Evidence for the Fractional Quantum Hall State at $\nu = \frac{1}{7}$

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(Received 10 June 1988)

We report the magnetotransport measurements of a low-density, very low-disorder two-dimensional electron system realized in a GaAs/AlGaAs heterojunction. The diagonal magnetoresistance displays a structure near the filling factor $\nu = \frac{1}{7}$ which is interpreted as evidence for a developing fractional quantum Hall state. We therefore conclude, contrary to recent theoretical and experimental work, that the Wigner crystallization does not occur in this system for $\nu \geq \frac{1}{7}$.

PACS numbers: 71.45.–d, 73.20.Dx, 73.40.Kp

The nature of the ground state of a two-dimensional electron system (2DES) subjected to an intense perpendicular magnetic field B has been vigorously studied, both experimentally and theoretically. At sufficiently small Landau-level filling factors ν ($\nu = nh/eB$, where n is the 2DES density) the ground state is expected to be a Wigner crystal[1] (WC). On the other hand, it is now well established that the fractional quantum Hall effect[2] (FQHE) is the manifestation of a series of incompressible electron liquid states with strong short-range correlation but no long-range order.[3] These new collective ground states have energies lower than that of the WC at moderate ν and, prior to this report, have been observed at fractional fillings down to $\nu = \frac{1}{5}$. As ν is further decreased, however, the (interpolated) energy of consecutive FQHE states lowers not as fast as the WC energy and the 2DES is expected to undergo a first-order phase transition at the crossover of these energies. The outstanding question is the following: What is the critical filling ν_W for the transition from the FQHE states to the WC?

An early estimate by Laughlin[3] gave $\nu_W \simeq \frac{1}{10}$. The value $\nu_W = \frac{1}{10}$ was also obtained by Levesque, Weiss, and MacDonald,[4] who combined their Monte Carlo results for the FQHE states energy with the WC energy calculated within the Hartree-Fock approximation. Subsequently, Lam and Girvin improved the WC energy calculation by using a variational wave function which includes electron correlations.[5] By combining their WC results with the Monte Carlo FQHE results of Ref. 4, Lam and Girvin obtained $\nu_W^{-1} = 6.5 \pm 0.5$. Further support for this value came from the magnetoroton theory of collective excitations in the FQHE[6] where the magnetoroton minimum is interpreted as a precursor to the FQHE gap collapse, associated with the WC transition occurring at ν_W a little *greater* than $\nu = \frac{1}{7}$.

On the other hand, it has been recognized very early that disorder can destroy the FQHE. This empirical observation[2,7] recently received a theoretical footing,[8] and now it is generally believed that the disorder potential reduces the gap for the collective excitations in the stronger FQHE states and leads to the collapse of the weaker FQHE states. The uncertainty in the influence of disorder is the chief difficulty in the interpretation of the experimental results in the low-ν range. Mendez *et al.*[9] have measured the magnetotransport coefficients of a dilute 2DES ($n = 6\times10^{10}$ cm^2) down to $\nu = \frac{1}{11}$ at $T \simeq 0.5$ K, and initially interpreted the absence of any evidence for the FQHE at $\nu < \frac{1}{5}$ and the extreme weakness of the $\nu = \frac{1}{5}$ structure in ρ_{xx} as due to the transition into the WC state. A slow progress in sample quality has resulted in observation of the much better developed FQHE at $\nu = \frac{1}{5}$,[10] with ρ_{xy} quantized to better than 0.3% and the dip in ρ_{xx} reaching ~95% depth (relative to background) at 60 mK.[11] The difficulty of performing measurements in the low-ν, low-T range has limited the experimental work in this important area until very recently, when Willett *et al.* performed an extensive study of the activated magnetotransport in a high-mobility, low-density 2DES.[12] They interpreted their results as not inconsistent with either the disorder-induced localization or the Wigner condensation transition at $\nu_W \simeq 0.2$.

In this paper we present our magnetotransport data which provide evidence, for the first time, for the existence of the FQHE at $\nu = \frac{1}{7}$. We argue, therefore, that the energy is lower for the FQHE liquid state than for the WC at $\nu = \frac{1}{7}$ and, correspondingly, that the transition to the WC would occur at $\nu < 0.14$.

Our samples were squares cut from an GaAs/AlGaAs heterojunction similar to those described previously,[13] but with a very thick, 2700 Å, graded composition AlGaAs spacer layer. The magnetotransport measurements reported here were done with an Oxford Instruments TLM-200 top-loading dilution refrigerator and a high-field superconducting magnet. A brief illumination by a red light-emitting diode at a low temperature was used to prepare a 2DES with very low disorder and with the electron areal concentrations in the 2×10^{10} cm^{-2} $\leq n \leq 5.5\times10^{10}$ cm^{-2} range.

Figure 1(a) shows a representative trace of the diagonal resistivity, ρ_{xx}, as a function of B measured by the van der Pauw technique. In the range $\nu < \frac{1}{3}$, besides the strong minima at $\nu = \frac{2}{7}$ and $\frac{1}{5}$, the data display clear evidence for three previously unreported FQHE states at $\nu = \frac{3}{11}$, $\frac{2}{9}$, and, notably, $\frac{1}{7}$. The feature in ρ_{xx} at $\nu = \frac{1}{7}$ is very similar to that seen in lower-quality samples at

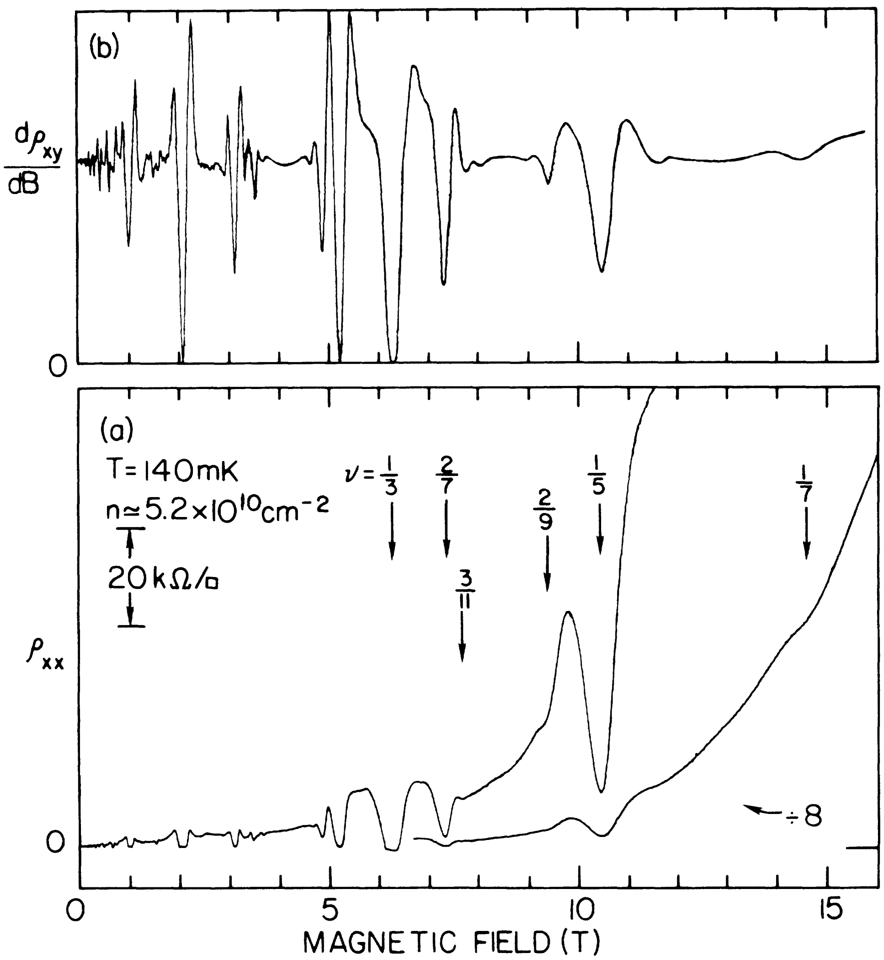

FIG. 1. (a) Diagonal resistivity ρ_{xx} vs B. ρ_{xx} was measured by the ac (3 Hz) van der Pauw technique with 4-nA rms current through the sample for the low-field trace and 0.25 nA for the high-field trace (resistivity scale changed by a factor of 8). (b) Numerically differentiated $d\rho_{xy}/dB$ vs B; ρ_{xy} is shown as the upper trace in Fig. 2.

$\nu=\frac{1}{5}$. Experience with the $\nu=\frac{1}{5}$ FQHE state shows that as the sample quality improves such structures turn into a dip and, eventually, a plateau in the Hall resistance develops. Therefore, it is very likely that the structure in ρ_{xx} at $B=14.7$ T is due to the developing FQHE state $\nu=\frac{1}{7}$.

The corresponding Hall data, ρ_{xx}, are shown in Fig. 2. The two lower traces (overlapping at $\nu>0.25$, but split at lower ν) were taken from the two sets of contacts, as described in the caption. Since in this sample at low temperatures ρ_{xx} is not much smaller than ρ_{xy} for $\nu<0.25$, there is a considerable admixture of ρ_{xx} into ρ_{xy}. The upper ρ_{xy} trace in Fig. 2 is the average of the two lower traces and is very linear (except for the plateaus) in the experimental range. On the other hand, averaging of the Hall resistivities obtained from the same contacts, but for both directions of B does not eliminate the ρ_{xx} admixture. This puzzling behavior is not fully understood at present, but seems to indicate that the current distribution in the sample is not uniform and that the distribution depends on the direction of B. The value of ρ_{xy} (the average) is very close to $7h/e^2$ at $\nu=\frac{1}{7}$; we interpret this as evidence that the sample (including the contacts) is still well behaved at the conditions (B,T) of the experiment.

Figure 1(b) gives the magnetic field derivative of the upper ρ_{xy} trace in Fig. 2. As Chang and Tsui[14] have noted, $(d\rho_{xy}/dB)B$ is quite similar to ρ_{xx}. It is interesting to note that despite a high level of "noise" (caused by numerical differentiation), the features (dips) due to a developing FQHE are stronger in the derivative trace, relative to the background level (see, e.g., the dips at $\nu=\frac{3}{11}$ and $\frac{2}{9}$). The derivative trace shows a dip at $\nu=\frac{1}{7}$; however, it also deviates upwards, above the lower-field level. It is not clear at present whether this behavior is real or results from the uncanceled admixture of ρ_{xx} into ρ_{xy}.

The structure in ρ_{xx} at $\nu=\frac{1}{7}$ is observable up to 0.38 K, at which temperature it is barely discernible. At temperatures below 140 mK, the $\nu=\frac{1}{7}$ feature does not

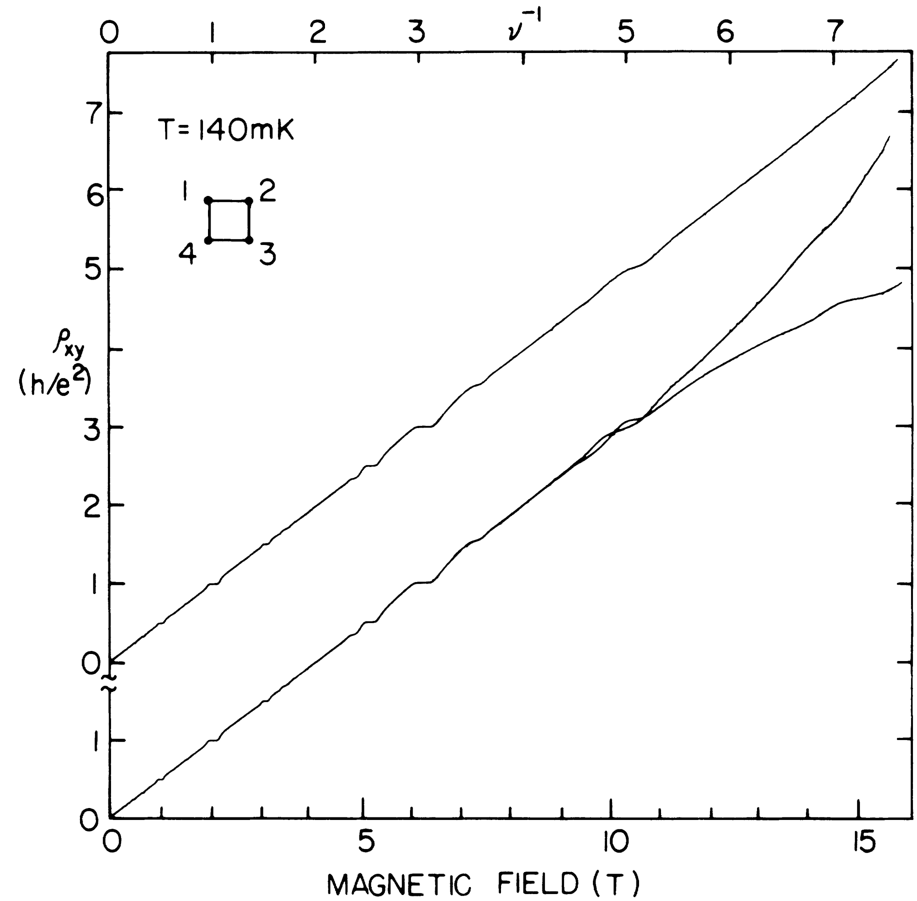

FIG. 2. The two lower traces give the Hall resistivities ρ_{xy} vs B as obtained from contact pairs (1–3) and (2–4) with constant current (1 nA rms) passed through pairs (2–4) and (1–3), respectively. The admixture of ρ_{xx} into the ρ_{xy} data is nearly completely removed by averaging the two traces, as shown in the upper trace.

strengthen appreciably while the background resistivity increases sharply for $\nu < \frac{1}{5}$. The structure at $\nu = \frac{1}{7}$ has been observed so far in two samples in the electron concentration range $2.8 \times 10^{10}\ \mathrm{cm}^{-2} \leq n \leq 5 \times 10^{10}\ \mathrm{cm}^{-2}$ (changed by different illumination conditions).

It seems very plausible that GaAs/AlGaAs heterostructure samples contain macroscopic gradients of the electron concentration and of the degree of disorder despite the extremely low disorder on the microscopic scale. In the presence of macroscopic gradients, the magnetic-field-induced localization due to disorder occurs at different magnetic fields (and ν) in different parts of a sample. Then the coexistence of the $\nu = \frac{1}{7}$ FQHE in parts of the sample with least disorder and the activated transport in the parts of the sample with more disorder is not surprising. At finite temperatures ρ_{xx} is nonzero everywhere in the sample and the measured magnetoresistance contains contributions from all over the sample. However, a coexistence of a FQHE state and the WC at pretty much the same conditions (n, ν, T) is very unlikely. Thus we conclude that since there is strong evidence for the existence of the $\nu = \frac{1}{7}$ FQHE state, the liquid-solid transition occurs at a $\nu_W < \frac{1}{7}$ in the large-n limit[15] (and in a 2DES with yet less disorder than achieved so far). We also conclude that the magnetic-field-induced localization in presently available samples is due to disorder; however, it is clear that in high-quality (low-disorder) 2DES the electron-electron interaction is still important in the localized state which, appropriately then, can be called "Wigner glass."

We would like to acknowledge the excellent technical help of L. W. Engel, T. Sajoto, and M. Santos. This work is supported by the National Science Foundation through Grants No. DMR-8212167, No. ECS-8553110, and No. DMR-8705002, by the U.S. Office of Naval Research through Contract No. 00014-82-K-0450, and by U.S. Department of Defense Grant No. DAALO3-87-G-0105.

Note added.—After this work was completed, we learned of the work by E. Y. Andrei *et al.*,[16] who claimed to have observed evidence for a magnetophonon mode of a Wigner solid in a 2DES. Their data, however, appear to be fitted much better by an acoustic lattice mode in the GaAs/AlGaAs host material.[17]

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