B = 16$ T ($\nu \simeq 1$) but grows in intensity with increasing field, until for $B > 18$ T ($\nu < 0.9$) it is the dominant feature of the spectrum. The emission is well polarized and this identifies it as arising from transitions between the lowest spin-split Landau level and the uppermost valence level ($+\frac{1}{2} \rightarrow +\frac{3}{2}$). The band at lower energy may be attributed to shakeup processes in which the optical recombination takes place with simultaneous creation of low-lying excitations,[10] or to carriers confined in shallow potential fluctuations. The energies of the PL peaks are plotted in Fig. 2 as a function of magnetic field (note that many-body effects renormalize the $B \rightarrow 0$ and $B > 0$ peak energies *below* that for bulk GaAs[11]). The magnetic fields that corresponds to filling factors $\nu = 1$ and $\nu = \frac{2}{3}$, indicated by arrows, were obtained from the diagonal magnetoresistance trace shown in the lower inset. For $\nu < 1$ the intrinsic emission shows multiplet structure and differs markedly from the "plateaus" observed at higher filling factors.[12]

The second anomaly occurs when $B \gtrsim 20$ T ($\nu < 0.8$), where we discern another new peak which first appears as a weak high-energy shoulder $\simeq 0.7$ meV above the main peak (denoted as U in Fig. 1). This new high-energy emission increases in intensity with increasing field, and as shown in Fig. 3, in the vicinity of $\nu = \frac{2}{3}$ it becomes a well-developed doublet. At higher fields the higher-energy component of the doublet becomes dominant. Figures 3(a) and 3(b) show this behavior at two temperatures, $T = 0.4$ and 0.8 K. At the higher temperature a larger field is needed to produce equal intensity components. The bars denote the position and relative

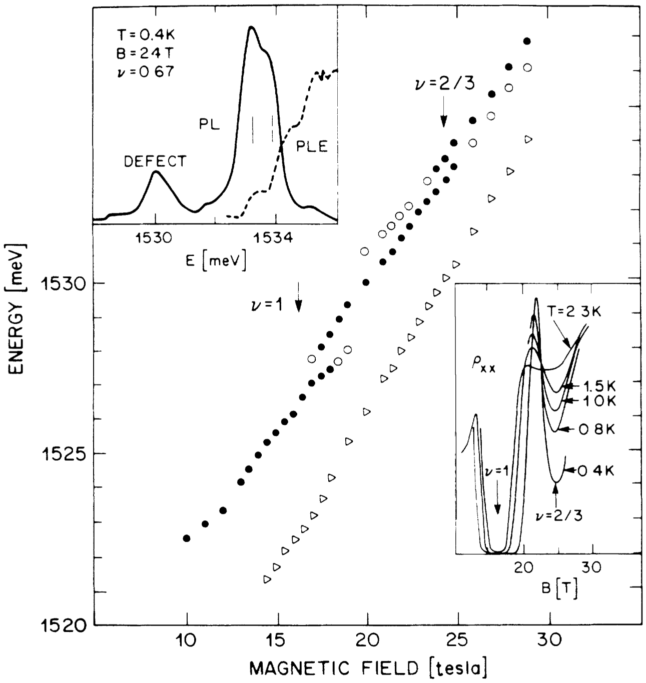

FIG. 2. Peak energies in PL spectra of the 2D electron gas in GaAs quantum wells. The intrinsic peaks are represented by filled (open) circles for strong (weak) intensities. The triangles are for extrinsic (defect) peaks. Upper inset: emission (PL) and excitation (PLE) spectra in the FQHE regime. Lower inset: magnetoresistance $\rho_{xx}(B)$.

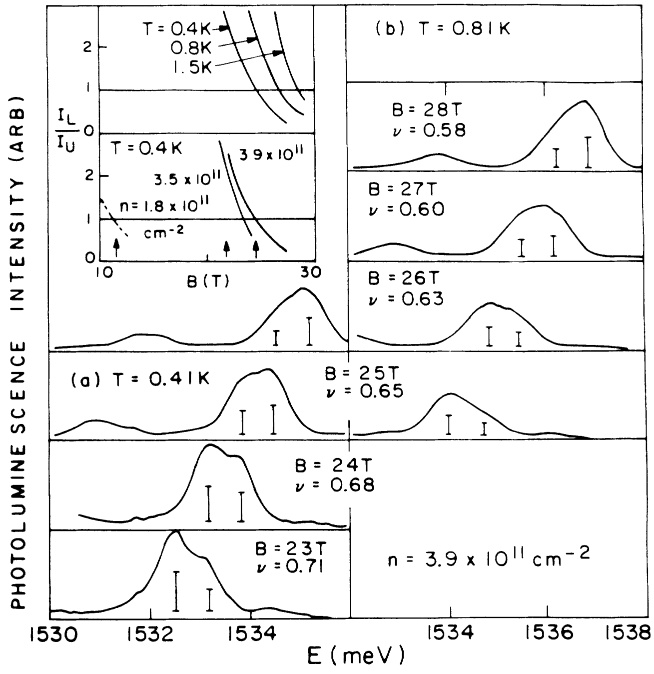

FIG. 3. Photoluminescence spectra of the 2D electron gas in GaAs quantum wells in the regime of the FQHE, for temperatures (a) $T = 0.41$ and (b) 0.8 K. The vertical bars represent energy positions and relative intensities ($\times \frac{1}{2}$) for the Gaussian doublet components. Inset: the intensity ratio I_L/I_U. (Solid lines have replaced discrete data points for clarity.)

intensities of the components determined from fits with the sum of two Gaussians. The field-dependent energies of the upper (U) and lower (L) peaks are displayed in Fig. 2. Note that their energy separation is nearly *field independent* and at low temperatures they coexist over a large range of fields, $20 \lesssim B \lesssim 30$ T. The persistence of the anomaly over such a wide field interval indicates that it is not related to resonant polaron coupling[13] (Landau-level splitting equal to LO phonon energy) that occurs at $B \simeq 22$ T.

The rapid increase in the intensity of the high-energy peak at $\nu < 1$ indicates that it is influenced by changes in the screening response of the 2D electron gas with decreasing filling factors. For increasing field below $\nu = 1$ the lowest spin-split Landau level becomes partially occupied and the screening wave vector of the electron gas increases.[14] The electron density increases near the positive charge and the increased electron-hole overlap produces an enhanced optical matrix element (oscillator strength). The temperature dependence of the optical anomaly should be similar to that of the minimum in ρ_{xx}. This is in agreement with experiment, where the spectral line shapes and intensities undergo only minor changes in the range $0.4 \leq T \leq 3$ K.

The behavior at $\nu < 0.8$ is strikingly different. Figure 4 displays the temperature variation (at fixed B) of the intensities of the L and U components of the emission doublet at $\nu = 0.68$. These measurements exemplify the large temperature dependence of the anomaly at $\nu < 0.8$, in which *changes of 50 mK in sample temperature could be noticed in the spectra.* The anomaly disappears for $T > 2$ K, when a singlet emission emerges. The large temperature dependence of the anomaly is unexpected because the temperature change, 1.5 K = 0.13 meV, is considerably smaller than the splitting between the two components of the doublet (0.5–0.7 meV). Such temperature dependence cannot be explained by defect recombination and changes in the populations of electrons and photoexcited holes because *with increasing temperature it is the lower-energy peak that becomes stronger.* The inset in Fig. 4 compares the intensity ratio of the peaks, I_L/I_U, with that of the activated behavior of the minimum in ρ_{xx} at $\nu = \frac{2}{3}$, where the activation energy $\Delta/2 = 0.44$ K is lower than in a comparable-mobility single heterojunction.[15] The temperature dependence of I_L/I_U is similar to that of the FQHE at $\nu = \frac{2}{3}$.

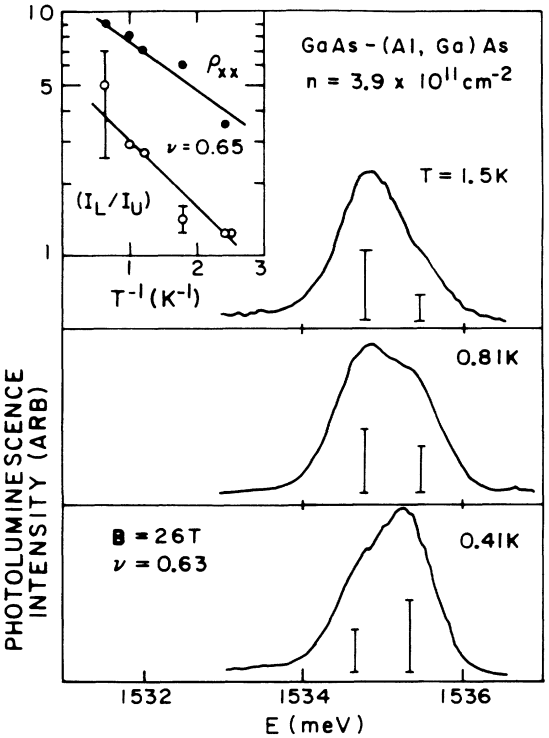

FIG. 4. Temperature dependence of the PL optical anomaly of the 2D electron gas in GaAs quantum wells. Inset: $\log(I_L/I_U)$ and magnetoresistance $\log(\rho_{xx})$ vs $1/T$.

The field dependence of the anomaly near $\nu \simeq \frac{2}{3}$ is summarized in the inset of Fig. 3, which shows I_L/I_U vs B. The upper traces display the temperature dependence for a given density. The curves have similar B dependences but shift to higher fields for higher temperature. Note that the crossover $I_L/I_U = 1$ shifts to higher B for higher T. Additional evidence that the anomaly is related to the $\nu = \frac{2}{3}$ FQHE is shown by the field dependence of I_L/I_U for samples with densities differing by more than a factor of 2. The arrows in the lower part of the inset, indicating $\nu = \frac{2}{3}$ from the ρ_{xx} minima, show reasonable agreement with the condition $I_L/I_U = 1$. Unfortunately, in the lowest-density sample the intrinsic peak at $\nu \simeq \frac{1}{3}$ was obscured by the defect band which is close in energy at these fields.

It is of interest to compare the present work with results reported[5] for optical emission from Si inversion layers at $\nu = \frac{7}{3}$ and $\frac{8}{3}$. Because of the reduced overlap between electrons and photoexcited holes on spatially separated acceptors, many-body corrections to the recombination energy are believed to be small and the dependence of photon energy on filling factor was used to estimate the gap of the FQHE. In our case, the presence of the hole is a major perturbation known to cause substantial many-body[10,16] and excitonic[17] effects. For this reason, the splitting of the doublet near $\nu = \frac{2}{3}$ is nearly constant with filling factor and is not used to estimate the energy gap of the FQHE.

In our interpretation of optical recombination in the extreme magnetic quantum limit the anomalies are related to the response of the 2D electron gas to the presence of the hole in a valence Landau level. For $\nu < 1$ there is enhanced screening because the electrons can change their state within the lowest Landau level. Further changes in the screening response are caused by condensation of the electrons into incompressible many-body states. In the FQHE regime the response to the hole should be treated like the cases of charged impurities and disorder.[18] A quantitative description of the optical anomalies is beyond the scope of this study. It should include many-body and excitonic interactions and account for the fact that it is the higher-energy peaks that become dominant for increasing field or decreasing temperature.

We thank B. I. Halperin, P. Hawrylak, P. Platzman, L. J. Sham, H. L. Störmer, and D. C. Tsui, for discussions. K. Baldwin, B. Brandt, L. Rubin, and J. P. Valladares provided expert assistance. One of us (B.B.G.) acknowledges support of the Massachusetts Institute of Technology through a Bantrell Postdoctoral Fellowship. The National Magnet Laboratory is supported by the National Science Foundation Grant No. DMR-8511789.

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