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Experimental Investigation of the Edge States Structure at Fractional Filling Factors¶

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We experimentally study the electron transport between edge states in the fractional quantum Hall effect regime. We find an anomalous increase of the transport across the 2/3 incompressible fractional stripe in comparison with the theoretical predictions for the smooth edge potential profile. We interpret our results as a first experimental demonstration of the intrinsic structure of the incompressible stripes arising at the sample edge in the fractional quantum Hall effect regime. *© 2005 Pleiades Publishing, Inc.*

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The concept of the edge states (ESs) was first introduced by Halperin [1] to describe the transport phenomena in two-dimensional (2D) systems in the integer quantum Hall effect regime. ES, arising at the intersections of distinct Landau levels with a Fermi level, can be introduced for both sharp [2] and smooth [3] edge potential profiles. Experimentally, the existence of ES was proved not only in transport experiments along the sample edge (for a review, see [4]) but also across it [5–7].

This single-electron description is not applicable to the fractional quantum Hall effect, which is fundamentally a many-body phenomenon [8]. The electron system forms a many-body ground state below the Fermi level and an excited state above it. A set of compressible stripes, separated by the incompressible regions with fractional fillings, is expected to exist at the sample edge for the case of the smooth edge potential [9]. One-dimensional chiral Luttinger liquid states are predicted theoretically for the opposite case of the sharp potential jump at the sample edge [10, 11]. The ES structure in the later case was found to be determined by the hierarchical structure [12] of the bulk ground state [10, 11]. The transport along the sample edge, however, is not sensitive to the form of the edge potential but only to the filling factor in the bulk. It can be described by modified Buttiker formulas [9, 10] in good agreement with experiments [13] in Hall-bar geometry with cross gates. For this reason, these experiments cannot be used to distinguish between the proposed models. In real experiments, the strength of the potential profile cannot be regarded as infinitely large, so the model of the smooth edge potential seems to be more realistic. On the other hand, experiments on tunneling into the fractional edge demonstrate the complicated structure of the edge excitation spectrum [14, 15], which is expected for the sharp edge [11]. This controversial situation demands the investigation of the fractional ES structure for real samples.

It was shown theoretically [16] that, after smoothening the sharp edge potential, a transition takes place and new branches of ESs appear. For example, the edge that had one right-moving ES before the transition has two right-moving ESs and one left-moving ES after it. The same prediction about the edge reconstruction with smoothing the edge potential was made using the composite-fermion language [17]. Experimentally, the edge reconstruction picture can be verified by studying the electron transport across the sample edge in the quasi-Corbino geometry, because this experiment was shown to be very sensitive to the ES structure [18].

Here, we experimentally study the electron transport between different ES in the fractional quantum Hall effect regime. We find an anomalous increase of the transport, at some filling factors, in comparison with the prediction of the simple Beenakker model [9] of fractional ES. We interpret our results as the first experimental demonstration of the intrinsic structure of the incompressible stripes arising at the reconstructed sample edge in the fractional quantum Hall effect regime in accordance with the model of Wen and Chamon [16].

Our samples are fabricated from two molecular beam epitaxial-grown GaAs/AlGaAs heterostructures

¶ The text was submitted by the authors in English.

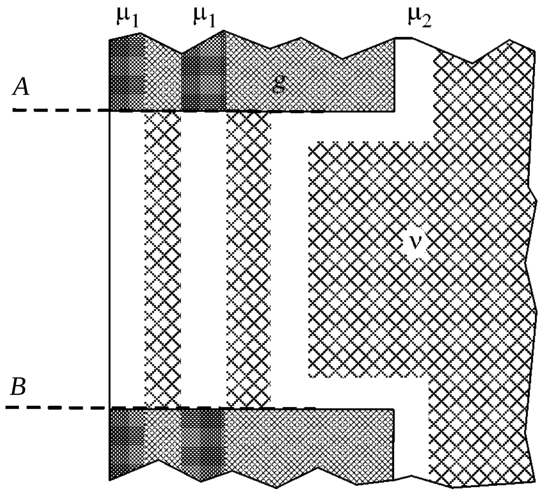

Fig. 1. Schematic diagram of the gate-gap region in the pseudo-Corbino sample geometry. The dark area represents the Schottky-gate. The hatched area indicates incompressible regions in the sample. In a quantizing magnetic field at total filling factor ν, one set of the edge states (the number is equal to the filling factor under the gate, g; $g < \nu$) is propagating under the gate along the etched edge of the sample and carry the electrochemical potentials μ_1. The other edge states (their number is $\nu - g$) are going along the gate edge and carry electrochemical potentials μ_2. In the gate-gap region, both sets of the edge states are running in parallel, leading to the current across the incompressible region between them, if $\mu_1 \neq \mu_2$.

with different carrier concentrations and mobilities. One of them (*A*) contains a two-dimensional electron gas (2DEG) located 210 nm below the surface. The mobility at 4 K is 1.93×10^6 cm^2/(V s), and the carrier density is 1.61×10^{11} cm^{-2}. For heterostructure *B*, the corresponding parameters are 150 nm, 1.83×10^6 cm^2/(V s), and 8.49×10^{10} cm^{-2}.

The measurements are performed in the quasi-Corbino sample geometry [5, 6]. In this geometry, a sample has two nonconnected etched mesa edges (the inner and the outer ones, as Corbino disks) with independent ohmic contacts at every edge. ES originating from one mesa edge are redirected to the other mesa edge by using the split-gate technique. As a result, ES from independent ohmic contacts run together along the outer etched edge of the sample in the gate-gap region as depicted in Fig. 1. The gate-gap width (*AB*) is 5 μm for samples from wafer *A* and 0.5 μm for ones from wafer *B*. The available fractional filling factors and the electron concentration in the ungated region were obtained from the usual magnetoresistance measurements. Also, magnetocapacitance measurements were performed to characterize the electron system under the gate. The contact resistance at low temperatures is about 100 Ω per contact, as was determined from two-point magnetoresistance measurements. The temperature of the experiment is 80 mK; the magnetic field is up to 14 T.

We studied the *I–V* characteristics of the gate-gap region by applying dc voltage between the outer and the inner ohmic contacts and by measuring the dc current that appeared. In the integer quantum Hall effect regime, the dissipative conductance component is close to zero in the 2DEG. For this reason, the measuring current is the current between two groups of independently-contacted ES in the gate-gap (see Fig. 1). If the equilibration length for the transport between them is smaller than the gate-gap width, we can expect a full equilibration in the gate-gap and a linear *I–V* trace. In the opposite regime, charge transfer does not change the chemical potentials of the ES significantly, and the applied voltage V directly affects the value of the potential barrier between the ES, thus, leading to its disappearance at some positive voltage $V_{th} > 0$ (because of the negative electron charge). The zero potential barrier means zero equilibration length between the ES. Thus, in spite of the strongly nonlinear *I–V* trace in this case, a positive branch above V_{th} has to be linear as in the opposite regime. It was experimentally established [5, 6] that V_{th} and the slope of the linear part of the positive branch are universal characteristics reflecting the potential barrier value between ES and the redistribution of the electrochemical potential imbalance between them. They coincide with the theoretical values (the spectral gap and the equilibrium redistribution obtained from Buttiker formulas [2]) with a possible 10% deviation. This 10% deviation is connected to the potential disorder at the sample edge and is a constant for the given sample. It does not depend on the cooling procedure and other occasional parameters.

Typical *I–V* curves in the integer quantum Hall effect regime are shown in Fig. 2 for the filling factor combination $\nu = 2$, $g = 1$. The *I–V* traces reflect the electron transport between two spin-split edge states, because, at $\nu = 2$, two spin-split energy levels are filled in the bulk. The equilibration length in this case can reach a millimeter [19], which is much higher than the gate-gap width for both samples *A* and *B*. Every experimental *I–V* trace is strongly nonlinear with the linear part on the positive branch. Tilting the sample plane with respect to the magnetic field allows us to introduce an in-plane field component, keeping the filling factor by adjusting the value of the total field. As can be seen from Fig. 2, in-plane field affects affect the linear part of *I–V* only by increasing the V_{th} value, leaving the slope to be nonaffected. We can conclude for our samples that the in-plane magnetic field does not change the equilibrium mixing of ES in the integer quantum Hall effect regime.

Examples of the *I–V* curves for fractional fillings are shown in Fig. 3 for $\nu = 2/3$, $g = 1/3$. As it can be seen from the inset to the figure, the *I–V* curve is strongly nonlinear at the lowest temperature of 30 mK for the sample *B* with the smallest gate-gap width 0.5 μm (also, nonlinear *I–V*'s for fractional fillings were reported in [20]). By increasing the temperature and the

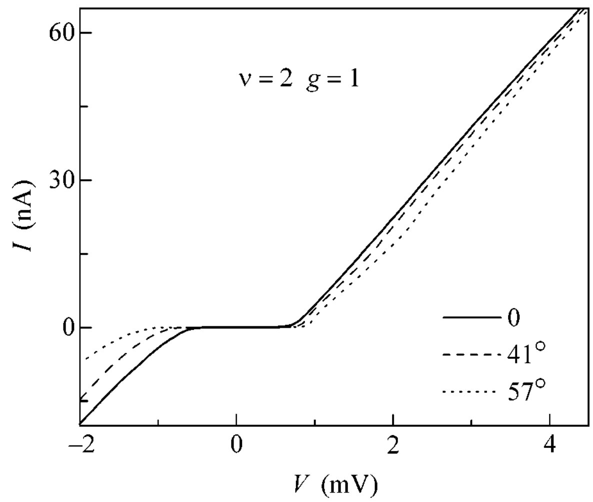

Fig. 2. *I–V* curves for the sample *A* for filling factors $\nu = 2$ and $g = 1$ at different tilt angles: $\theta = 0$ (solid line), $\theta = 41°$ (dashed line), $\theta = 57°$ (dotted line). Experimental slope of the positive branch is constant and equals to $2.2h/e^2$, the equilibrium Buttiker value is $2h/e^2$. Perpendicular magnetic field equals to 3.34 T, gate voltage $V_g = -268$ mV.

gate-gap width (80 mK and 5 μm for sample *A*), the equilibration length between the fractional ES can be made smaller than the gate-gap width, thus, leading to the fully linear *I–V* (see the main part of Fig. 3). In this letter, we focus our attention on the analysis of the linear *I–V* curves at fractional filling factors.

The most intriguing results are obtained for the following filling factor combinations: $\nu = 1$, $g = 1/3$ and $\nu = 1$, $g = 2/3$. In Fig. 4, the experimental slopes of the linear *I–V* curves are shown in dependence on the sample tilt angle in the magnetic field. The slopes for $\nu = 1$, $g = 1/3$ behave as in the integer case: they are practically independent of the in-plane field. The experimental values for $\nu = 1$, $g = 2/3$ differ significantly from the ones for $\nu = 1$, $g = 1/3$ in the normal field and approach them with increasing the in-plane field component (see Fig. 4). It can also be seen from the inset in Fig. 4, where the original *I–V* curves for different tilt angles are shown for the filling factor combination $\nu = 1$, $g = 2/3$. Let us stress that curves *I–V* are well reproducible.

Because the gate-gap region in our quasi-Corbino geometry is formed electrostatically by using the split-gate, it is obvious to use the Beenakker model [9] of fractional ES in the smooth edge profile to describe the experiment. In this model, the edge potential is supposed to be smooth enough to introduce the local filling factor ν_c. At the sample edge, it is monotonically changing from the bulk value $\nu = 1$ to zero. Incompressible stripes are formed around fractional local filling factors $\nu_c = 2/3$ and 1/3. Buttiker formulas can easily be generalized to this situation [9]:

$$I_\alpha = \frac{e}{h}\nu_\alpha\mu_\alpha - \frac{e}{h}\sum_\beta T_{\alpha\beta}\mu_\beta,$$

where I_α is the current in the ES α corresponding to the fractional filling factor ν_α and connected to a contact

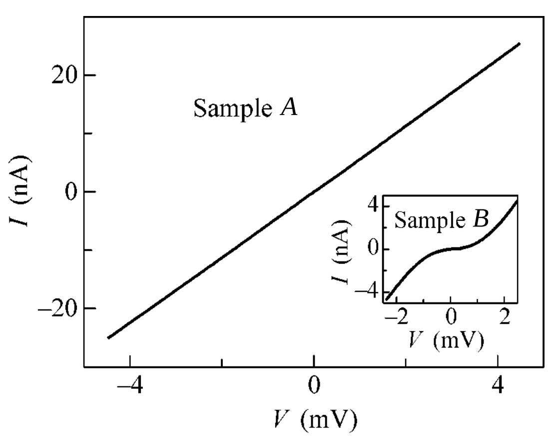

Fig. 3. *I–V* curves for the samples *A* (main field) and *B* (inset) for filling factors $\nu = 2/3$ and $g = 1/3$. Magnetic field equals to 10 T for the sample *A* and to 4.85 T for the sample *B*. The gate-gap width and the temperature of the experiment are different for both samples: 5 μm and 80 mK for the sample *A* and 0.5 μm and 30 mK for the sample *B*. The experimental slope of the linear *I–V* curve is $6.8h/e^2$, the equilibrium Buttiker value is $6h/e^2$.

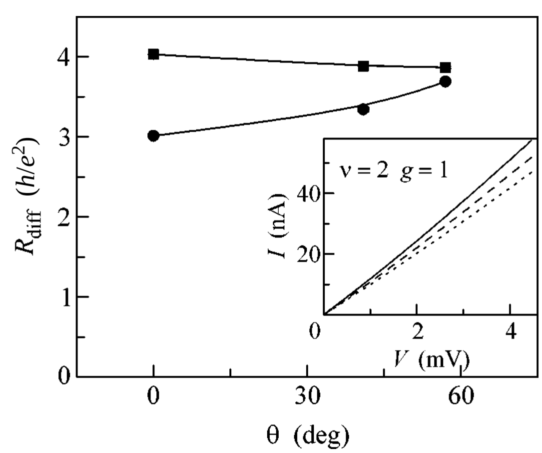

Fig. 4. Experimental slopes of linear *I–V* curves for the sample *A* for filling factor combinations $\nu = 1$ and $g = 1/3$ (squares) and $\nu = 1$ and $g = 2/3$ (circles) as functions of tilt angle. Error bars are within the symbol size. The equilibrium Buttiker value is $4.5h/e^2$ for both filling factor combinations. The normal magnetic field is constant and equals to 6.68 T. Inset shows the original *I–V* curves for filling factors $\nu = 1$ and $g = 2/3$ at different tilt angles: $\theta = 0$ (solid line), $\theta = 41°$ (dashed line), $\theta = 57°$ (dotted line). *I–V* curves are independent of the cooling cycle and well reproducible.

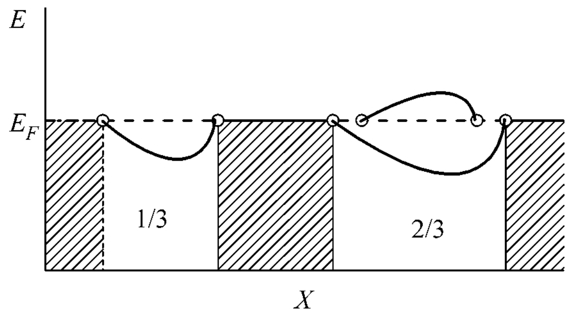

Fig. 5. Schematic energy diagram of the sample edge in the fractional quantum Hall effect regime. Hatched regions represent compressible stripes with electrons at the Fermi level. In the incompressible "puddles" between them, the energy of the fractional ground state is sketched (it is asymmetric because of the edge potential). It is a simple Laughlin fractional ground state for the puddle with 1/3 local filling factor. The ground state for the 2/3 local filling is more complicated: it is electron ground state for the filling factor 1 and hole fractional for the filling factor 1/3. It leads to the two counterpropagating branches of ES per edge of this puddle. ES are denoted by open circles.

with electrochemical potential μ_α; e and h are the electron charge and the Planck constant, respectively; and $T_{\alpha\beta}$ are the Buttiker coefficients for the transmission from contact β to contact α.

This formula can easily be applied to our experimental geometry, while the only difference from the integer case is the presence of constant weight coefficients ν_α. Slopes of the linear I–V curves can be calculated under the assumption of full equilibration between all the ES in the gate-gap:

$$R_{\text{diff}} = \frac{h}{e^2}\frac{\nu}{g(\nu - g)}.$$

Correspondingly, we can expect that, as for integer ES, (i) the linear curve I–V means the full equilibration between ES in the gate-gap; (ii) the experimental slopes should coincide with the calculated ones within 10%, as was discussed above; (iii) these slopes should be independent of the in-plane magnetic field component, as presented in Fig. 2. Moreover, we can expect from the calculations that slopes I–V for the filling factor combinations $\nu = 1$, $g = 1/3$ and $\nu = 1$, $g = 2/3$ will coincide exactly. In the experiment, however, the former filling factor combination (as well as $\nu = 2/3$, $g = 1/3$) behaves as described, while the I–V slope for $\nu = 1$, $g = 2/3$ is 1.5 times smaller than the theoretical value, approaching the values for $\nu = 1$, $g = 1/3$ with increasing the in-plane field component. Thus, we can conclude that electron transport at $\nu = 1$, $g = 2/3$ is anomalously enhanced in comparison with the equilibrium electrochemical potential redistribution, while, at $\nu = 1$, $g = 1/3$, it is about the theoretical value. For these two filling factor combinations, the filling factor in the gate-gap $\nu = 1$ is the same as well as the other parameters of the sample edge (the potential profile, disorder, etc.). The only difference is the incompressible stripe, which separates the ES from the inner and outer contacts in the gate-gap: it corresponds to $\nu_c = 2/3$ for $\nu = 1$, $g = 2/3$ and to $\nu_c = 1/3$ for $\nu = 1$, $g = 1/3$.

This behavior cannot be explained within the model of Beenakker, where the local filling factor $\nu_c = 2/3$ has no difference from any other one. On the other hand, 2/3 has a very special character in the model of sharp edge potential profile of MacDonald [10]. Here, $\nu = 2/3$ is regarded as the electron ground state of the filling factor 1 and the Laughlin hole fractional one with the positive fractional charge 1/3. Both ones make their contributions into the ES formation, thus, leading to two counter propagating ES at one edge: the outer integer for electrons and the inner fractional for holes. This model cannot be directly applied to our experiment, because the electrostatical edges in any case are not sharp and even etched ones are very doubtful. It was predicted [16, 17] that, while smoothing the edge profile, edge reconstruction occurs and quantum Hall "puddles" form with local fractional filling factors (see Fig. 5). Each boundary of the fractional quantum Hall puddle still can be regarded as a sharp boundary of the quantum Hall system with a particular fractional filling factor. This leads to the formation of a number of counterpropagating fractional ES at every sample edge. Of course, the net current along the edge is still dependent on the bulk filling factor only, so in our experiment, the detailed structure of the ES is important only in the gate-gap, where the charge transfer across the edge occurs. Also, the etched edge seems to be sharp enough to apply this model of reconstructed ES.

Let us consider the filling factor combination $\nu = 1$, $g = 2/3$. At low temperatures, the bulk of the sample is in the incompressible state at filling factor $\nu = 1$ in the ungated region and at $g = 2/3$ under the gate. Approaching the etched edge, incompressible "puddles" of lower fractional fillings are formed (see Fig. 5). In the gate-gap, they correspond to $\nu_c = 2/3$; 1/3, while only $g_c = 1/3$ is present under the gate. It is clear that an incompressible puddle with $\nu_c = 2/3$ in the gate-gap is directly connected to the incompressible state $g = 2/3$ under the gate, while the puddles $\nu_c = 1/3$ and $g_c = 1/3$ form the incompressible stripe along the etched edge as is shown in Fig. 1. It means that the picture of compressible and incompressible states, presented in Fig. 1, still survive in the fractional quantum Hall regime, but the structure of the ES is very different. Fractional ES are formed at the edges of every incompressible puddle. The current across the sample edge can flow only by tunneling between these ES through the incompressible regions and by diffusion in the compressible ones. At the filling factor combination $\nu = 1$, $g = 2/3$, the tunneling in the gate-gap takes place across the 2/3 incompressible puddle (see Figs. 1, 5). As it is described above, fractional ES at every edge of the puddle with $\nu_c = 2/3$ are the counterpropagating electron integer ES with current $\mu_\alpha \frac{e}{h}$ and the hole fractional with current $-\frac{1}{3}\mu_\alpha \frac{e}{h}$, thus, leading to the sum current $\frac{2}{3}\mu_\alpha \frac{e}{h}$ per one edge (see Fig. 5). Because of the complex nature of the ES for $\nu_c = 2/3$, they are not far away from each other, and we can expect that only these ES are mixing their electrochemical potentials in the gate-gap. A simple calculation gives in this case the resistance of $3h/e^2$. It is 1.5 times smaller than it would be if all the ES in the gate-gap mixed their electrochemical potentials and is in fact observed in the experiment in normal magnetic fields (see Fig. 4). The in-plane magnetic field increases the fractional gaps (it was verified for our samples by the usual magnetocapacitance spectroscopy) transforming fractional quantum Hall puddles into stripes of significant width. It makes the proposed mechanism ineffective, and the only way is to mix the electrochemical potentials of all the ES in the present gate-gap, as in the Beenakker model. As a result, the differential resistance increases to the value of $9/2\ h/e^2$. About the other fillings under consideration, $\nu = 1$, $g = 1/3$ and $\nu = 2/3$, $g = 1/3$; tunneling should occur between the ES in the $\nu_c = 1/3$ quantum Hall puddle. There is no complex ES structure in this case and the ES are far away from each other. The proposed mechanism is ineffective and mixing between all the existing ES in the gate-gap takes place at any in-plane field, as we observe in the experiment (see Figs. 3, 4).

As a result, we studied the electron transport across the sample edge in the fractional quantum Hall effect regime in the quasi-Corbino sample geometry. At the filling factor combination $\nu = 1$, $g = 2/3$, we observe an anomalous increasing of the current in comparison with the prediction of the simple Beenakker model [9] of fractional ES. We interpret our results as a first experimental demonstration of the intrinsic structure of the incompressible stripes arising at the reconstructed sample edge in the fractional quantum Hall effect regime in accordance with the model of Wen and Chamon [16].

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