Measurements of a composite fermion split-gate device

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(Received 6 September 1995)

Recent theoretical and experimental work demonstrates that a two-dimensional electron gas at Landau-level filling factor $\nu=\frac{1}{2}$ can be described in terms of composite fermions (CF's) for which the effective magnetic field $B_{\rm eff}$ vanishes. We have measured the transport properties of CF's in a quantum point contact (QPC) defined by a wide split-gate device. Negative magnetoresistance due to suppression of backscattering in the QPC was observed both around zero magnetic field $B=0$ and $B_{\rm eff}=0$. We have also measured the resistance of a composite fermion QPC at $B_{\rm eff}=0$ as a function of gate voltage, with an applied magnetic field to maintain $\nu=\frac{1}{2}$ in the QPC. Using a simple model to compare the results for $B=0$ and $\nu=\frac{1}{2}$, we have determined that the channel widths for CF's are narrower than those for electrons.

The fractional quantum Hall effect (FQHE) is observed in high mobility two-dimensional (2D) electron systems in the low-temperature, high-magnetic-field regime.[1] It is believed that the FQHE arises from strong electron-electron interactions, causing the 2D electrons to condense into a fractional quantum Hall liquid.[2] Jain[3] introduced the concept of ''composite fermions,'' where each electron is bound to an even number of magnetic flux quanta, and in this picture the FQHE can then be understood as a manifestation of the integer quantum Hall effect[4] of weakly interacting composite fermions. It has been shown[5] that at Landau-level filling factor $\nu=\frac{1}{2}$, a 2D electron system can be mathematically transformed into a composite fermion (CF) system interacting with a Chern-Simons gauge field. A wide variety of experiments[6–13] have demonstrated that at $\nu=\frac{1}{2}$ the effective magnetic field $B_{\rm eff}$ acting on the composite fermions (CF's) is zero.

Using the split-gate[14] (SG) technique, a 1D channel[15] or a quantum point contact[16] (QPC) can be defined in the 2D electron gas (2DEG). Low-field four-terminal measurements of such a channel show negative magnetoresistance R_{xx} given by[17]

$$R_{xx}=\left(\frac{h}{2e^2N_e(B)}\right)-R_{xy}, \tag{1}$$

where $N_e(B)$ is the number of occupied magnetoelectric subbands in the channel, R_{xy} is the Hall resistance of the bulk 2DEG region, and B is the applied perpendicular magnetic field. Assuming spin degeneracy and ignoring the discreteness of $N_e(B)$, for $W_e<2l_c$, $N_e(B)$ in a square-well confinement is[17]

$$N_e(B)=\left(\frac{k_F l_c}{\pi}\right)\left\{\arcsin\left(\frac{W_e}{2l_c}\right)+\left(\frac{W_e}{2l_c}\right)\left[1-\left(\frac{W_e}{2l_c}\right)^2\right]^{1/2}\right\}, \tag{2}$$

where k_F is the Fermi wave vector in the channel, $l_c=\hbar k_F/eB$ is the cyclotron radius, and W_e is the channel width for electrons. Increasing the magnetic field causes electrons to execute skipping orbits towards the channel boundary, suppressing backscattering near the entrance to the channel, giving rise to negative magnetoresistance (NMR) centered around $B=0$.

In this paper we present low-temperature measurements of a wide SG device fabricated on a GaAs/$Al_{0.3}Ga_{0.7}As$ heterostructure. Over the measurement range, the channel defined by the SG is very wide (as shown later) and at least 12 spin-degenerate 1D subbands are occupied. For such a wide channel the confining potential can be described as a square well with a carrier density that is uniform across the channel. Such uniformity allows us to measure a composite fermion QPC at $B_{\rm eff}=0$ as a function of gate voltage V_g, where an applied magnetic field maintains $\nu=\frac{1}{2}$ in the channel. Recently Khaetskii and Bauer[18] have considered CF transport in a bar-gated sample where a small negative voltage reduces the carrier density beneath the gate, inducing an effective magnetic field in those regions. Injected CF's approaching the slightly depleted regions are bent back to the source contact by the induced effective field. We shall show that our experimental results qualitatively agree with this theory.

The SG device T139-3 (0.3 μm long and 1.2 μm wide) was lithographically defined on the surface of the sample, 297 nm above the 2DEG. It has been recently demonstrated[19] that clean 1D channels showing good conductance quantization at zero magnetic field can be defined in such deep 2DEG's. After brief illumination with a red light emitting diode, the carrier concentration of the 2DEG was $\approx 1.4\times10^{15}$ m^{-2}, with a mobility of 350 m^2 V^{-1} s^{-1}. Experiments were performed in a ^{3}He cryostat at 0.3 K and the magnetoresistance was measured using a current of 10 nA with standard four-terminal ac phase-sensitive techniques. Seven samples measured from three different wafers showed similar characteristics, and measurements taken from one of these are presented in this paper.

Figure 1 shows the four-terminal transverse R_{xy} and longitudinal R_{xx} magnetoresistance measurements for $V_g=0$. The minima in R_{xx} coincide with the Hall plateaus and a broad minimum in R_{xx} is observed at $\nu=\frac{1}{2}$, indicating that the carrier density in our wafer is uniform and that the presence of the earthed split gate has little influence on the carrier density of the 2DEG. When a negative voltage of -0.7

0163-1829/96/53(12)/7596(3)/$10.00

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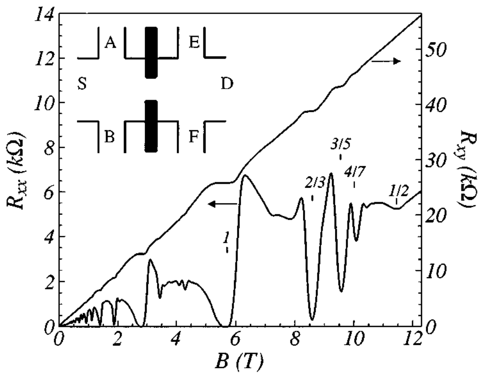

FIG. 1. Longitudinal R_{xx} and transverse R_{xy} magnetoresistance for $V_g=0$ V. The inset shows the SG device configuration. The black regions correspond to the surface gates. *S* and *D* are source and drain contacts. *A, B, E,* and *F* are voltage probes.

V was applied to the SG, the channel was defined and NMR centered around $B=0$ was observed. It is noted that a resistance $R_{xx}(V_g=0)$ due to the bulk 2DEG was measured in series with the channel resistance.[17] After subtracting this contribution ($\approx 100\ \Omega$) we used Eqs. (1) and (2) to estimate that the channel width varies from 0.39 to 0.88 μm over the gate voltage range of $-3 \leqslant V_g \leqslant -0.7$ V. In this range of V_g the channel is very wide and we assume that the carrier density n_s is uniform across the channel. $n_s(V_g)$ can be varied by changing V_g on the SG, whereas the carrier concentration of the bulk 2DEG remains unchanged. We can obtain $n_s(V_g)$ by two measurements. First, by taking the magnetic field at the midpoint of the $\nu=1$ two-terminal quantized Hall plateau, we determine $n_s(V_g)$ from the relations $\nu eB/h = n_s$. Second, for $V_g \leqslant -2.1$ V we observed extra minima in R_{xx} around 8 T corresponding to $\nu=\frac{2}{3}$ in the channel, see Fig. 2, also allowing us to calculate $n_s(V_g)$. The carrier concentrations $n_s(V_g)$ obtained by these two measurements are within 0.5%. For consistency we use $n_s(V_g)$ determined by the first measurement.

Figure 2 shows the high-field magnetoresistance measurements at various gate voltages. For $V_g=0$ V, the minima in

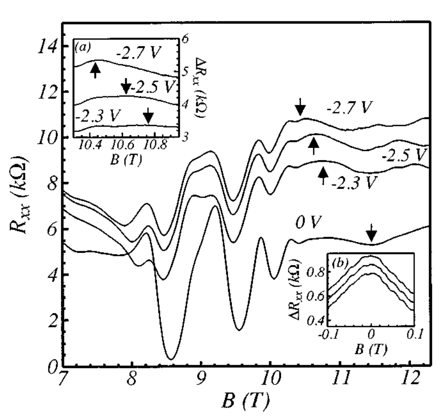

FIG. 2. $R_{xx}(B)$ at various V_g. For clarity the trace for $V_g=-2.5$ V is vertically offset by 0.3 kΩ. Insets (a) and (b) show the magnetoresistance ΔR_{xx} centered around $\nu=\frac{1}{2}$ and $B=0$, respectively. The position of $\nu=\frac{1}{2}$ in the channel at various V_g is indicated by arrows.

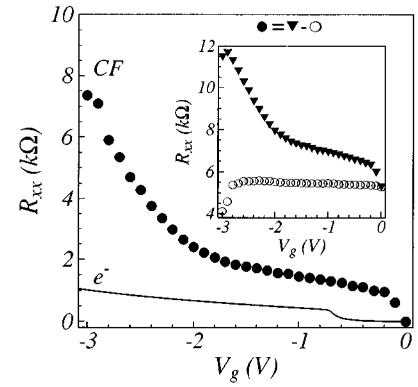

FIG. 3. Inset: The measured resistance (marked by ▼) and the series resistance (marked by ○) as a function of V_g. Main figure: the resistance of the CF QPC given by ●=▼−○ as a function of V_g. The resistance of the electron QPC (after subtraction of the constant series resistance of the 2DEG of 93.3 Ω) is plotted as a solid line.

R_{xx} around $B=8.6$, 9.5, and 10 T arise from the $\nu=\frac{2}{3}$, $\frac{3}{5}$, and $\frac{4}{7}$ states in the bulk 2DEG measured in series with the QPC. For $V_g=-2.3$, -2.5, and -2.7 V, the magnetoresistance minima arising from the $\nu=\frac{2}{3}$ and $\frac{3}{5}$ states in the bulk 2DEG differ by less than 1% of the original value of those for $V_g=0$ V. When the channel is defined, NMR around $\nu=\frac{1}{2}$ is observed as indicated by arrows for $V_g=-2.3$, -2.5, and -2.7 V. After subtraction of the series resistance, the corrected resistance $\Delta R_{xx} \equiv R_{xx}(V_g) - R_{xx}(V_g=0)$ shows NMR around $\nu=\frac{1}{2}$ and $B=0$, as displayed in the insets of Figs. 2(a) and 2(b), respectively. We believe that the NMR in ΔR_{xx} around $\nu=\frac{1}{2}$ is evidence of suppression of backscattering of CF's in an effective magnetic field. If we consider that there is a factor of $\sqrt{2}$ between the Fermi wave vector of electrons and that of CF's and there is no spin degeneracy for CF's, the fit to Eqs. (1) and (2) is very poor. Thus it is not a reliable method to determine the channel widths for CF's. As shown later, we can determine the channel widths for CF's using a simple alternative model.

We now describe the measurements of a CF QPC at $B_{\mathrm{eff}}=0$. For $V_g=0$ V, measurements of the sample at $\nu=\frac{1}{2}$ yield a resistivity of 611 $\Omega/\square$, equivalent to a mobility of 7.38 $\mathrm{m^2\,V^{-1}\,s^{-1}}$.[8] The corresponding composite fermion mean free path is approximately 0.7 μm, which is longer than the length of the SG device. Thus we believe that the effect of CF scattering from impurities within the QPC is not significant. For various gate voltages, the measured resistance when $\nu=\frac{1}{2}$ in the channel is indicated by arrows, see Fig. 2. Note that at equal *B* a background resistance due to the bulk 2DEG $R_{xx}(V_g=0)$ was measured in series with the CF QPC. Therefore the corrected resistance of the CF QPC (marked by ●) is given by the measured resistance when $\nu=\frac{1}{2}$ in the channel (marked by ▼) after subtraction of the series resistance (marked by ○), as shown in Fig. 3. The resistance of the electron QPC at $B=0$ after subtraction of the constant series resistance of the 2DEG (93.3 Ω) as a function of V_g is also displayed for comparison. Two features can be clearly seen in this figure: (i) At equal V_g, the resistance of the CF QPC is higher than the electron QPC. (ii) The definition voltage of the CF QPC is ≈ -0.3 V, larger than that of the electron QPC (-0.7 V). The latter can be explained by a recent theory[18] as follows. At $\nu=\frac{1}{2}$, applying a small negative V_g induces a strong $B_{\rm eff}$ under the SG and the CF's cannot traverse these regions. In this case, CF's can only go through the channel, causing the channel to be defined at a larger V_g when electrons are not fully depleted underneath the SG.

Finally, we use a simple model to calculate the channel widths for CF's. At $B=0$, the resistance of an electron QPC can be written as $R_e=h/2e^2N_e$, where N_e is the number of occupied 1D subbands in the channel and the factor of 2 is due to spin degeneracy. Assuming a square-well potential $N_e=2W_e/\lambda_e$, we have $R_e=h\lambda_e/4e^2W_e$, where λ_e is the Fermi wavelength in the channel. Provided that 1D subbands also exist in a CF QPC, the resistance of such a device is $R_{\rm CF}=h/e^2N_{\rm CF}$, where $N_{\rm CF}$ is the number of occupied CF subbands, and there is no spin degeneracy. Following the same argument, we obtain $R_{\rm CF}=h\lambda_e/2\sqrt{2}e^2W_{\rm CF}$, where $\lambda_{\rm CF}$ is the Fermi wavelength of CF's and $\sqrt{2}\lambda_{\rm CF}=\lambda_e$. Thus the ratio of $R_{\rm CF}$ to R_e for a given gate voltage V_g is

$$\frac{R_{\rm CF}}{R_e}=\frac{\sqrt{2}W_e}{W_{\rm CF}}. \tag{3}$$

We determine $W_e(V_g)$ from fits of experimental data ΔR_{xx} centered around $B=0$ to Eq. (1), and $R_{\rm CF}/R_e$ comes from the results shown in Fig. 3. Thus, according to Eq. (3), we are able to deduce $W_{\rm CF}(V_g)$. As shown in Fig. 4, $W_{\rm CF}(V_g)$ is smaller than $W_e(V_g)$ at equal V_g, in agreement with recent experimental results.[11] The reason for $W_{\rm CF}(V_g)<W_e(V_g)$ is stated as follows. At $\nu=\frac{1}{2}$, the lateral partial depletion from the SG causes a slight reduction in the carrier density near the boundary of the channel, inducing a strong effective magnetic field which bends the CF trajectories back to the source contact. Thus CF's cannot go through those regions with a very slight reduction in the carrier density, consequently reducing the channel width. As shown in Fig. 4, we have a good linear fit $W_e(V_g)=(0.1944V_g+0.9498)$ μm. This predicts a pinch-off voltage of -4.89 V when $W_e=0$, in close agreement with the measured value -5.18 V. For CF's, there is a good linear fit $W_{\rm CF}(V_g)=(0.1624V_g+0.5396)$ μm for $-2.9\leqslant V_g\leqslant-1.5$ V. The slope of $W_{\rm CF}(V_g)$ differs from that of $W_e(V_g)$ by around 20%. However, for $-1.5\leqslant V_g \leqslant -1$ V, the widths for CF's only slightly decrease as V_g is made more negative. This is not fully understood at present.

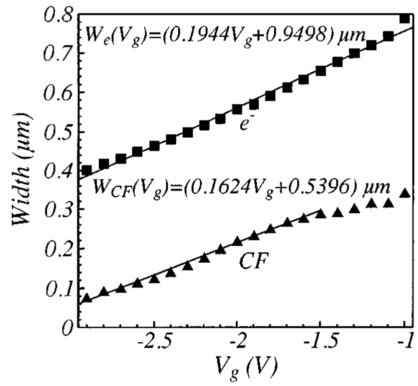

FIG. 4. The channel widths for electrons (solid squares ■), and for CF's (solid triangles ▲) at various applied gate voltages, as deduced from Eqs. (1) and (3). The straight line fits are discussed in the text.

Recently a theory paper was published by Khaetskii *et al.*[20] on ballistic transport of a composite fermion in a QPC defined by a split gate. When the electrostatic potential in the QPC is approximated by a saddle-point profile, around $\nu=\frac{1}{2}$ they predict observation of quantized conductance steps in such a QPC as a function of applied *magnetic field*. This approach is in contrast to the present work where we report measurements of a CF split gate as a function of applied *gate voltage* at $B_{\rm eff}=0$.

In conclusion, we have observed negative magnetoresistance due to suppression of backscattering in a quantum point contact both around $B=0$ and $\nu=\frac{1}{2}$. We have also measured the resistance of a composite fermion quantum point contact as a function of gate voltage at $B_{\rm eff}=0$. Using a simple model, we have determined the channel widths for composite fermions at various gate voltages.

This work was funded by the United Kingdom (UK) Engineering and Physical Sciences Research Council. We thank C.J.B. Ford and G. Kirczenow for helpful discussions and N. Iredale for experimental assistance. C.T.L. acknowledges support from Hughes Hall college and the Committee of Vice-Chancellors and Principals, UK.

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