Ballistic composite fermions in semiconductor nanostructures

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We report the results of two fundamental transport measurements at a Landau level filling factor ν of $\frac{1}{2}$. The well-known ballistic electron transport phenomena of quenching of the Hall effect in a mesoscopic cross-junction and negative magnetoresistance of a constriction are observed close to $B=0$ and $\nu=\frac{1}{2}$. The experimental results demonstrate semiclassical charge transport by composite fermions, which consist of electrons bound to an even number of flux quanta.

Among the many experiments which demonstrate the ballistic nature of electron transport in a clean two-dimensional sytem, reports by Ford *et al.* on quenching of the Hall effect in a cross junction[1] and by van Houten *et al.* on short constriction negative magnetoresistance[2] are seminal. In this paper we report the demonstration of these fundamental effects at a Landau level filling factor ν of $\frac{1}{2}$, where a Chern-Simons gauge transformation maps the strongly interacting electron system onto a system of weakly interacting composite fermions in a zero effective magnetic field.[3,4]

In a small magnetic field applied perpendicular to the two-dimensional electron gas (2DEG), magnetic focusing experiments show that electrons travel with circular trajectories with a radius $r_c=v_F/\omega_c$, where v_F is the Fermi velocity and ω_c is the cyclotron frequency.[5] In a narrow wire, the Hall voltage is found to "quench," rapidly dropping below its classical value at some critical magnetic field.[6] Control over the precise geometry of a cross-shaped sample can even result in a Hall voltage of opposite sign to that predicted classically, an effect attributed to a combination of ballistic electron transport and largely specular reflection from the device edges channeling electrons into the "wrong" voltage probe.[1] In a mesoscopic Hall bar, electron collimation and a small amount of diffuse boundary scattering lead to a peak in the magnetoresistance at an intermediate magnetic field before the onset of negative magnetoresistance due to suppression of interedge scattering.[7] A ballistic constriction exhibits negative four-terminal magnetoresistance, because, with an increase in magnetic field, a larger fraction of the edge states in the unpatterned 2DEG are transmitted.[2]

At higher magnetic fields, the Hall resistance is found to take on quantized values $R_H=h/\nu e^2$ with integral ν.[8] High mobility, low-density 2DEG samples show a rich structure in magnetoresistance with minima at $\nu=p/q$ with integral p,q, and an increasing number of predominantly odd denominator fractional minima have been resolved with their associated plateau in Hall resistance. The odd denominator minima have been explained in terms of a hierarchy of quasiparticle states.[9,10]

At $\nu=\frac{1}{2}$, there is a broad minimum in magnetoresistance without a corresponding Hall resistance plateau, and composite fermions are thought to be the principal agents of charge transport. These composite fermions, composed of electrons bound to an even number of magnetic flux quanta, experience an effective zero magnetic field at precisely $\nu=\frac{1}{2}$.[3,4] Evidence continues to accumulate for the existence of a Fermi surface at $\nu=\frac{1}{2}$ and charge transport by composite fermions.[11–16]

Experimental results were obtained from split-gate-type devices fabricated on two wafers, 1 and 2, grown by MBE. Measurements were made after brief illumination with a red LED in a pumped ^{3}He cryostat at 300 mK. A current of 10 nA and standard ac phase-sensitive detection was used for the four-terminal resistance measurements. Wafer 1 has sheet carrier density $n_s=1.3\times10^{11}$ cm^{-2}, mobility $\mu=3.0\times10^6$ cm^2 V^{-1} s^{-1}, and a 2DEG depth of 300 nm; and wafer 2 has $n_s=1.2\times10^{11}$ cm^{-2}, $\mu=1.8\times10^6$ cm^2 V^{-1} s^{-1}, and a 2DEG depth of 300 nm. Figure 1(a) shows the geometry of the cross junction, which consists of four symmetric openings each 0.8 μm wide. Figure 1(b) shows the device used to study a constriction, which is comprised of six split gates in series with a finger width of 0.3 μm, a pitch of 0.5 μm, and a constriction width of 1 μm. In the experiment, split gates 2, 4, and 6 are held at a gate voltage of 0.6 V, and split gates 1, 3, and 5 are held at a negative gate voltage to give a voltage probe separation of 1 μm. The split gates 2 and 4 above the voltage probes are held positive in order to ensure that the sheet carrier density is not reduced below that in the center of the channel, eliminating unwanted reflection of edge states in an applied magnetic field.[17] The assumption that the voltage probes are ideal in this respect is justified over the measurement range, as shown by the presence of good zeros in the magnetoresistance.

Figure 2 shows the Hall resistance V_{CE}/I_{SD} with zero applied gate voltage for the cross geometry sample. The Hall

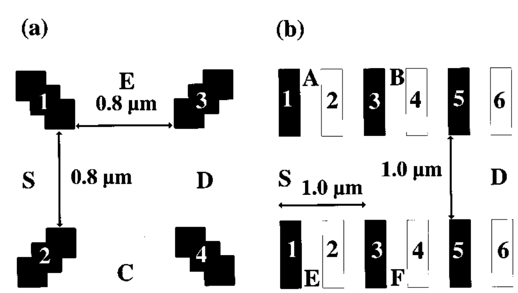

FIG. 1. Schematic diagrams of (a) the cross-junction device, and (b) the constriction device.

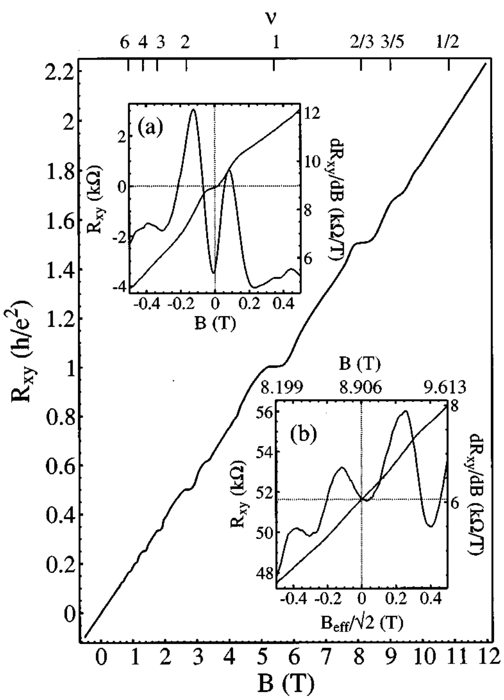

FIG. 2. Hall resistance of the cross-junction device with zero applied gate voltage. Inset: Hall resistance (left scale) and dR_{xy}/dB (right scale) with applied gate voltages of $V_1=V_2=-1.7$ V and $V_3=V_4=-1.5$ V, (a) around $B=0$ and (b) near $\nu=\frac{1}{2}$.

resistance is linear both in the vicinity of $B=0$ and $\nu=\frac{1}{2}$, with well-developed quantized Hall plateaus away from these magnetic fields. Using the sheet resistivity ρ_{xx} at $\nu=\frac{1}{2}$ (400 Ω/square) we estimate the composite fermion mean free path to be approximately 1 μm, larger than the distance across the junction. The insets of Fig. 2 show the Hall resistance and numerical derivative dR_{xy}/dB (a) near $B=0$ and (b) near $\nu=\frac{1}{2}$ when the cross junction is defined. The magnetic-field scale of inset (b) is reduced by a factor $\sqrt{2}$ to account for the spin polarized enhancement in Fermi wave vector at $\nu=\frac{1}{2}$.[4,18] Lithographic imperfections lead to a slight asymmetry in the Hall resistance about $B=0$ and $\nu=\frac{1}{2}$ and so gate biases are adjusted to compensate, but the same gate voltages are used at $B=0$ and at $\nu=\frac{1}{2}$. With applied gate voltages of $V_1=V_2=-1.7$ V and $V_3=V_4=-1.5$ V, a cross-shaped junction is defined and quenching of the Hall effect is observed at $B=0$. Quenching close to $\nu=\frac{1}{2}$ is not so strong, but the deviation from linearity is shown qualitatively by a minimum in dR_{xy}/dB at $\nu=\frac{1}{2}$, demonstrating the ballistic nature of charge transport. When an electric current flows in a composite fermion system, an induced effective electric field arises from the current of magnetic flux quanta pairs.[18] The Hall resistance therefore remains finite at $\nu=\frac{1}{2}$, with a value of $2h/e^2$, and we only observed a minimum in the Hall *slope* at $\nu=\frac{1}{2}$, compared to the zero in Hall *resistance* at $B=0$.

We now discuss the results of measurements of the ballistic constriction. Figure 3 shows the longitudinal magnetoresistance V_{AB}/I_{SD} of the constriction device with $V_2=V_4=V_6=0.6$ V for fixed voltages of $V_1=V_3=V_5=-0.2$, -1.0, -1.4, -1.8, -2.6, and -3 V. Measurements using voltage probes E and F were similar to those using probes A and B. When the 2DEG is depleted beneath gates 1, 3, and 5, the device resembles a mesoscopic Hall bar with a width and length of 1 μm and the present results may be compared with those in the literature for such structures.[7,19] The small size of the active region also minimizes unwanted effects due to wafer nonuniformity. A shift of the $\nu=1$ Shubnikov–de Haas zero (at about 5 T) towards a lower magnetic field indicates that the sheet carrier density in the channel drops from 1.2 to 1.1×10^{11} cm^{-2} over this range of gate voltage. The magnetoresistance at the smallest negative defining gate voltage resembles that of a macroscopic Hall bar with a shallow minimum in magnetoresistance at $B=0$ and $\nu=\frac{1}{2}$.

Macroscopic 2DEG samples typically show a longitudinal resistivity two orders of magnitude greater at $\nu=\frac{1}{2}$ than at $B=0$.[13] Random fluctuations in carrier concentration causing a corresponding fluctuation in effective magnetic field and an increase in effective mass at $\nu=\frac{1}{2}$ both contribute to an enhanced scattering rate for composite fermions. We believe that this is the reason for the presence of a single broad peak at $\nu=\frac{1}{2}$, compared with the double peaks at $B=0$.[19] There is also a peak at $\nu=\frac{3}{2}$, but it is less well defined than at $\nu=\frac{1}{2}$, in a similar fashion to the observation of weak commensurability oscillations at $\nu=\frac{3}{2}$ by Kang *et al.*[13] Deleterious effects due to the high series resistance of the unpatterned 2DEG at $\nu=\frac{1}{2}$ are minimized by the use of voltage probes in close proximity to the constriction under investigation.[20]

As the defining gate voltage is made more negative, the double peak structure develops close to $B=0$ and broad single peaks develop at $\nu=\frac{1}{2}$ and $\nu=\frac{3}{2}$, indicated by circles and triangles, respectively, in Fig. 3. The Landauer-Büttiker formalism states that scattering of electrons is necessary to establish local equilibrium between voltage probe and sample.[21,22] A difference in chemical potential between voltage probes is not established in a mesoscopic Hall bar at $B=0$ if collimation of ballistic electrons occurs, and a longitudinal four-terminal resistance minimum results. The double peak structure close to $B=0$ has been observed before only in the highest mobility mesoscopic Hall bars where a nonspecular component of the boundary scattering gives a peak in resistance when $W/r_c=0.55$, where W is the effective Hall bar width.[7,19] In the present work, the measured peak value at ±0.050 T implies an effective channel width of 0.6 μm, comparable with the lithographic dimension. The magnetoresistance structure is symmetric about $B=0$ and this symmetry remains about $\nu=\frac{1}{2}$ and $\nu=\frac{3}{2}$, particularly for the largest gate voltages and supports recent theory predicting effective magnetic fields of opposite sign about $\nu=\frac{1}{2}$.[4] We suggest that composite fermion negative effective magnetic-field effects are only observed when a semiclassical trajectory does not cross a boundary between positive and

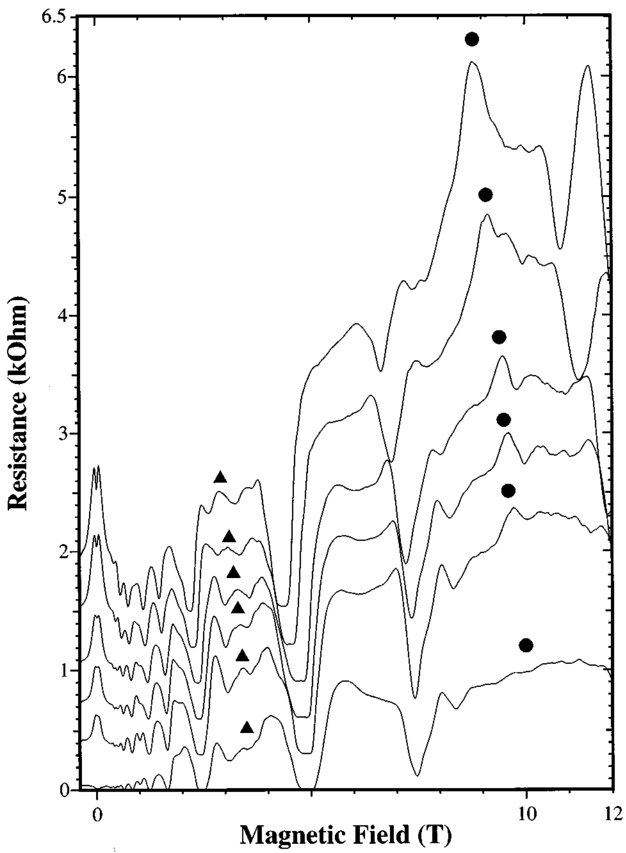

FIG. 3. Longitudinal magnetoresistance of the constriction device with $V_2=V_4=V_6=0.6$ V for fixed voltages of $V_1=V_3=V_5=-0.2$, -1.0, -1.4, -1.8, -2.6, and -3 V from lowest to uppermost trace, respectively. Curves are offset by 300 Ω for clarity.

negative effective field between voltage probes.[20]

The magnetoresistance for $|B|<0.4$ T excluding the central minimum is well described by the equation giving the four-terminal resistance of a ballistic constriction,

$$R_{4t}=(h/e^2)(1/N_{\min}-1/N_{\max}), \quad (1)$$

where $N_{\min}$ and $N_{\max}$ are the number of occupied one-dimensional (1D) subbands in the channel and unpatterned 2DEG, respectively.[2] The enhancement of composite fermion scattering results in broader single peaks at high magnetic field. The peak heights at $B=0$, $\nu=\frac{1}{2}$, and $\nu=\frac{3}{2}$ increase with an increase in gate voltage as the number of occupied 1D subbands in the constriction decreases, according to Eq. (1). These results are consistent with ballistic composite fermion transport and the formation of 1D composite fermion subbands in a constriction at $\nu=\frac{1}{2}$.

Low-temperature four-terminal magnetoresistance measurements have been performed on a mesoscopic cross junction and a constriction defined by Schottky gate metallization above a two-dimensional electron gas in a GaAs/Al$_x$Ga$_{1-x}$As heterostructure with low sheet carrier density and high mobility. The longitudinal and Hall resistance at small applied magnetic field are compared with that close to Landau level filling factors of $\nu=\frac{1}{2}$ and $\nu=\frac{3}{2}$ as the structures are defined.

For the cross geometry sample, the onset of quenching is observed as nonlinearity in the Hall resistance both at low B and near a Landau level filling factor of $\frac{1}{2}$. For the constriction, peaks in the longitudinal magnetoresistance are observed both near $B=0$ and when $\nu=\frac{1}{2}$. The effects are more pronounced as the confining gate voltage is increased in magnitude.

Both phenomena occur due to the influence of sample geometry on the semiclassical ballistic charge carrier trajectories. We propose that analogous mechanisms apply both near $B=0$ and near $\nu=\frac{1}{2}$ and $\nu=\frac{3}{2}$, with composite fermions as the principal agents of charge transport at high magnetic field rather than electrons.

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