Observation of excess conductance of a constricted electron gas in the fractional quantum Hall regime

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We present experimental results on the conductance of a two-dimensional electron system of filling factor v_{2D} in the fractional quantum Hall regime, containing a constricted region of lower filling factor v_t. Conductance fluctuations are observed as a function of the voltage on the gate defining the constriction. The temperature dependence of the fluctuations exhibits three distinct regimes, governed by v_t. For temperatures below 100 mK, and for $v_{2D} = \frac{1}{3}$, one anomalous peak increases to a value above the quantized conductance $v_{2D}(e^2/h)$ of the bulk.

The two-terminal conductance G of a noninteracting two-dimensional electron system (2DES) is limited by the number N of quantum channels times e^2/h. The maximum $N(e^2/h)$ is observed only in the absence of backscattering. This is the basis of the edge-channel formulation of the integer quantum Hall effect,[1] where both the Hall conductance G_H and G are quantized to the value $N_{2D}(e^2/h)$, where N_{2D} is the number of edge channels at the Fermi energy (or equivalently the number of Landau levels below the Fermi energy).

In the fractional quantum Hall effect (FQHE), G_H and G are quantized at $v_{2D}(e^2/h)$ where the filling factor v_{2D} is equal to one of a series of fractional values. An interpretation of v_{2D} in terms of edge channels has been formulated by several authors.[2–4] These theories take the form of a Landauer formula, in which the quantum channels contribute with a fractional weight. In Refs. 2 and 3 all weight factors are positive. This implies for the two-terminal conductance G of a constricted 2DES the inequality

$$G \leq v_{2D}(e^2/h) . \tag{1}$$

MacDonald[4] has provided an alternative description of the FQHE involving positive as well as negative weight factors, corresponding to electron and hole channels, respectively. In this formulation, G can in principle exceed $v_{2D}(e^c/h)$. Experimental results consistent with the existence of fractional electron channels have been reported,[5–8] but fractional hole channels have not yet been observed. This paper reports a violation of Eq. (1) that may be indicative of the selective reflection of hole channels, but not in a way that has been anticipated theoretically.

A schematic drawing of the device is shown in the inset of Fig. 1. A standard Hall bar of width 400 μm and length 860 μm is fabricated by etching a mesa on an $Al_xGa_{1-x}As/GaAs$ heterostructure with a 2DES of extremely low density $(4.5 \times 10^{10}$ cm$^{-2})$ and high mobility $(5 \times 10^6$ cm^2/V s). Measurements of the Hall conductance show well-defined fractional plateaus at $v_{2D} = \frac{2}{3}, \frac{1}{3}, \frac{2}{5}$, and $\frac{1}{5}$ with vanishing longitudinal resistance at $\frac{2}{3}$ and $\frac{1}{5}$ and nonzero but well-defined minima at $\frac{1}{3}$ and $\frac{2}{5}$. A

narrow channel is formed near the center of the Hall bar by applying a gate voltage of $V_g < -0.3$ V on a split gate of lithographic width varying from 0.5 to 1.5 μm and length 8.5 μm. All measurements are made with a double ac lock-in technique using an excitation voltage below 5 μV. The diagonal four-terminal conductance $G_{24,13}$ is obtained by passing current between contacts 2 and 4 and measuring the voltage between contacts 1 and 3. This is equivalent to an ideal two-terminal conductance measurement in which the nonideal contact resistance has been eliminated.[9]

Figure 1 shows the results of such a conductance measurement as a function of gate voltage at $B = 5.7$ T for six temperatures between 45 and 200 mK. The filling factor in the bulk of the sample is $v_{2D} = \frac{1}{3}$, independent of V_g. For $V_g \lesssim -0.40$ V, a series of conductance fluctuations is observed until the constriction shuts off at $V_g \approx -0.60$ V.
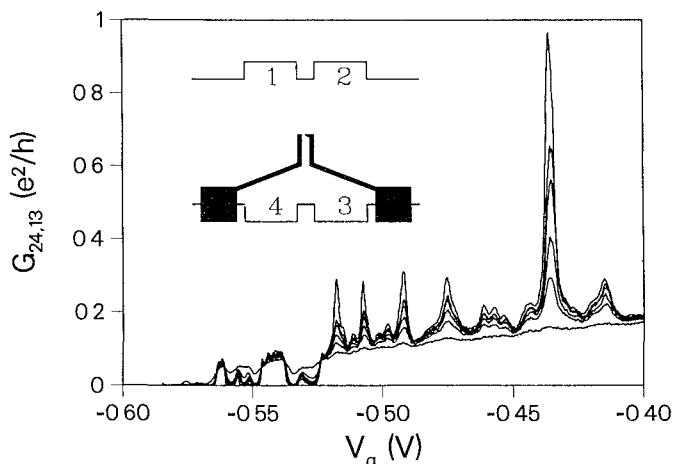

FIG 1. Conductance as a function of gate voltage for six different temperatures (45, 70, 80, 95, 120, and 200 mK, from top to bottom) at $B = 5.7$ T $(v_{2D} = \frac{1}{3})$. The dotted line shows the conductance with $V_g = 0$, and is $\approx \frac{1}{3}(e^2/h)$. The conductance of one peak approaches e^2/h, exceeding the bulk conductance. Inset: Schematic drawing of device geometry with the gates shaded and the contacts labeled 1–4. The magnetic field points into the page.

As the temperature is decreased, most of the conductance peaks approach, but do not rise above, the bulk conductance $\frac{1}{7}$ (e^2/h), shown as a dotted line in the figure. One peak, however, rises well above this value, approaching e^2/h at 45 mK. The height of this anomalous peak is strongly temperature dependent, dropping below the bulk conductance at $T \approx 120$ mK. The excess conductance peak was also measured two terminally, using either contacts 1 and 3 (G_{13}) or contacts 2 and 4 (G_{24}). In both cases the peak height was still considerably higher than the bulk conductance, but lower than in Fig. 1, due to the contribution of the contact resistance.

This excess conductance peak was discovered in the course of a systematic study of the magnetic field, gate voltage, and temperature dependence of conductance fluctuations of a constricted 2DES in the fractional quantum Hall regime. The results of this study are shown in Figs. 2-4. In Fig. 2(a), the conductance versus gate voltage at 45 mK is shown for a number of magnetic fields. The anomalous conductance peak is the dominate feature at higher fields. The traces show a region of slowly decreasing conductance with a sequence of partially formed plateaus, followed by a region of sharp reproducible fluctuations. The fluctuations are reproducible from run to run, but not among different samples. On increasing B, the onset of the fluctuations shifts to less negative V_g. To the right of this transition a plateau, with conductance near
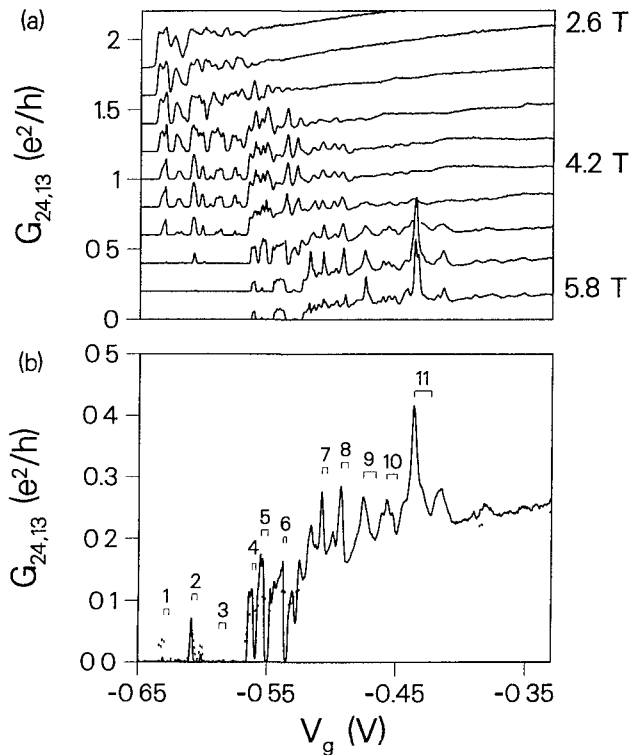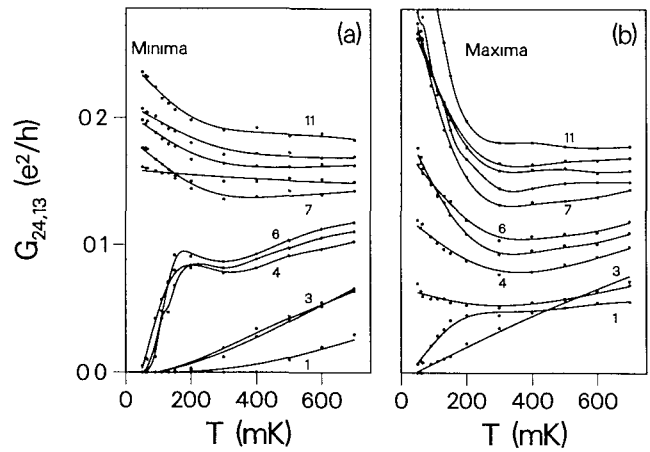

FIG 3 Conductance of selected (a) minima and (b) maxima from Fig 2(b) as a function of temperature. Increasing index indicates decreasing V_g or increasing filling factor v_c in the constriction. Three different types of temperature dependencies may be distinguished (see text)

$\frac{2}{7}$ (e^2/h), is observed in a number of the traces. This suggests that the fluctuations only occur for filling factor $v_c \lesssim \frac{2}{7}$ in the constriction. The pattern of fluctuations itself hardly varies with magnetic field, except for small shifts. We conclude that the position of an individual peak is determined by V_g and thus by the density in the constriction, while the onset of the fluctuations is determined by the filling factor v_c.

In Fig. 2(b), the conductance trace measured at 5.0 T is plotted separately, for $T = 45$ (solid line) and for 200 mK (dotted line). It is clear that most of the structure seen at 45 mK has disappeared at 200 mK. In order to obtain a more detailed temperature dependence, the conductance has been measured at a number of temperatures between 45 and 700 mK. The results are plotted in Figs. 3(a) and 3(b) for the maxima and minima marked 1 through 11 in Fig. 2(b), in order of increasing v_c. Three different types of temperature dependence in Fig. 3 may be distinguished, corresponding to three different regimes of v_c. As the

FIG 2 (a) Conductance as a function of gate voltage measured at ten magnetic fields from 2.2 ($v_{2D} = 0.85$) to 5.8 T ($v_{2D} = 0.32$) The trace at $B = 5.8$ T is plotted with no offset, each successive trace, corresponding to a decrease of 0.40 T, is offset from the previous one by 0.2(e^2/h) (b) Conductance as a function of V_g at $B = 5.0$ T ($v_{2D} = 0.37$) for $T = 45$ (solid line) and 200 mK (dotted line) The temperature dependencies of the extrema 1-11 are plotted in Fig. 3.
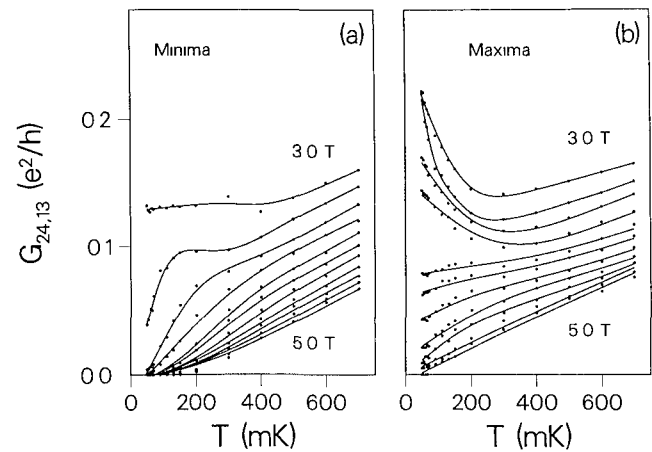

FIG 4 Conductance of the (a) minimum and (b) maximum labeled 3 in Fig 2(b), as a function of temperature for eleven equally spaced magnetic fields ranging from $B = 3.0$ ($v_{2D} = 0.62$) to 5.0 T ($v_{2D} = 0.37$) Note the similarity to Fig 3.

temperature is reduced in the high v_c regime, the maxima increase sharply below 100 mK, whereas the minima increase gradually. In the low v_c regime, both the maxima and the minima decrease gradually. Finally, in the intermediate v_c regime, the minima decrease sharply while the maxima are strongly enhanced. To show that the three regimes are determined by filling factor rather than by density, the temperature dependence of the extrema of peak 3 are plotted in Figs. 4(a) and 4(b) for eleven equally spaced fields between 3.0 and 5.0 T. The qualitative similarity between Figs. 3 and 4 is striking. This proves that transitions among the three regimes of different temperature dependence may be achieved by either an increase in density or a decrease in magnetic field, both of these changes corresponding to an increase in filling factor.

There are a number of possible mechanisms for conductance fluctuations in a narrow constriction in high magnetic fields. These include (1) resonant backscattering of electrons through a state localized on an impurity;[10] (2) Coulomb blockade oscillations due to tunneling through two potential barriers in series;[11-13] (3) pinning and depinning of a charge density wave.[14,15] The three types of temperature dependence observed at different values of v_c (Figs. 3 and 4) suggest that more than one mechanism is responsible for the fluctuations that we observe. In the low v_c regime, the Coulomb blockade or charge-density wave models are the most appropriate, whereas for high v_c a description in terms of resonant backscattering may be adequate.

The excess conductance peak lies in the high v_c regime. The peak height exceeds the bulk conductance for a certain range of magnetic field values only. Figure 5 shows the peak conductance and the 2DES conductance (for $V_g=0$) versus B. As a function of decreasing magnetic field, in a range where the bulk conductance remains within 10% of $\frac{1}{3}(e^2/h)$, the conductance peak is seen to decrease in a stepwise fashion, with plateaus near $1(e^2/h)$, $\frac{2}{3}(e^2/h)$, and $\frac{1}{3}(e^2/h)$. These measurements were made at 45 mK, which is our lowest obtainable temperature. Additional experiments at lower temperature would be needed to prove that the conductance actually saturates on these plateau values.

We do not have a definitive explanation for the excess conductance, which violates Eq. (1). Büttiker[1] has pointed out that the two-terminal conductance of a short, wide sample in the integer quantum Hall regime can exceed $N_{2D}(e^2/h)$ due to conduction along paths percolating through the bulk of the sample. In our case this would require a macroscopically large correlation length of the impurity potential greater than $\approx 400\ \mu$m. It is then conceivable that the formation of a constriction could modify the location of percolating paths and thereby give rise to the excess conductance observed in our experiment.

An alternative interpretation is in terms of reflection of hole channels at the constriction. It is important to note that if all sample edges are in local equilibrium, the bulk 2DES can be treated as an Ohmic conductor in series with the constriction. In this case the series conductance G cannot exceed the 2DES conductance, according to Ohm's
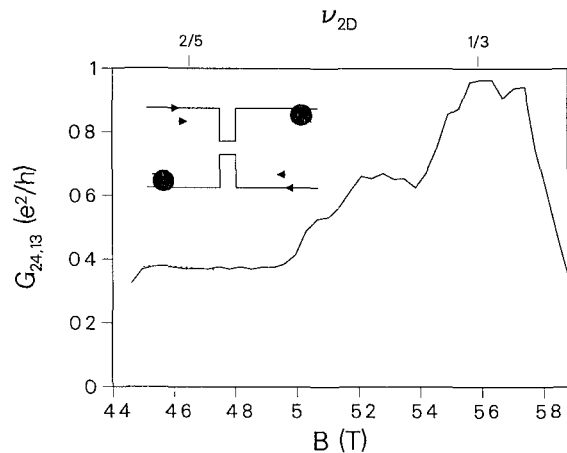

FIG. 5. The excess peak conductance (solid line) and the conductance at $V_g=0$ (dotted line) as a function of magnetic field for $T=45$ mK. As the magnetic field varies over the $\frac{1}{3}$ plateau of the unconstricted 2DES, plateaus in the peak conductance are observed near $1(e^2/h)$, $\frac{2}{3}(e^2/h)$, and $\frac{1}{3}(e^2/h)$. Inset: Depiction of possible mechanism for producing the observed excess conductance peak (see text).

law. Violation of Eq. (1), therefore, requires the absence of local equilibrium at some of the sample edges. These ideas are illustrated in the diagram in Fig. 5, which shows one electron channel (solid line) tunneling resonantly through a constriction and one hole channel (dashed line), which is reflected. Equilibration occurs only at two of the four distinct edges of the sample (indicated by a shaded circle). The electron and hole channels contribute to the Landauer formula with fractional weight factors $\alpha > 0$ and $-\beta < 0$, respectively, where $\alpha - \beta = v_{2D}$. The diagram in Fig. 5 corresponds to a conductance $G = \alpha(e^2/h)$ which exceeds the bulk value $(\alpha - \beta)(e^2/h) = v_{2D}(e^2/h)$ obtained in the absence of the constriction. The experimental data in Fig. 5 suggest the presence of two hole channels, each having weight factor $\frac{1}{3}$, and one electron channel, with weight factor 1, such that $v_{2D} = 1 - \frac{1}{3} - \frac{1}{3} = \frac{1}{3}$. Reflection of zero, one, and two hole channels then increases the conductance from $\frac{1}{3}$ to $\frac{2}{3}$ to $1 \times e^2/h$.

In conclusion, we have observed conductance fluctuations as a function of the voltage on the gate defining the constriction in a 2DES in the fractional quantum Hall regime. The temperature dependence of the fluctuations as well as the gate voltage beyond which they are observed are shown to be governed by the filling factor in the constriction. One anomalous peak exceeds the conductance $v_{2D}(e^2/h)$ of the bulk 2DES. This excess conductance cannot be understood in terms of the present edge channel formulation of transport in the fractional quantum Hall regime.

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