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Fractionally quantized Hall effect in two-dimensional systems of extreme electron concentration

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We report magnetotransport measurements, down to 0.050 K and up to 20 T, in two-dimensional systems with dilute and dense electron densities. The emphasis is on the latter regime, where the Hall resistance shows quantization for level filling factors at $\nu=\frac{4}{3}$ and $\frac{5}{3}$, and the magnetoresistance presents well-defined structures at $\nu=\frac{7}{3}$ and $\frac{8}{3}$. These results indicate that the fractional quantum Hall effect is a general phenomenon not restricted to the lowest-orbital Landau level.

It has been experimentally[1] shown that the Hall resistance ρ_{xy} of a two-dimensional electron system (2DES), in the presence of a strong magnetic field B perpendicular to it, can take quantized values given by $h/\nu e$,[2] where $\nu=\frac{1}{3},\frac{2}{3}$. This fractional quantum Hall effect occurs in very high-mobility 2DES of density N_s, at fields such that $N_s=eB\nu/h$ so that ν physically represents the magnetic-level filling factor. Simultaneous to the quantization of ρ_{xy}, the magnetoresistance ρ_{xx} aproaches zero values, which indicates the formation of a mobility gap. More recently, additional minima in ρ_{xx} for higher-order fractions $\nu=\frac{2}{5}$, $\frac{3}{5}$, $\frac{2}{7}$, $\frac{4}{3}$, and $\frac{5}{3}$, and in some cases, also corresponding structures in ρ_{xy} have been resolved.[2] Similar observations have been reported[2,3] in two-dimensional hole systems (2DHS). These results have led to several calculations for the ground state of 2D electrons in a strong magnetic field[4-6] in the extreme quantum limit, that is, when $\nu<1$. Laughlin has found[5] that the ground state has the characteristics of a quantum liquid whose elementary excitations have a fractional charge νe. Moreover, he has predicted the existence of a series of ground states, with decreasing density, for $\nu=\frac{1}{5}$, $\frac{1}{7}$, etc., ending in a Wigner crystal.

Recently we performed magnetotransport experiments at 0.51 K in an extremely dilute 2DES (0.6×10^{11} cm^{-2}) and, by using magnetic fields up to 28 T, filling factors as low as $\frac{1}{11}$ were reached.[7] Except for a very weak structure in ρ_{xx} at $\nu\simeq\frac{1}{5}$, no additional features were observed beyond a very pronounced minimum at $\nu=\frac{1}{3}$. In this Rapid Communication we report an extension of that work to the crucial low-temperature region down to 0.068 K. The results support the earlier observations within the available field range.

In addition, we report similar measurements with focus on the other extreme: a rather dense 2DES (5.8×10^{11} cm^{-2}). The results show not only perfect Hall plateaus for $\nu=\frac{4}{3}$ and $\frac{5}{3}$ but also a well-defined minimum in ρ_{xx} for $\nu=\frac{8}{3}$. The latter observation strongly suggests the existence of the fractional quantum Hall effect above the ground-state Landau level ($n=0$).

The samples of this work were GaAs-GaAlAs heterostructures grown by molecular-beam epitaxy, using a procedure described elsewhere.[8,9] Very high electron mobilities were achieved, exceeding 10^6 cm^2/V s at 4.2 K in some cases. The magnetotransport experiments were done with a Bitter coil up to 20 T, using a dilution refrigerator that alowed us to decrease the temperature to 0.05 K.

Typical magnetoresistance and Hall resistance traces as a function of magnetic field are shown in Fig. 1. At low fields, ρ_{xx} presents zero-resistance states, with corresponding quantizations of ρ_{xy} for submultiples of h/e^2. This constitutes the normal quantum Hall effect (QHE). The fractional QHE appears at high fields, where additional quantizations are observed at $3h/2e^2$ and $3h/e^2$, with simultaneous vanishing magnetoresistance. Weaker features are also present in ρ_{xx}, associated with higher-order fractions. The shoulder present around 16 T in the bottom ρ_{xx} curve is possibly associated with the $\frac{2}{7}$ fraction, although in the absence of a well-defined minimum, and more importantly of a plateau in ρ_{xy}, it is difficult to assign it any precise value of ν. Surprisingly weak is the structure of the top trace, at 17.5 T, corresponding to $\nu\simeq\frac{4}{5}$. This contrasts with a previous observation,[2] at 0.55 K and about the same field, of a clear minimum at $\nu=\frac{2}{5}$ in a 2DES with a lower electron density and mobility. Experiments carried out in high-

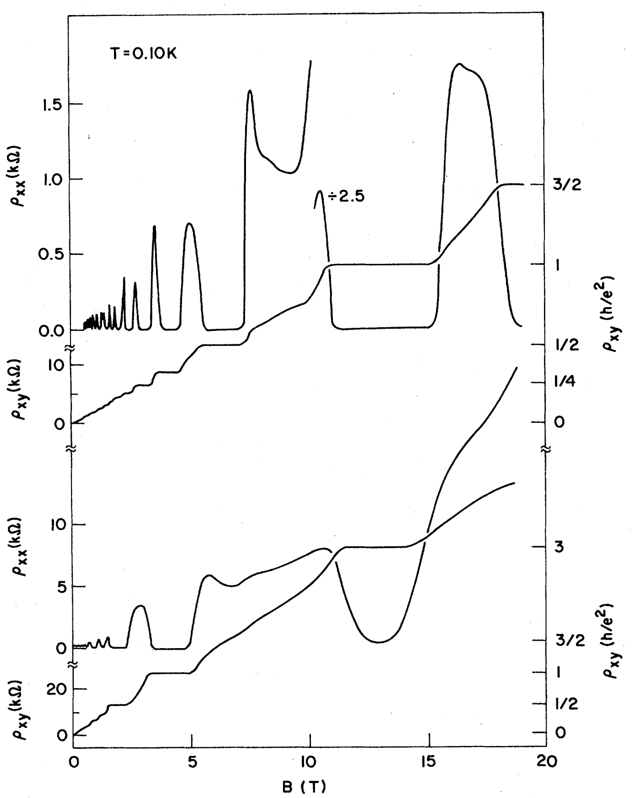

FIG. 1. Magnetoresistance per square, ρ_{xx}, and Hall resistance, ρ_{xy}, for samples A (top) and B (bottom), vs magnetic field. Carrier concentration and Hall mobility are 3×10^{11} cm^{-2} and 1×10^{6} cm^2/V s, respectively, for sample A, and 1.05×10^{11} cm^{-2} and 3.5×10^{5} cm^2/V s for sample B.

mobility 2DHS, while revealing minima for $\nu=\frac{2}{5}$ and $\frac{3}{5}$ and showing corresponding Hall quasiplateaus, failed to show the slightest trace of a structure around $\frac{4}{5}$ (Ref. 3).

These results indicate a very different behavior of the fraction $\frac{4}{5}$ from that of $\frac{2}{5}$ or $\frac{3}{5}$, and, on the premise of electron-hole symmetry, they suggest that an anomalous behavior may be expected at the complementary fraction $\frac{1}{5}$. Figure 2 shows the magnetoresistance, at 0.068 K, of the dilute 2DES with a carrier concentration of 0.6×10^{11} cm^{-2} and a mobility of 4.1×10^{5} cm^2/V s. The trace of ρ_{xx} shows a broad curvature change in the vicinity of $\frac{1}{5}$. The Hall voltage (not shown) presented a plateau at $\nu=\frac{1}{3}$, and beyond that point, increased linearly with increasing field.

The data presented here, when compared with our previous measurements at 0.51 K (Ref. 7), indicate a very slight enhancement, with decreasing temperature, of the curvature of ρ_{xx} at $\nu\simeq\frac{1}{5}$. This, together with the overall weakness of the structure, suggests the onset of some additional phenomenon which tends to dominate at low filling factors. One possible mechanism is the presence of localization in the Landau-level tail, which would preclude the observation of any high-fraction energy gap. Another possibility is that in such a dilute system the magnetic field is high enough to induce a transition from a quantum liquid to a Wigner solid. Recent theoretical calculations[10,11] appear to lend support to the latter, although the theoretical critical filling factor for

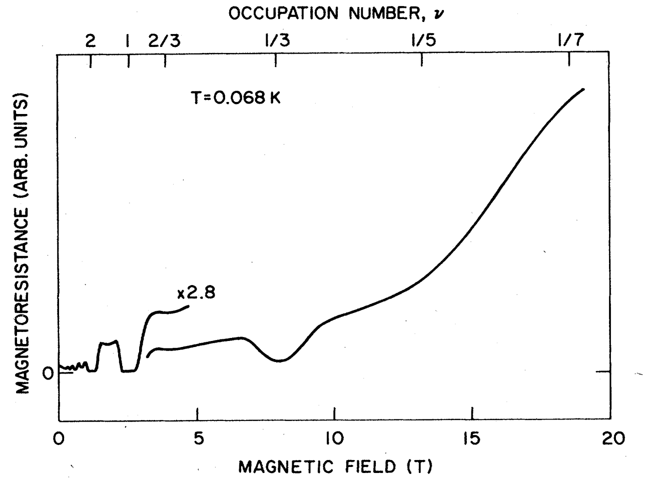

FIG. 2. Magnetoresistance vs magnetic field for a dilute 2DES with an electron density of 0.6×10^{11} cm^{-2} and a mobility of 4.1×10^{5} cm^2/V s.

the solid formation is sensitive to the approximations used in the calculations.

For the other extreme case studied in detail here, the filling factor is $\nu>1$ at high fields. The data shown in Fig. 3 correspond to sample A of Fig. 1. By illuminating it momentarily at low temperature and taking advantage of the

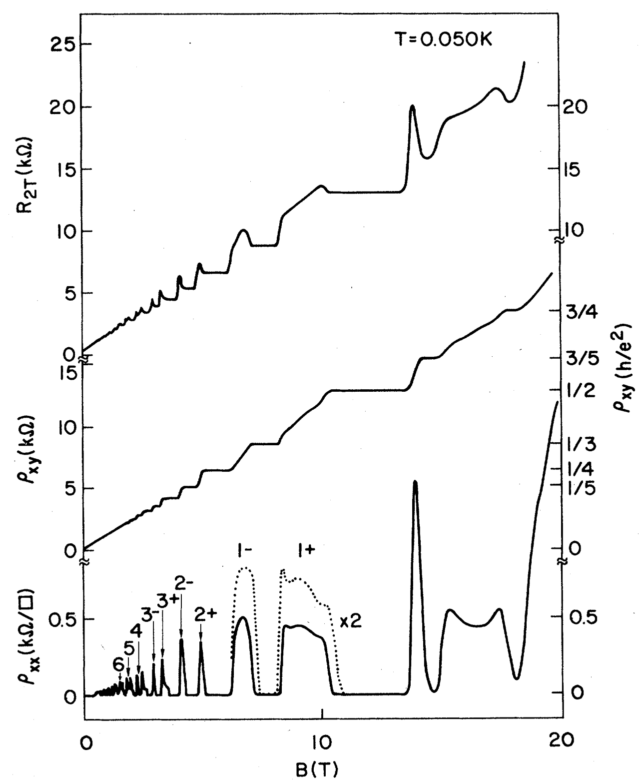

FIG. 3. Magnetoresistance, Hall resistance, and two-terminal resistance (from bottom to top) vs magnetic field, for sample A after being exposed to light. The Landau-level index n of the various magnetoresistance peaks is shown. The dotted line corresponds to data taken at $T=0.30$ K.

persistent photoconductive effect present in *n*:GaAlAs-GaAs heterostructures, the carrier concentration was increased from 3×10^{11} to 5.8×10^{11} cm^{-2}, while the mobility increased from 1×10^{6} to 1.7×10^{6} $cm^2/V\,s$.

At very low magnetic fields, Shubnikov–de Haas oscillations down to at least Landau level $n=30$ were observable, and the spin splitting could be resolved for $n=7$. Zero resistance was reached for $B=2.2$ T, corresponding to $\nu=10$, as determined from the value of the plateau of ρ_{xy}. In addition to plateaus for integer values of ν up to $\nu=2$, ρ_{xy} showed quantization to $3h/5e^2$ and $3h/4e^2$ (to better than 5×10^{-3}, which is the uncertainty in our measurements), demonstrating unambiguously the fractional quantum Hall effect for $\nu=\frac{5}{3}$ and $\frac{4}{3}$. For these filling factors ρ_{xx} showed very deep minima, which in the case of $\frac{5}{3}$ nearly vanished in resistance.

A minimum in the magnetoresistance, and an additional structure are observable for $2<\nu<3$ with corresponding features appearing in ρ_{xy}. The dotted curve in Fig. 3 shows the amplified data taken at $T=0.30$ K. The small thermal broadening, slightly asymmetrical, helps to reveal the feature at the higher field, but at even higher temperatures both structures gradually disappear. The estimated values of ν from the positions of the structures are 2.68 and 2.34. These values are very close to $\frac{8}{3}$ and $\frac{7}{3}$, respectively, and strongly suggest that they are a manifestation of the fractional QHE. This is significant because it indicates that this effect is general and applicable to all Landau levels, not only to the ground state. Very recently, MacDonald[12] has generalized, for higher Landau levels, the states proposed by Laughlin for the extreme quantum limit and has concluded that the fractional QHE is not restricted to the lowest-orbital Landau level.

We should note the presence of an additional broad minimum in ρ_{xx}, for $B\simeq16.8$ T, corresponding to $\nu\simeq1.43$. Similar minima have been observed in other samples of comparable quality and higher carrier concentration, and are possibly associated with $\nu=\frac{7}{5}$, although it might also be the result of overlapping of several higher-order-fraction minima.

The upper trace of Fig. 3 shows the two-terminal resistance R_{2T}. It presents a hybrid behavior between ρ_{xx} and ρ_{xy}. When the Fermi level is inside a magnetic level, that is, $\rho_{xx}\neq0$, it behaves as ρ_{xx}; however, when $\rho_{xx}=0$ it becomes quantized. This type of behavior was first observed by Fang and Stiles in Si MOS structures.[13] They showed that in the quantum Hall regime, the resistance between any pair of terminals on the periphery of an arbitrarily shaped sample is given by the Hall resistance, $h/\nu e^2$. In practice, R_{2T} has slightly larger values, from which the contact resistance can be deduced.

Finally, let us note the presence of tails in the magnetoresistance peaks of Fig. 3. These tails appear for states with Landau-level index $n>2$ and are observable up to $n=7$. We attribute them to the presence of scattering centers introduced by the persistent photoconductivity effect. Details of this observation will be reported in a forthcoming paper.

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