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High-magnetic-field transport in a dilute two-dimensional electron gas

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We report the measurement, at 0.51 K and up to 28 T, of the magnetoresistance and Hall resistance of a dilute two-dimensional electron system with 6×10^{10} cm^{-2} carriers in a GaAs-GaAlAs heterojunction. The existence of an anomalous quantized Hall effect for a fractional Landau-level filling factor of $\frac{1}{3}$ was confirmed. The magnetoresistance showed a substantial deviation from linearity above 18 T and exhibited no additional features for filling factors below $\frac{1}{5}$ down to $\frac{1}{11}$. The results suggest that a transition from a quantum liquid to a crystalline state may take place.

The discovery of the quantized Hall effect (QHE), first in Si inversion layers[1] and later in GaAs-GaAlAs, InGaAs-InP, and InAs-GaSb heterostructures,[2-4] has spurred a large number of experimental and theoretical studies,[5-11] and it is now reasonably well understood. Recently, an anomalous QHE was observed by Tsui, Stormer, and Gossard,[12] for two-dimensional (2D) electrons at a GaAs-GaAlAs interface. The Hall resistance ρ_{xy} was quantized when $\frac{2}{3}$ or $\frac{1}{3}$ of the lowest Landau level was occupied and this quantization was accompanied by a corresponding minimum in the transverse magnetoresistance ρ_{xx} which, at sufficiently low temperatures, tends to vanish. An elegant theory by Laughlin[13] has been able to account for these results on the basis of the formation at high magnetic fields of an incompressible quantum fluid with fractionally charged excitations. He has predicted a series of ground states characterized by the variational parameter m ($m=3,5,\ldots$), decreasing in density and ending in a Wigner crystal. The Hall plateau at the Landau-level filling factor $\nu=\frac{1}{3}$ (and its complementary $\frac{2}{3}$) would then correspond to the highest-density ground state $m=3$. Most recently, Stormer *et al.*[14] have observed new structures in ρ_{xx} at $\nu=\frac{5}{3}, \frac{4}{3}, \frac{4}{5}, \frac{3}{5}, \frac{2}{5}$, and $\frac{2}{7}$, and, for the case of $\nu=\frac{2}{5}$, it has a corresponding feature in ρ_{xy}. These results suggest that the anomalous Hall effect occurs at exact rational fractions n/m ($n=1,2,3,4,\ldots$). While the $\frac{1}{3}$ and $\frac{2}{3}$ structures can be seen as the electron-hole symmetric states of $m=3$, proposed by Laughlin,[13] no such interpretation seems possible for the $\frac{3}{5}$, $\frac{2}{5}$, and $\frac{2}{7}$ structures. Stormer *et al.*[14] have speculated that many-particle ground states underlying fractional quantization exist not only for $1/m$ but also for their multiples. As a result of experimental limitations, the crucial region covering $\nu=\frac{1}{5}$ and below has hitherto remained inaccessible.

In this Rapid Communication we report investigations of the magnetoresistance and Hall resistance in a 2D electron gas dilute enough so that Landau-level filling factors as low as $\frac{1}{11}$ can be covered at fields below 30 T. Our results confirm the anomalies observed previously corresponding to $\nu=\frac{2}{3}$ and $\frac{1}{3}$ and provide evidence of a new structure around $\frac{1}{5}$ at a temperature of 0.51 K. However, no trace of any structure at $\frac{1}{7}$, $\frac{1}{9}$, or $\frac{1}{11}$ has been found. While the observation of structures at $\frac{1}{9}$ or $\frac{1}{11}$ may be argued to require lower temperatures, the lack of structure at $\frac{1}{7}$, at temperatures and fields for which the $\frac{2}{7}$ structure has been observed in more dense systems,[14] is suggestive that a transition from a liquid to a crystalline state may be already occurring.

The samples studied were epilayers grown by molecular-beam epitaxy on semi-insulating GaAs substrates. Special care was taken, in terms of substrate preparation and system cleanliness, to ensure very-high-quality layers. Following a growth procedure reported elsewhere,[15] it was possible to evaporate undoped GaAs films with a residual carrier concentration (p type) of $\sim 1\text{–}2\times10^{14}$ cm^{-3}. The structures of this work consisted of a 2-μm undoped GaAs layer, an undoped Ga$_{0.7}$Al$_{0.3}$As spacer, 400-Å Si-doped Ga$_{0.7}$Al$_{0.3}$As, and 100-Å Si-doped GaAs. Hall patterns were photolithographically delineated and Ohmic contacts were made into the epilayers.[2,12] The concentration of the 2D electrons confined at the undoped GaAs-Ga$_{0.7}$Al$_{0.3}$As interface was varied in different samples by varying the spacer thickness d. For the two samples A and B discussed in this paper, d was 200 and 520 Å, respectively. Carrier concentration and Hall mobility at 4 K were 2.8×10^{11} cm^{-2} and 4×10^{5} cm^2/V sec for sample A, and 0.6×10^{11} cm^{-2} and 4.1×10^{5} cm^2/V sec for sample B. The latter sample, with its extremely low carrier concentration, was the focus of the present study. The magnetotransport experiments were performed at the National Magnet Laboratory, with a field up to 22 T with a Bitter coil alone, or up to 28 T by placing a Bitter coil inside a superconducting magnet.

Figure 1(a) shows the magnetoresistance for sample A at two different temperatures. The data at 4.2 K exhibit already zero-resistance states for fields as low as 3 T (corresponding to $\nu=4$), as a result of the high electron mobility. The quantum limit ($\nu=1$) is reached at 12 T, beyond which no additional structure, up to 22 T, is observed at this temperature. On the other hand, at 1.3 K, a clear minimum is developed, at 18 T, corresponding to a filling factor of $\frac{2}{3}$. This temperature dependence agrees with that reported by Tsui *et al.*[12] for $\nu=\frac{1}{3}$, which occurred at similar fields in more lightly doped samples. The additional feature at 8 T is similar to the one originally assigned to $\nu=\frac{3}{2}$,[12] but it was later shown to be a doublet corresponding to $\frac{4}{3}$ and $\frac{5}{3}$.[14] It is worth noting that, in Fig. 1(a), the zero-resistance regions

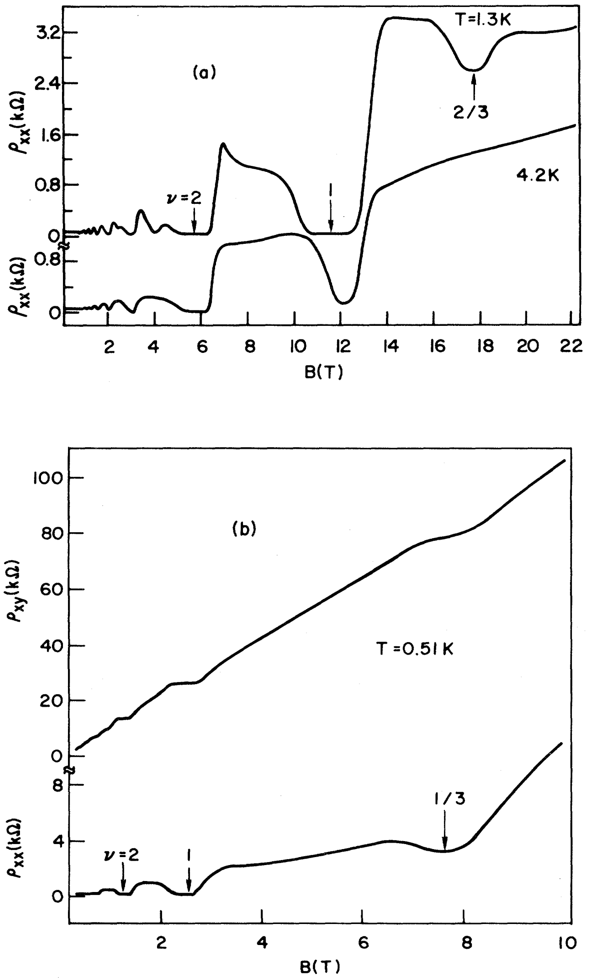

FIG. 1. (a) Magnetoresistance vs magnetic field, at two different temperatures, for a GaAs-$Ga_{0.7}Al_{0.3}As$ heterojunction with an electron concentration of 2.8×10^{11} cm^{-2} (sample A). (b) Magnetic field dependence, up to 9 T, of the magneto and Hall resistance, at 0.51 K, for a heterojunction with an electron concentration of 0.6×10^{11} cm^{-2} (sample B).

are relatively narrow even at the lower temperature. This is again a consequence of the high sample quality: As the origin of the zero-resistance regions (as well as the Hall plateaus) is the pinning of the Fermi level to the localized states (due to impurities, defects, etc.) between Landau levels, a decrease of those states should decrease the width of those regions. The same is observed in Fig. 1(b), which shows the magnetoresistance and Hall resistance for sample B at 0.51 K. Because of the very dilute electron gas, the quantum limit is reached at 2.55 T and a clear minimum is observed at 7.7 T, for $\nu=\frac{1}{3}$. A corresponding plateau, still in its developing stage, is evident in ρ_{xy}. The Hall plateaus show their expected values $h/\nu e^2$. Weak features corresponding to $\nu=\frac{4}{3}-\frac{5}{3}$ at 1.7 T and $\nu=\frac{2}{3}$ at 3.9 T are barely visible because of the magnetic field dependence of their amplitude.

Shown in Fig. 2 are the results for sample B for fields up to 28 T, covering the range of filling factors from $\frac{1}{3}$ to $\frac{1}{11}$, as indicated on top of the figure. The upper trace (ρ_{xy}) varies with the field essentially linearly after the initial feature at $\nu=\frac{1}{3}$. The lower trace (ρ_{xx}), exhibiting no pronounced structure throughout the field range, behaves initially in a similar manner in accordance with the free-electron theory.[12] However, it contains a faint curvature change near 12 T, and departs significantly from linearity beyond 18 T. These are amplified in the insert of Fig. 2 by plotting the derivative of ρ_{xx} with respect to B. The minimum shown therein corresponds to the curvature change in ρ_{xx} as marked by a broken arrow. It occurs at a filling factor of 0.21, suggesting that the feature may be associated with $\nu=\frac{1}{5}$. The surprisingly low intensity of this feature would then imply that the underlying mechanism for its appearance has begun to be modified.

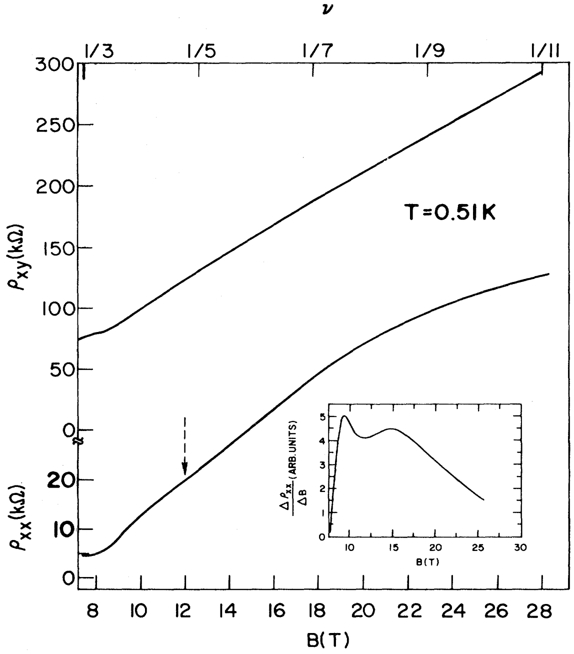

FIG. 2. High-field magneto and Hall resistance of sample B at 0.51 K. The insert corresponds to the derivative with respect to the field of the magnetoresistance. The minimum of the curve in the insert is indicated in the main figure by a broken arrow.

Stormer *et al.*[14] have observed the $\frac{2}{5}$, $\frac{3}{5}$, and $\frac{4}{5}$ structures at low fields, and also the $\frac{2}{7}$ structure at 20 T, only 2 T above the field where the $\frac{1}{7}$ structure is conspicuously absent in Fig. 2. Their experiments were carried out at the same temperature and with samples having similar mobilities to ours. The only apparent difference lies in the number of carriers, at least twice lower in the present case. In such a dilute system the average distance between electrons is 400 Å, versus 2000 Å for the residual impurity distance. It is possible that, with such a large electron spacing, a field in the vicinity of 18 T is sufficient to induce a transition from a liquid to a crystal, so that many-particle ground states could not exist. This would account for the weakness of the feature at $\frac{1}{5}$ and the absence of features at $\frac{1}{7}$ as well as their associated multiples at low fields. The departure from a linear behavior of ρ_{xx}, beyond 18 T, also suggests that some type of transition is taking place. For instance, in narrow-gap semiconductors, in the quantum limit, a kink in

ρ_{xx} has been interpreted as caused by a Wigner condensation.[16] From Laughlin's theory one cannot determine the crystallization point, although a crude interpolation of his ground-state energies[13] converges to the energy of the charge density wave near $m = 10$, If, in fact, the transition occurs at $m = 7$, as our results seem to suggest, a reduction in the sample temperature below 0.5 K would not be expected to produce any significant effect in the magnetoresistance.

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