Transport properties of a two-dimensional electron system at even-denominator fillings of the lowest Landau level

H. W. Jiang*
Francis Bitter National Magnet Laboratory, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139 and Department of Electrical Engineering, Princeton University, Princeton, New Jersey 08544

L. W. Engel and D. C. Tsui
Department of Electrical Engineering, Princeton University, Princeton, New Jersey 08544

H. L. Stormer, L. N. Pfeiffer, and K. W. West
AT&T Bell Laboratories, Murray Hill, New Jersey 07974
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We observe magnetotransport minima at Landau-level filling factors $\nu=\frac{1}{4}$ and $\frac{3}{4}$ distinctly different from the transport signatures of the fractional quantum Hall effect. These features are similar to the anomalies reported earlier at half-filled Landau levels. Tilting the magnetic field away from normal incidence has no observable effect on the strength of the minima. The strong similarity between the transport properties at $\nu=\frac{3}{2}$, $\frac{3}{4}$, $\frac{1}{2}$, and $\frac{1}{4}$ suggests a common origin.

The two-dimensional electron system (2DES) realized in $GaAs/Al_xGa_{1-x}As$ heterostructure in the presence of high magnetic field is an ideal system for studying many-particle interactions. Prime examples of such novel many-particle states are the incompressible quantum liquids which exhibit the fractional quantum Hall effect (FQHE).[1] In a single-layer 2DES, the FQHE is observed exclusively at odd-denominator Landau-level filling factors, with only one exception at $\nu=\frac{5}{2}$.[2] Magnetic-field tilting studies[3] have shown in this even-denominator state the importance of the spin degree of freedom, and the results are consistent with a spin-unpolarized incompressible liquid.[4,5] There remains the question as to the existence of other even-denominator FQHE states, or more generally, as to the nature of the ground state at other even-denominator filling factors.

Early on, Jiang *et al.* reported transport anomalies in the lowest Landau level at half-fillings $\nu=\frac{1}{2}$ and $\frac{3}{2}$ distinctively different from the characteristic FQHE features.[6] The magnetoresistance R_{xx} developed deep minima but did not reach a zero-resistance state, and the Hall resistance ρ_{xy} remained featureless. These observations were subsequently confirmed by Sajoto *et al.*[7] In surface-acoustic-wave experiments, Willett *et al.* observed an anomalous sound propagation at $\nu=\frac{1}{2}$ and proposed an interpretation in terms of a phase separation into patches of two different electron densities.[8] This interpretation was inspired by earlier calculations by Halperin, which showed upward cusps in the ground-state energy of the electron system at even-denominator fillings.[9] More recently, magneto-optical studies by Buhmann *et al.* also uncovered an uncommon feature in photoluminescence at $\nu=\frac{1}{2}$.[10] Although all of these anomalies occur at the same filling factor, it remains unclear whether they have a common origin, and furthermore what this origin may be. Theoretically, in addition to a large number of early theoretical studies,[11] several new proposals on the ground state at even-denominator fillings have appeared. Chui proposed a quasisolid wave function[12] for $\nu=\frac{1}{2}$. Moore and Reed model the $\nu=\frac{1}{2}$ state as consisting of composite particles made of electrons with an even number of flux quanta attached.[13] Composite particles have also been used by Jain[14] to propose a model for high-order FQHE states. Halperin, Lee, and Read[15] recently developed a Fermi-liquid theory which employs such composite particles for an analysis of the different experimental facts $\nu=\frac{1}{2}$ such as recent surface-acoustic-wave experiments.[16] Greiter, Wen, and Wilczek suggested an incompressible paired Hall state[17] for spinless fermions at $\nu=\frac{1}{2}$. This novel state may in fact be realized in recent experiments on the double-layer 2DES in a wide quantum well in which a $\nu=\frac{1}{2}$ FQHE with vanishing ρ_{xx} and quantized ρ_{xy} has been observed.[18] Its applicability to the anomalies at $\nu=\frac{1}{2}$ in single-layer 2DES remains questionable. Ho and Kahng considered the possibility of a ground state which resulted from the crystallization of quasiparticles of the $\nu=1$ state and termed it an anyon crystal.[19] Kivelson, Lee, and Zhang developed a global phase diagram of the quantum Hall effect[20] and classified the electronic state at even-denominator fillings as states called Hall metals. The possible link between the theoretical models and the experimental observations is not clear, and the common ground among the different theories is even more ambiguous. Further experimental studies, as well as theoretical work, are required to unravel the nature of the ground state at even-denominator filling factors.

The main purpose of this paper is to present experimental data of the anomalous electronic transport behavior at other even-denominator Landau-level filling factors $\nu=\frac{1}{4}$ and $\frac{3}{4}$. We demonstrate the similarities of the transport properties at $\nu=\frac{3}{4}$ and $\frac{1}{4}$ to those at half-fillings and provide evidence for the spin-polarized nature of the electron system at these anomalies. The transport properties at these even-denominator fractional fillings can be generalized and compared to those at the fractional quantum Hall states. Although our experiments cannot resolve the nature of the ground state, they establish a strong link among these even-denominator fillings and suggest that they belong to the same family.

We used two ultrahigh-mobility modulation-doped $GaAs/Al_xGa_{1-x}As$ heterostructures for our experiments. Sample 1 has a low-field mobility $\mu=8\times10^6$ cm^2 / V s and a carrier density $n=1.1\times10^{11}$ cm^{-2}. The same specimen has been used for the studies of magnetotransport around $\nu=\frac{1}{5}$.[21] Sample 2 with $n=1.7\times10^{11}$ cm^{-2} and $\mu=9\times10$ cm^2/V s earlier had shown strong anomalies at half-fillings.[6] Both samples are squares of $\sim4\times4$ mm^2 with eight symmetrically placed In contacts. We employed conventional lock-in techniques at 13.2 Hz and currents below 10 nA to avoid electron heating. Sample temperatures down to 70 mK and magnetic fields up to 30 T were achieved in a dilution refrigerator placed in the hybrid magnet at the National Magnet Laboratory. Experiments down to 25 mK in fields up to 15 T were conducted in a dilution-refrigerator–superconducting magnet system at Princeton University. In the latter setup, the sample could be rotated *in situ* with a maximum tilting angle of 90° between the field direction and the sample normal.

Figure 1 shows the diagonal resistance as a function of magnetic field for sample 1 at $T=70$ mK. A minimum at $\nu=\frac{1}{4}$ is apparent at a magnetic field of $B\approx19$ T. The strength of the $\nu=\frac{1}{4}$ minimum is comparable to the neighboring FQHE states at $\nu=\frac{2}{9}$ and $\frac{3}{11}$. To our knowledge, this is the first time a deep minimum at $\nu=\frac{1}{4}$ has been observed. The feature at $\nu=\frac{1}{4}$ is relatively broad in comparison to the FQHE states. This is similar to the earlier observations at $\nu=\frac{1}{2}$ and $\frac{3}{2}$.[6] The asymmetric shape is probably related to the emergence of another higher-order FQHE state at $\nu=\frac{3}{13}$ on the high-field side. Earlier experiments indicated only an inflection at $\nu=\frac{1}{4}$ superimposed on a rapidly rising background at the temperature $T\rightarrow0$.[21] The difference between the earlier result and the present data is probably caused by variations in this background. It has been established that there exists an insulating phase in a narrow regime of filling factors $\frac{2}{9}<\nu<\frac{1}{5}$ in this sample.[21] At 70 mK the peak resistance of this insulating phase reaches a value as high as $\sim10^6$ Ω in this sample. Small variations in sample inhomogeneity can give rise to considerable changes in the background resistance, and, due to its proximity, can suppress the feature at $\nu=\frac{1}{4}$. Sample homogeneity is known to depend critically on cooldown and illumination procedures, and therefore the appearance and the strength of the $\nu=\frac{1}{4}$ feature is subject to considerable run-to-run variations.

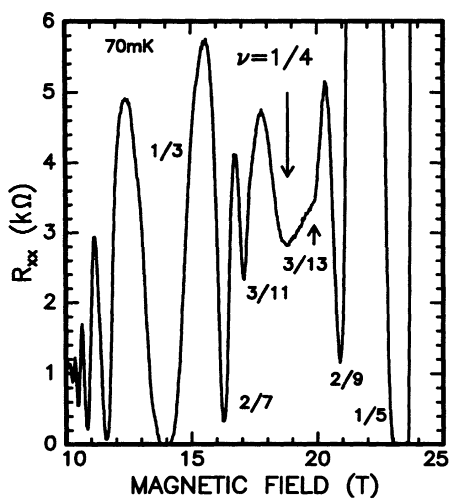

FIG. 1. Diagonal resistance R_{xx} as a function of magnetic field for sample 1 at $T=70$ mK. Since the sample is of square shape, $\rho_{xx}\sim R_{xx}$. A distinct minimum at $\nu=\frac{1}{4}$ is indicated by the arrow.

A transport feature around $\nu=\frac{3}{4}$ was detected early on[22,23] and also appeared in our early studies.[6] Figure 2 shows the minimum at $\nu=\frac{3}{4}$ for sample 2 at our lowest temperature of 25 mK. The V-shape feature resembles the structure at $\nu=\frac{1}{2}$ and $\frac{3}{2}$ of our earlier report. Its sharpness increases as the temperature is lowered.

Despite the strengths of the minima at $\nu=\frac{1}{4}$ and $\frac{3}{4}$, the value of their lowest point does not approach $R_{xx}\rightarrow0$ but saturates at a nonzero resistance as $T\rightarrow0$. In fact, its temperature dependence is small. For example, the minimum around $\nu=\frac{3}{4}$ drops less than 5% from 500 to 50 mK. The values of resistance at saturation have no apparent universal significance, since they are sample and background dependent. Distinct minima develop at $T\approx150$ mK. They are very well centered at $\nu=\frac{1}{4}$ and $\frac{3}{4}$ and therefore cannot be regarded simply as an artifact due to the developing flanks of neighboring FQHE states. At higher T, the features broaden and deviate from the exact field positions of $\nu=\frac{1}{4}$ and $\frac{3}{4}$. This characteristic temperature is much lower than the temperature of ~2 K for the $\nu=\frac{1}{2}$ and $\frac{3}{2}$ features.

In the FQHE, it is well known that a deep minimum in the diagonal resistance corresponds to a well-developed plateau in Hall resistance. The even-denominator

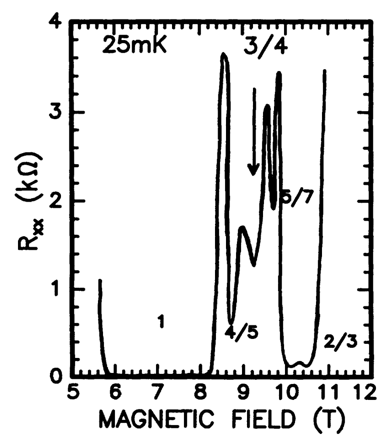

FIG. 2. Diagonal resistance R_{xx} as a function of magnetic field for sample 2 at $T=25$ mK. A sharp minimum is apparent at $\nu=\frac{3}{4}$.

anomalies behave differently. Although the depths of the minima for $\nu=\frac{1}{4}$ and $\frac{3}{4}$ are comparable to their neighboring higher-order FQHE states at $\nu=\frac{2}{9},\frac{3}{11}$ and $\frac{4}{5},\frac{5}{7}$, respectively, the Hall resistance is structureless at $\nu=\frac{1}{4}$ and $\frac{3}{4}$, whereas plateaus are visible for the FQHE states. In this regard, the new even-denominator states also resemble the anomalies at $\nu=\frac{1}{2}$ and $\frac{3}{2}$.[6]

To investigate the spin configuration of the even-denominator states, we performed magnetic-field tilt experiments for $\nu=\frac{3}{2}$ and $\frac{3}{4}$. The sample of Fig. 2 develops a $\nu=\frac{3}{2}$ state at $B\approx 4.5$ T, which is sufficiently low B for tilt experiments. Such a low magnetic field also favors a possible spin reversal. In Fig. 3, we show the traces of R_{xx} versus magnetic field for several tilt angles θ. The Zeeman energy increases by $1/\cos(\theta)$ as the tilting angle increases. Even though this increase reaches as much as a factor of 3 at the largest angle $\theta=79°$, it has no apparent effect on the strength of the feature at $\nu=\frac{3}{2}$. The robustness of the $\nu=\frac{3}{2}$ state against tilting is in sharp contrast to the odd-denominator FQHE states at $\nu=\frac{8}{5}$ and $\frac{7}{5}$, which have vanished at the highest tilt angle $\theta=79°$. From these experiments we conclude that the ground state at $\nu=\frac{3}{2}$ is most likely spin polarized, in contrast to the spin-unpolarized FQHE state at $\nu=\frac{5}{2}$.

In Table I we summarize the characteristic properties of the 2DES at even-denominator fillings and compare them with those at the FQHE states at odd-denominator fillings and at $\nu=\frac{5}{2}$. The strong similarity of the transport properties leads us to conclude that the electronic ground states at $\nu=\frac{3}{2}$, $\frac{3}{4}$, $\frac{1}{2}$, and $\frac{1}{4}$ belong to the same family.

It can be argued that anomalies at $\nu=\frac{1}{2}$ and $\frac{3}{2}$ may be related to electron-hole symmetry at half-filling; however, at quarter filling, such as at $\nu=\frac{1}{4}$ and $\frac{3}{4}$, no such symmetry exists in any single-particle picture. We therefore postulate that these even-denominator states are of many-particle origin.

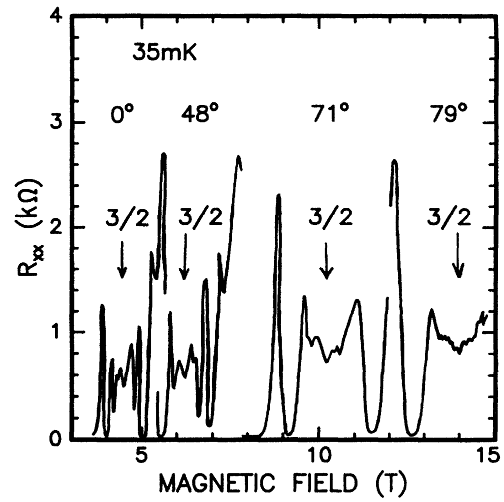

FIG. 3. R_{xx} vs magnetic field around $\nu=\frac{3}{2}$ at several tilt angles of $\theta=0°$, 48°, 71°, and 79° for sample 2 (θ is the angle between the magnetic-field direction and the sample normal). The feature at $\nu=\frac{3}{2}$ is unchanged as the spin Zeeman energy changes by as much as factor of 3. The minima of the FQHE state at $\nu=\frac{8}{5}$ and $\frac{7}{5}$ decrease as θ increases, and are not observable at $\theta=79°$.

Phase separation of the electron system at even-denominator filling has been proposed as the possible origin of anomalies in surface-acoustic-wave experiments. Could such a phase separation also explain the transport features? In this model, the homogeneous 2DES is assumed to have separated into clusters with higher and lower densities than the average density at that filling factor. The size of these clusters can be estimated by balancing the Coulomb (Hartree) energy gain due to breaking of the translational symmetry versus the energy cost in surface tension at the cluster boundaries. A size of order of 1 μm is obtained for a typical experimental situation.[24]

TABLE I. Comparisons of the transport properties at even-denominator fillings with those at FQHE states.

	FQHE	Even-denominator fillings
Filling factors	$\nu=p/q$, $q=$odd $\nu=\frac{5}{2}$	$\nu=\frac{3}{2}$, $\frac{3}{4}$, $\frac{1}{2}$, and $\frac{1}{4}$
Diagonal resistance	$\rho_{xx}\to 0$ as $T\to 0$ thermally activated	$\rho_{xx}\to$ constant as $T\to 0$ not activated (roughly linear in T), $\rho_{xx}(0)$ is sample dependent
Hall resistance	plateau at $\rho_{xy}=(h/e^2)^*(q/p)$	no apparent plateau
Temperature scale	disappear at $T\approx E_{\text{gap}}/k_B$ (E_{gap} is the quasiparticle excitation gap)	persist to about 10 K for $\nu=\frac{1}{2}$ and $\frac{3}{2}$, well-defined features appear at about 150 mK for $\nu=\frac{1}{4}$ and $\frac{3}{4}$
Upon tilting (increase Zeeman energy)	spin-unpolarized FQHE states at $\nu=\frac{5}{2}$, $\frac{8}{5}$, and $\frac{7}{5}$ disappear	no apparent effect

The electron clusters represent charge-density fluctuations similar to those in a charge-density wave. In the limit of negligible potential fluctuations, they form a network of the clusters. As long as the sample size is much larger than the size of the cluster, transport is expected to see no difference between a phase-separated state and a homogeneous state. In the limit of strong potential fluctuation, the clusters will be pinned by the random potential similar to a charge-density wave. Then we expect a significant increase in the resistance and non-Ohmic transport. In our experiment neither an increase in resistance nor a non-Ohmic transport is observed at these even-denominator fillings. We therefore conclude that the phase-separation model is not able to provide a satisfactory explanation of the electrical transport data at even-denominator fillings. Recent theoretical models based on composite fermions at even-denominator fractions hold some promise to provide an insight into these unique transport features.

In summary, we have presented evidence for the similarity of the transport properties at even-denominator filling factors $\nu=\frac{3}{2}$, $\frac{3}{4}$, $\frac{1}{2}$, and $\frac{1}{4}$, and have laid out the clear distinction between these anomalous properties and those of the FQHE states.

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*Present address: Department of Physics, University of California, Los Angeles, CA 90024.

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