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Fractional quantum Hall effect at low temperatures

A. M. Chang
Department of Electrical Engineering and Computer Science, Princeton University, Princeton, New Jersey 08544

M. A. Paalanen
Bell Laboratories, Murray Hill, New Jersey 07974

D. C. Tsui
Department of Electrical Engineering and Computer Science, Princeton University, Princeton, New Jersey 08544

H. L. Störmer and J. C. M. Hwang*
Bell Laboratories, Murray Hill, New Jersey 07974
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We report a systematic study of the $\frac{2}{3}$ fractional quantum Hall effect at low temperatures (65–770 mK) for a GaAs-$Al_xGa_{1-x}As$ sample of very high mobility (10^6 cm^2/V sec). We find the $\frac{2}{3}$ Hall plateau to be accurately quantized. The diagonal and Hall resistivities are observed to be activated at each given filling factor $\nu = nh/eB$ around $\frac{2}{3}$. The activation energy has a maximum value, Δ_{max}, at $\nu = \frac{2}{3}$ and decreases to each side as ν moves away. By varying the sample mobility and density simultaneously with a backgate bias, we find Δ_{max} strongly mobility and magnetic field dependent.

Recently, Tsui, Störmer, Gossard, and Hwang[1,2] reported the discovery of quantized Hall plateaus at fractional values $\frac{1}{3}$ and $\frac{2}{3}$ in the high-mobility two-dimensional electron gas (2D EG) in GaAs-$Al_xGa_{1-x}As$ heterostructures. The plateaus are observed at low temperatures in the presence of a strong magnetic field perpendicular to the electron gas. In contrast to the ordinary quantum Hall effect (QHE), the fractional effect occurs near fractional filling of the lowest Landau level instead of complete filling of a Landal level—the $\frac{1}{3}$ near $\frac{1}{3}$ filling and $\frac{2}{3}$ near $\frac{2}{3}$ filling. At the same time, the diagonal resistivity (ρ_{xx}) approaches zero, indicating the development of a zero resistance state. Subsequent experiments[3] reveal that the $\frac{1}{3}$ plateau is quantized to an accuracy of better than one part in 10^4 and that the $\frac{1}{3}$ and $\frac{2}{3}$ states have qualitatively similar temperature developments manifest in a thermally activated ρ_{xx}. Recent theoretical results[4,5] indicate that these unusual phenomena are associated with the formation of an incompressible electron fluid arising from the strong electron-electron Coulomb interaction. A theory due to Laughlin[4] predicts the existence of $\frac{1}{3}$ charged excitations and a gap in the excitation spectrum, in qualitative agreement with experiment. However, the theory does not explicitly take disorder into account. Disorder has important consequences[4]: It gives rise to a finite width in the fractional Hall plateaus and reduces the observed activation energy from the theoretically predicted value. Existing data[6] indicate that higher mobility samples have a larger $\frac{1}{3}$ excitation energy.

In this Communication, we report the first systematic study of the low-temperature (65–770 mK) magnetotransport of a fractional quantum effect in a GaAs-AlGaAs sample of extremely high mobility ($\sim 10^6$ cm^2/V sec), in magnetic fields between 66 and 106 kG. Several significant results are obtained for the $\frac{2}{3}$ effect. We establish the existence of the $\frac{2}{3}$ quantum number by verifying the accuracy of Hall resistivity ρ_{xy} quantization to 3 parts in 10^4. We find ρ_{xx} to be thermally activated over a dynamic range of two decades in ρ_{xx} and a factor of 6 in temperature. This result clearly demonstrates the existence of a gap in the excitation spectrum. We investigate the role of disorder in two ways: (i) We study the activation energy of ρ_{xx} and ρ_{xy} as a function of the filling factor $\nu = nh/eB$, where n is the electron density, B the magnetic field, and h/e the flux quantum, and observe a resonancelike curve. This curve characterizes the width of the $\frac{2}{3}$ Hall plateau, and provides a measure of the number of localized states. It gives us a basis to speculate on some properties of the excited states. (ii) We investigate the maximum activation energy Δ_{max}, which occurs at $\nu = \frac{2}{3}$, as a function of B and mobility μ. We find Δ_{max} strongly dependent on μ and B and smaller than the excitation gap predicted by Laughlin. Extrapolation of the data suggests the existence of a mobility threshold below which Δ_{max} vanishes. Other than the $\frac{2}{3}$ effect, we have observed dip structures in ρ_{xx} near $\nu = \frac{5}{3}$, $\frac{4}{3}$, $\frac{4}{5}$, and $\frac{3}{5}$, consistent with a recent report of extra structures near these values.[7] Only $\frac{5}{3}$ and $\frac{4}{3}$ show plateau development in ρ_{xy} as well. The $\frac{5}{3}$ plateau is accurately quantized (1.1 part in 10^3) and has a flatness which is exceedingly sensitive to μ, again suggesting the existence of a threshold.

Our sample is a modulation-doped GaAs-$Al_xGa_{1-x}As$ heterostructure grown by molecular-beam epitaxy. The layered structure consists of 1-μm undoped GaAs, 370 Å of undoped AlGaAs, and 400 Å of Si-doped (2×10^{18} cm^{-3}) AlGaAs. Electrons ionized from the Si donors are confined to the GaAs and AlGaAs interface, forming a two-dimensional gas. The region of undoped AlGaAs separates the electrons from the donors and reduces impurity scattering. We are able to vary the electron density continuously between 1 and 2.1×10^{11} cm^{-2} using a backside gate.[8] Concomitantly the mobility increases with the density according to a power law.[9] The highest mobility achieved is 1.5×10^{6} cm^2/V sec at $n=2.1\times10^{11}$ cm^{-2}.

In Fig. 1 we present data for ρ_{xx} and ρ_{xy} vs ν near $\nu=\frac{2}{3}$. At low temperatures, ρ_{xy} develops a plateau at a value $h/(\frac{2}{3}e^2)$, centered about $\nu=\frac{2}{3}$, while ρ_{xx} shows a dip with a minimum at $\frac{2}{3}$. We are able to vary ν in two ways, either by changing B while keeping n constant, or vice versa. We have performed standard measurements to characterize the $\frac{2}{3}$ effect. At 65 mK, we find ρ_{xy} accurately quantized to 3 parts in 10^4. The lowest ρ_{xx} achieved is 10 Ω/□. The I-V relation is linear down to an electric field of less than 10^{-5} V/cm. This indicates that the ground state is not a pinned charge-density wave; it is consistent with the present picture of an incompressible quantum fluid.

The temperature dependence of ρ_{xx} and $\Delta\rho_{xy}=\rho_{xy}-h/(\frac{2}{3}e^2)$ is observed to be activated. In Fig. 2(a) we present data for ρ_{xx} taken at $B=92.5$ kG. The different curves show that ρ_{xx} is activated not just at $\nu=\frac{2}{3}$, but also at various ν about $\frac{2}{3}$. ν is varied by varying n. In Fig. 2(b), we plot the activation energy Δ for both ρ_{xx} and $\Delta\rho_{xy}$ as a function of ν. Within our resolution, their activation energies are identical. The resulting curve has a maximum value, Δ_{max} at $\nu=\frac{2}{3}$, and decreases to each side. This resonancelike curve is characterized by a width $\Delta\nu$, determined by the points at which Δ vanishes. For Fig. 2(b), $\Delta_{max}=0.830\pm0.03$ K and $\Delta\nu=0.1\pm0.01$. We note that at

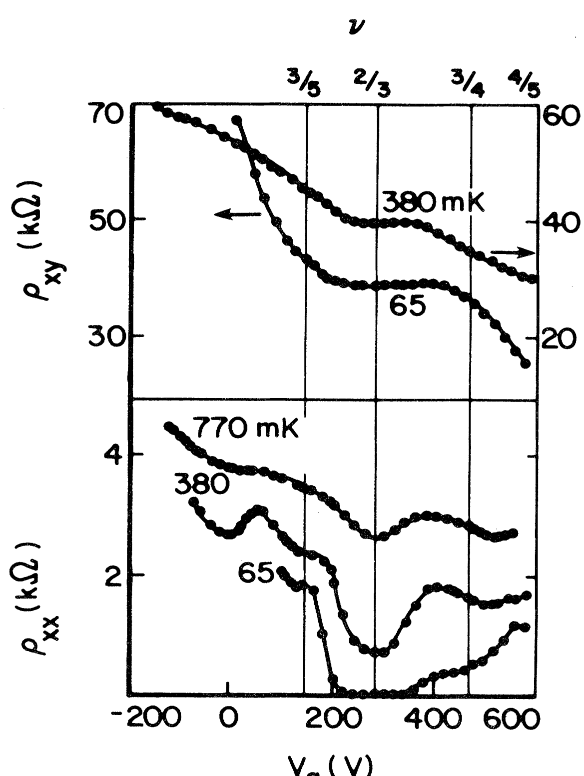

FIG. 1. ρ_{xx} and ρ_{xy} vs backgate voltage and filling factor ν at $B=104.5$ kG.

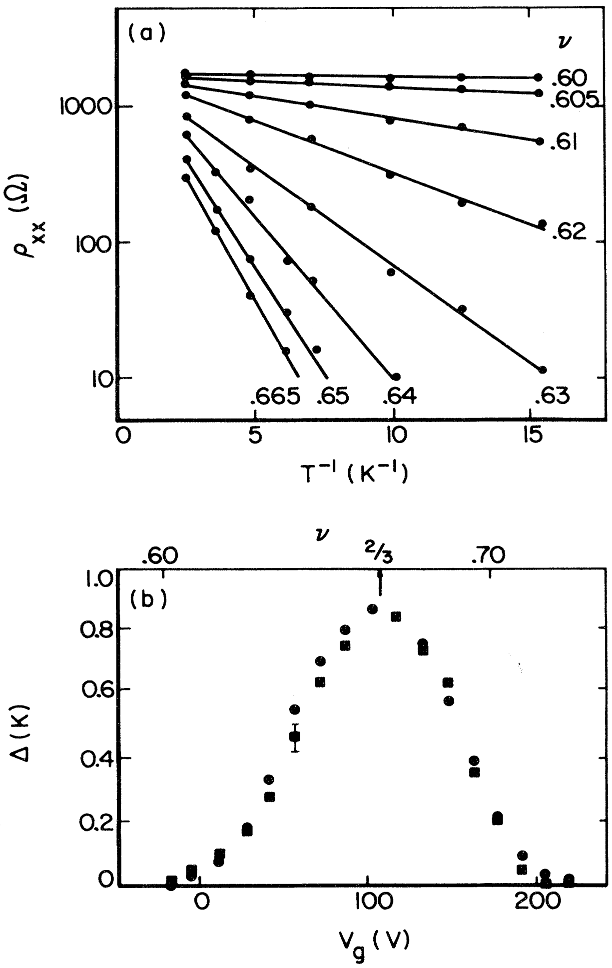

FIG. 2. (a) ρ_{xx} as a function of inverse temperature, for various filling factors ν about $\frac{2}{3}$. The magnetic field is 92.5 kG and the electron density is varied by applying a backgate voltage. (b) The activation energy Δ as a function of gate voltage and ν.

$\frac{2}{3}$, the activation energy of $\Delta\rho_{xy}$ cannot be determined since ρ_{xy} does not change. We have also obtained a similar curve by keeping n fixed and varying B. In this case, the sample mobility $\mu=52\,000$ cm^2/V sec, $\nu=\frac{2}{3}$ occurs at $B=66.8$ kG, $\Delta_{max}=0.38\pm0.05$ K, and $\Delta\nu=0.14\pm0.02$.

In Fig. 3, we show Δ_{max} as a function of μ and B. Notice that these two variables are not independent. When the field position of $\nu=\frac{2}{3}$ is moved by changing n, μ varies according to $n^{1.5}$. The activation energy decreases as μ and B are lowered and shows an approximately linear dependence on μ. Extrapolation of the data gives a mobility threshold $\sim4.5\times10^{5}$ cm^2/V sec and a field threshold of ~60 kG, at which Δ_{max} vanishes.

We invoke a phenomenological model of the fractionally charged excitation spectrum, based on Laughlin's theoretical results, to gain an understanding of the data. Laughlin's theory proposed a new ground state for the strongly interacting electron gas which is a highly correlated quantum fluid. This state has the lowest energy at $\nu=\frac{1}{3}$ and carries

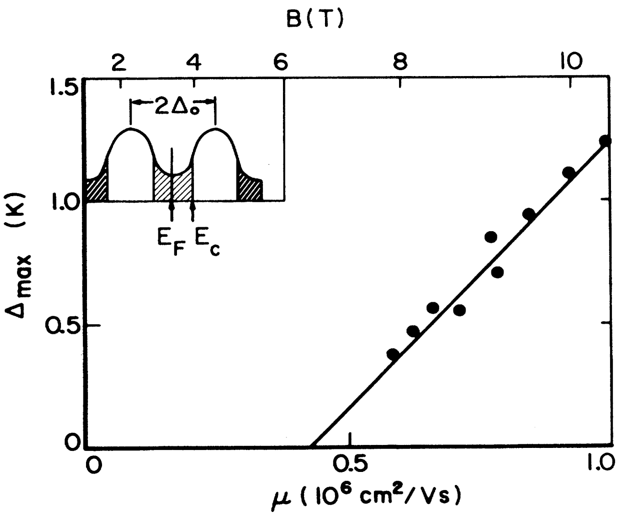

FIG. 3. Maximum activation energy Δ_{max}, which occurs at $\nu=\frac{2}{3}$, as a function of mobility μ and field B. The solid line is a guide for the eye. Insert shows the underlying energy structure of impurity-broadened Landau levels. The shaded regions denoted localized states and E_F is the Fermi energy.

a Hall current of $\frac{1}{3}e^2/h$ times the Hall voltage. By electron-hole symmetry arguments, a similar state exists at $\nu=\frac{2}{3}$. The theory further predicts the existence of fractionally charged quasiparticle and quasihole bands. If we assume that disorder broadens these bands, we can arrive at a qualitative understanding of the observed activated behavior of ρ_{xx} at different values of ν, and the decrease of Δ_{max} with increasing disorder.

The behavior of ρ_{xx} near $\nu=\frac{2}{3}$ is similar to that close to integer ν values in the ordinary QHE. The underlying energy structure is illustrated in the insert of Fig. 3. In the integral case, the neighboring Landau levels are separated by a gap $2\Delta_0=\hbar\omega_c$ between the centers and are broadened due to impurity scattering. The tail states of each level are localized and separated from the extended states in the middle at an energy E_c. The activated behavior of ρ_{xx} is observed whenever the Fermi level E_F falls into the region of localized states in the mobility gap, and it results from thermal excitation of electrons (or holes) into the extended states. We can envision a similar situation for the $\frac{2}{3}$ QHE. According to Laughlin's prediction, at $\nu=\frac{2}{3}$ a gap

$$E_{gap}=2\Delta_0=0.04\frac{e^2}{\epsilon l_0}\propto\sqrt{B} \qquad (1)$$

(where $l_0^2=\hbar/eB$ and ϵ is the dielectric constant) develops between the centers of $\frac{1}{3}$ charged quasiparticle and quasihole bands. At $\nu=\frac{2}{3}$, if an electron is added (removed), three quasiparticles (holes) are formed occupying the lowest available energy states. Disorder broadens the bands and gives rise to localized states separated from the extended states at E_c. The measured activation energy will be the distance between E_c and the quasiparticle "Fermi energy" E_F. If E_c is not strongly dependent on small changes in n, an activated ρ_{xx} would be observed giving rise to the observed Δ vs ν curve. Moreover, it is plausible that as the impurity broadening becomes sufficiently large as a result of an excessive amount of disorder, the mobility gap will vanish, giving rise to a threshold in the activation energy.

Since three quasiparticles make up one electron, one may suspect (by angular momentum addition) that the quasiparticles should behave as fermions. We must point out, however, that if $2\Delta_0$ is the correct band-center separation,[10] our results are inconsistent with such a conclusion within the phenomenological picture. One indication of the inconsistency is obtained from Fig. 2. The total number of states in each quasiparticle band is equal to eB/h. Our Δ vs ν curve has a half-width of $\Delta\nu/2=0.05$, which implies that at the mobility edge, the band holds three times 0.05 or 0.15 eB/h quasiparticles, i.e., 15% of its total available states. If the quasiparticles were fermions, this would imply that 30% of the band is localized. At $B=92.5$ kG, Eq. (1) predicts a separation of 2.8 K from the center of the mobility gap to the band center, whereas the measured Δ_{max} is 0.83 K. This would imply that 30% of the fermions must reside in at most (assuming a constant density of states) the $0.83/2.8=30\%$ band tail region. More convincing evidence is contained in the result obtained at a fixed n about $B=66.8$ kG, where $\Delta\nu=0.14$ and $\Delta_{max}=0.38$ K. In this case, 42% of the fermions would have to reside in the 14% band tail region.[1] We may conclude that the quasiparticles cannot be fermions.

In conclusion, several interesting results have emerged from our study of the fractional QHE in the high-mobility, low-temperature regime. The $\frac{2}{3}$ state is accurately quantized. The I-V relation is linear at low electric fields, suggesting that it is not a pinned charge-density-wave state. Disorder plays an important role in determining the energy gap between the ground and excited states; the gap appears to have a mobility threshold. We are able to gain a qualitative understanding of the activated behavior in ρ_{xx} at each ν in terms of Laughlin's impurity-broadened quasiparticle-hole bands. Assuming the band-center separation to be equal to $2\Delta_0$ predicted by Laughlin, we demonstrate an inconsistency with the interpretation of the quasiparticles as fermions within a phenomenological picture of quasiparticle bands. Our results point to two important questions which remain to be answered. First, what is the nature of the fractionally charged excited states, and their filling behavior, and what governs their filling behavior, in light of the possibility that they are not fermions but mutually strong repulsive entities? Second, how does disorder affect Δ_0? We have assumed that the band center is unaffected by mobility and resides at the theoretically predicted gap value. However, we cannot rule out the possibility that Δ_0 depends on disorder.

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*Present address: General Electric Company Electronics Laboratory, P.O. Box 488, Syracuse, NY 13221.

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[10]Results from Ref. 3 and unpublished work on high-mobility samples indicate that the largest gap thus far observed for the $\frac{1}{3}$ effect has a value of ~ 3 K at 200 kG compared with a value of 4 K predicted by Eq. (1).