Magneto-optical Evidence for Fractional Quantum Hall States down to Filling Factor $\frac{1}{9}$

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Discontinuities have been observed in the energy dependence on magnetic field of the luminescence line corresponding to 2D electron-hole recombination in GaAs/AlGaAs heterojunctions at filling factors $\nu=\frac{2}{3}$, $\frac{1}{3}$, $\frac{4}{5}$, $\frac{3}{5}$, $\frac{2}{5}$, $\frac{1}{5}$, $\frac{1}{7}$, and $\frac{1}{9}$. We associate these energy-position shifts with discontinuous behavior of the chemical potential due to condensation of the 2D electrons into an incompressible Fermi-liquid state, and thereby evaluate the energy gaps at fractional filling factors down to $\frac{1}{9}$.

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The fractional quantum Hall effect (FQHE) is now understood to occur as a result of condensation of the two-dimensional (2D) electrons into incompressible quantum fluids at filling factors $\nu=p/q$ ($\nu=hn_S/eH$, where n_S is the 2D density, H is a perpendicular magnetic field, and p,q are integers with q odd) with quasiparticle excitations separated from the ground state by energy gaps Δ_G.[1-3] Experimental measurements of these energy gaps provide a rigorous test of the theories, which also predict that at sufficiently small ν [at $\nu\simeq\frac{1}{10}$ (Ref. 2)] a liquid-to-solid transition should occur when the ground-state energy of the Wigner crystal becomes lower than that of the quantum fluid.[2,3] So far, observation[4] of this changeover has proved controversial and fractional states down to $\nu=\frac{1}{7}$ have been detected.[5] The usual method for experimental determination of the FQHE gaps is activated magnetotransport.[6-9] However, in the region of small ν these measurements become extremely difficult due to strong localization at low temperatures and high magnetic fields. In this work we measure the FQHE gaps by means of magneto-optics which is much less sensitive to localization.

Optical measurements in the FQHE regime were first undertaken on Si-MOSFETs (metal-oxide-semiconductor field-effect transistors)[10] and then in GaAs/AlGaAs quantum wells.[11] Although in the Si-MOSFETs the measurements allowed determination of the quasiparticle gaps, this has so far not been achieved in a GaAs structure. Here we report the first optical measurements of the FQHE gaps at $\nu=\frac{2}{3}$, $\frac{1}{3}$, $\frac{4}{5}$, $\frac{3}{5}$, $\frac{2}{5}$, $\frac{1}{5}$, $\frac{1}{7}$, and $\frac{1}{9}$ in GaAs/AlGaAs single heterojunctions (SH). These have been determined from the discontinuous dependence on magnetic field of the energy position of the luminescence line.

The radiative transition studied was that due to a 2D electron recombining with a hole bound to a neutral acceptor (B line[12]) from a Be monolayer located in the GaAs (buffer width 50–100 nm) at a distance of 25 nm from the interface of a series of $GaAs/Al_xGa_{1-x}As$ ($x=0.28$–0.32) SH (mobility $\mu\simeq10^6$ cm^2/Vs under continuous illumination[13]). It was possible to change the concentration n_S by the excitation power[14] and for samples 1 and 2 the variation was $(1.9$–$2.5)\times10^{11}$ and $(0.54$–$1.2)\times10^{11}$ cm^{-2}, respectively. The high quality of our samples was confirmed by the observation of FQHE states at $\nu=p/q$ (with $q=3,5$) in magnetotransport measured in both the dark and under continuous illumination. The samples were mounted in a ^{3}He cryostat with optical access via a fiber-optic system. A sample temperature (measured by a coplanar RuO_2 resistance thermometer) of 340 mK was attained in the dark (400–600 mK under continuous illumination which was controlled by the high-energy tail of the luminescence line which is sensitive to temperature) in magnetic fields up to 28 T. Photoluminescence was excited using an Ar^+ laser (10^{-4}–10^{-3} W) and detected by a cooled GaAs photomultiplier and a triple spectrometer with 0.06-meV resolution.

In Fig. 1 we show luminescence spectra from two samples at various magnetic fields. The whole 2D energy spectrum below the Fermi energy, as observed at zero field, splits in transverse low magnetic fields into Landau levels [Fig. 1(a)]. From the relative intensities of the different Landau levels and their dependence on magnetic field we were able to evaluate n_S to an accuracy better than 2%. In the higher-quality sample (sample 2), the luminescence linewidth at low fields is approximately 2 times smaller than that of sample 1; its high-field behavior is shown in Fig. 1(c). We will consider the shape of the line measured at high fields from sample 2 further, below. Shubnikov–de Haas oscillations measured in sample 2 with a Hall-bar geometry are also shown in Fig. 1(b). They were taken under continuous illumination; hence the background of strong positive magnetoresistance due to parallel bulk photoconductivity. The high quality of this sample is confirmed here by the ob-

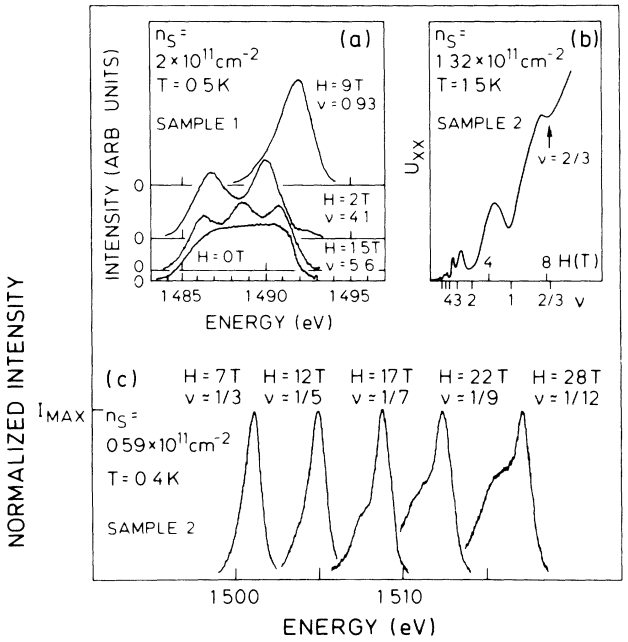

FIG. 1. The luminescence spectra measured (a) at 0.5 K in sample 1 and (c) at 0.4 K in sample 2 at various magnetic fields. (b) The transport Shubnikov-de Haas oscillations, measured at 1.5 K in sample 2 under continuous illumination.

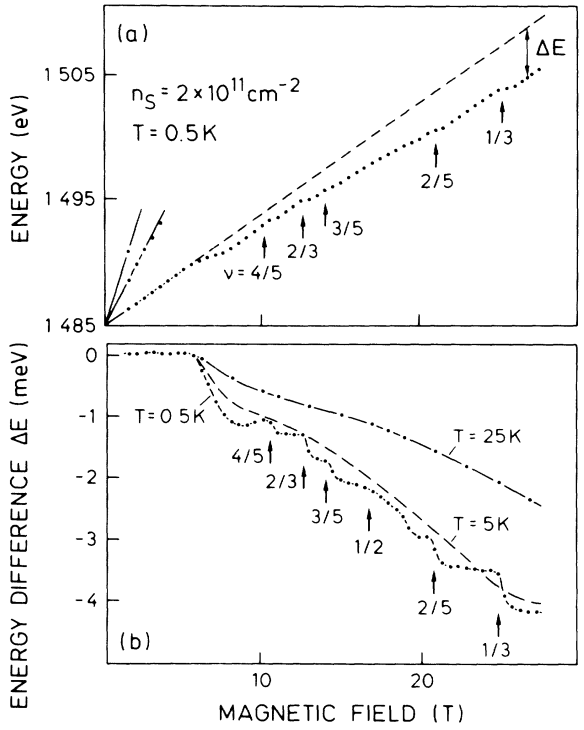

FIG. 2. (a) The dependence of the luminescence line peak position on magnetic field measured at 0.5 K for sample 1. (b) $\Delta E(H)$ measured for different temperatures.

servation of a minimum at $\nu=\frac{2}{3}$ at the rather high temperature of 1.5 K and the rather low magnetic field of 7 T (compare with Ref. 15).

The plot of the peak energies as a function of magnetic field [Fig. 2(a)] appears linear above $\nu=2$. However, below that, distinct steps are apparent in the magnetic-field dependence of the luminescence line position. The largest occurs between $\nu=2$ and $\nu=1$, which is the result of enhancement of the electronic spin splitting (the so-called g-factor enhancement[16]). It can be seen from this figure that as the magnetic field is further increased additional abrupt changes in the spectral position of the line are observed at low temperatures in the vicinity of $\nu=\frac{4}{5}$, $\frac{2}{3}$, $\frac{3}{5}$, $\frac{2}{5}$, and $\frac{1}{3}$. The sizes of these steps are small compared to the cyclotron energy (which mainly determines the dependence of the spectral position on H). Therefore, in Fig. 2(b) we have replotted the same data but this time as the energy shift (ΔE) from the line drawn through the low-field data. Here the discontinuities at $\nu=\frac{4}{5}$, $\frac{2}{3}$, $\frac{3}{5}$, $\frac{2}{5}$, and $\frac{1}{3}$ can be seen much more clearly. Note that in the vicinity of $\nu=p/q$ we also observe a small ($\simeq10\%$) broadening of the luminescence line. In addition, there appears to be a broad feature in $\Delta E(H)$ around $\nu=\frac{1}{2}$. In this sample, on raising the temperature to 5 K all the discontinuities associated with odd-denominator ν disappear except that due to $\nu=\frac{1}{3}$, which is severely weakened at 5 K and disappears completely at higher temperatures. Also to be noted is the persistence of the feature around $\nu=\frac{1}{2}$ at 5 K and even at 25 K. The low sensitivity to temperature of this feature, which (contrary to those at odd ν) spreads over a wide region of ν around $\frac{1}{2}$, is analogous to that reported for transport measurements.[15] The general dependence of ΔE on H in Fig. 2(b) which becomes less negative with rising temperature is due to magnetic-field-induced localization and can be used as a measure of the amount of disorder in a sample (instead of μ).

From a series of samples and a range of concentrations we have detected anomalies in the energy position at $\nu=\frac{2}{3}$, $\frac{1}{3}$, $\frac{4}{5}$, $\frac{3}{5}$, $\frac{2}{5}$, $\frac{1}{5}$, $\frac{1}{7}$, and $\frac{1}{9}$ as depicted in Fig. 3(a). It is important to stress that these results were absolutely reproducible, even after thermal cycling. The observation of structure due to such low filling factors has so far proved elusive in magnetotransport experiments. This has been due to large increases in background resistivity for $\nu<\frac{1}{5}$ caused by magnetic-field-induced localization due to disorder.[5] A magneto-optical measurement, which acts as a local probe, is less sensitive than a macroscopic probe, such as a magnetotransport measurement, to this localization. In Fig. 3(b) we compare the dependence of ΔE on H measured at three different temperatures in sample 2. At 0.4 K we observe discontinuities at all $\nu=1/q$ down to $\frac{1}{9}$ but practically no change in position at $\nu=\frac{1}{11}$. By 1.2 K the steps in $\Delta E(H)$ at $\nu=\frac{1}{7}$ and $\frac{1}{9}$ have disappeared while those associated with fractions with larger gaps remain. It is important to note that the actual position of the line corresponding to the data points for 1.2 K [dashed line in Fig.

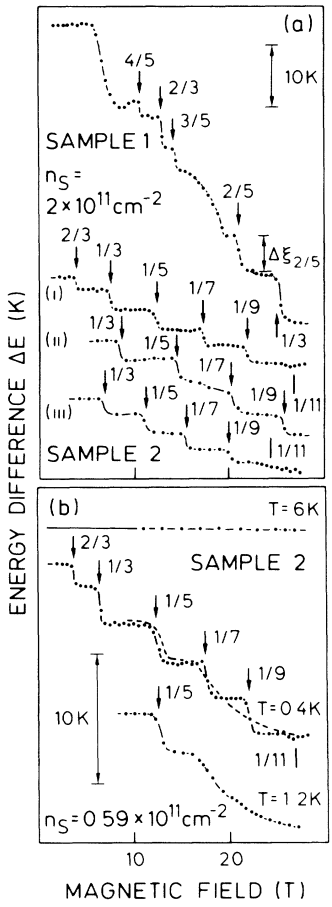

FIG. 3. (a) $\Delta E(H)$ measured for samples 1 and 2 at different concentrations: (i) 0.59×10^{11}, (ii) 0.7×10^{11}, (iii) 0.54×10^{11} cm^{-2}. (b) $\Delta E(H)$ measured for sample 2 at different temperatures. The dashed line depicts the actual position of the data measured at 1.2 K relative to that at 0.4 K.

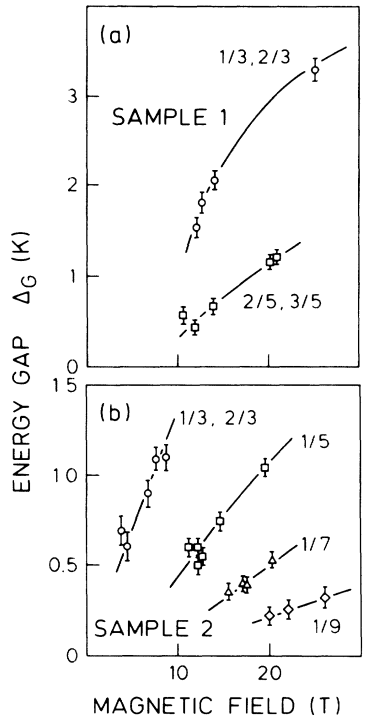

FIG. 4. The FQHE gaps vs magnetic field measured for different fractions for (a) sample 1 and (b) sample 2.

3(b)] cuts through the center of the steps observed at 0.4 K. At 6 K the slope of the data at high field does not differ from that at low field. This indicates that the degree of localization in sample 2 is much less than in sample 1.

According to the microscopic theory proposed by Laughlin[2] the ground-state energy of the 2D electron system $E(N)$ (N is the total number of electrons) at $T=0$ demonstrates cusps at $N=N_F$ corresponding to $\nu=p/q$. This results in a discontinuous change in the chemical potential $\xi=\Delta E/\Delta N$ at this point such that $\Delta\xi_{p/q}=(\Delta E/\Delta N)_{N_F}=q\Delta_G$, where Δ_G is the FQHE gap corresponding to $\nu=p/q$. Magneto-optics allows determination of the values $\Delta\xi_{p/q}$ since the spectral position of the luminescence line is directly influenced by changes in the chemical potential.[10] In Si-MOSFETs the energy gaps evaluated from luminescence measurements were found to quantitatively agree with those obtained from activated transport studies.[10] Taking the size of the step as $\Delta\xi_{p/q}$, as depicted in Fig. 3(a), we have plotted in Fig. 4 the so-determined Δ_G. These gaps depend strongly on sample quality[6,7] and we therefore show those for samples 1 and 2 in Figs. 4(a) and 4(b) separately. The gap values and their dependence on H obtained from sample 1 are comparable to those measured[6] by the activated Shubnikov-de Haas technique on samples with mobility $\mu=(0.4-1)\times10^6$ cm^2/Vs. On the other hand, the gaps measured in sample 2 correspond to the magnetotransport values obtained from extremely high-quality samples, $\mu=(0.1-1)\times10^7$ cm^2/Vs.[7-9] Note the existence of a finite threshold magnetic field due to residual disorder which strongly depends on the sample quality and is very small for sample 2.

In summary, we have studied by magneto-optics the FQHE in the low-density, high-magnetic-field regimes. We observe discontinuous behavior in the spectral position of the luminescence line at $\nu=\frac{2}{3}$, $\frac{1}{3}$, $\frac{4}{5}$, $\frac{3}{5}$, $\frac{2}{5}$, $\frac{1}{5}$, $\frac{1}{7}$, and $\frac{1}{9}$ from which we have determined the energy-gap values for the FQHE states $\nu=p/q$ with $q=3,5$, and for the first time for $\nu=\frac{1}{7}$ and $\frac{1}{9}$. The gaps obtained for $q=3,5$ are in agreement with those published from activated transport measurements[6-9] for similar quality samples. Finally, the lack of evidence for a FQHE state at $\nu=\frac{1}{11}$, together with the appearance of a second line [see Fig. 1(c)] to lower energy (which is sensitive to a critical temperature and filling factor, $\nu<\frac{1}{4}$), leads us to surmise that we are possibly observing the onset of a magnetically induced crystalline ordered state.[2,3,17] This, however, will be the subject of a future

publication.

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