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Experimental investigation of the edge states structure at fractional filling factors

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We experimentally study 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 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.

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The concept of the edge states (ES) was firstly 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 Fermi level, can be introduced for both sharp [2] and smooth [3] edge potential profile. Experimentally the existence of ES was proved not only in transport experiments along the sample edge (for a review see Ref. [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]. 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 can not be used to distinguish between the proposed models. In real experiments the strength of the potential profile can not be regarded as infinitely large, so the model of the smooth edge potential seems to be more realistic. On the other hand, experiments on tunnelling into the fractional edge demonstrate the complicated structure of edge excitation spectrum [14, 15] which is expected for the sharp edge [11]. This controversial situation demand 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 ES appears. The edge that had one right-moving ES before the transition, for example, is having two right-moving ES and one left-moving ES. The same prediction about the edge reconstruction with smoothing the edge potential was made by 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 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 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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Our samples are fabricated from two molecular beam epitaxial-grown GaAs/AlGaAs heterostructures 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 4K is 1.93 $\cdot 10^6 cm^2/Vs$ and the carrier density 1.61 $\cdot 10^{11} cm^{-2}$. For heterostructure B the corresponding parameters are 150 nm, 1.83 $\cdot 10^6 cm^2/Vs$ and 8.49 $\cdot 10^{10} cm^{-2}$.

Measurements are performed in the quasi-Corbino sample geometry [5, 6]. In this geometry a sample has two non-connected etched mesa edges (the inner and the outer ones, like Corbino disks) with independent ohmic contacts at every edge. ES, originating from one mesa edge, are redirected to the other mesa edge by using 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

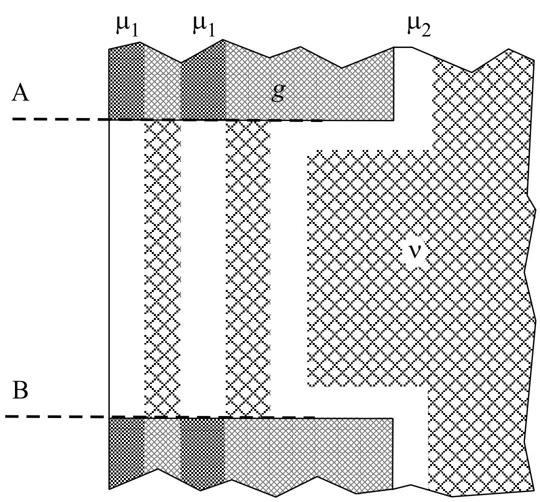

Fig.1. Schematic diagram of the gate-gap region in the pseudo-Corbino sample geometry. The dark area represents the Schottky-gate. The hatched area indicates incompressible regions in the sample. In a quantizing magnetic field at total filling factor ν, one set of the edge states (the number is equal 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 $\mu_1 \neq \mu_2$

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 usual magnetoresistance measurements. Also, magnetocapacitance measurements were performed to characterize the electron system under the gate. The contact resistance at low temperature is about 100 Ω per contact, as was determined from 2-point magnetoresistance measurements. The temperature of the experiment is 80 mK, the magnetic field is up to 14 T.

We study 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 appeared dc current. 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 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 ES significantly and the applied voltage V directly affects on the value of potential barrier between ES, leading to it's disappearance at some positive voltage $V_{th} > 0$ (because of the negative electron charge). Zero potential barrier, in order, means zero equilibration length between ES. Thus, in spite of the strongly non-linear $I - V$ trace in this case, a positive branch above V_{th} have to be linear like 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 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 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 non-linear, 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 total field. As it can be seen from Fig.2, in-plane field affects on the linear part of the $I - V$ only by increasing V_{th} value, leaving the

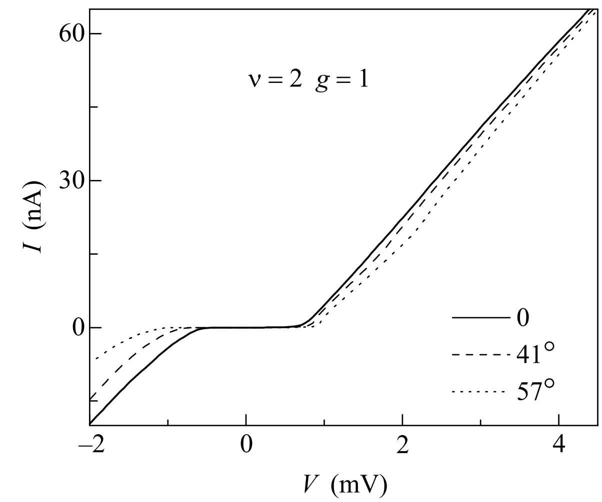

Fig.2. $I-V$ curves for the sample A for filling factors $\nu = 2$ and $g = 1$ at different tilt angles: $\theta = 0$ (solid line), $\theta = 41^\circ$ (dashed line), $\theta = 57^\circ$ (dotted line). Experimental slope of the positive branch is constant and equals to $2.2h/e^2$, the equilibrium Buttiker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

slope to be non-affected. 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

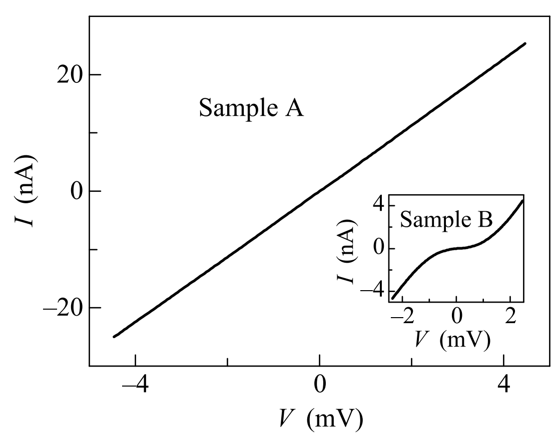

Fig.3. $I-V$ curves for the samples A (main field) and B (inset) for filling factors $\nu = 2/3$ and $g = 1/3$. Magnetic field equals to 10 T for the sample A and to 4.85 T for the sample B. The gate-gap width and the temperature of the experiment are different for both samples: 5 μm and 80 mK for the 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 $6h/e^2$

seen from the inset to the figure, $I-V$ curve is strongly non-linear at the lowest temperature of 30 mK for the sample B with the smallest gate-gap width 0.5 μm (also non-linear $I-V$'s for fractional fillings were reported in Ref. [20]). By increasing the temperature and the gate-gap width (80 mK and 5 μm for the sample A) the equilibration length between fractional ES can be made smaller than the gate-gap width, leading to the fully linear $I-V$, see the main part of Fig.3. In this Letter we put our attention on the analysis of the linear $I-V$ curves at fractional filling factors.

The most intriguing results are obtained for filling factor combinations $\nu = 1, g = 1/3$ and $\nu = 1, g = 2/3$. In Fig.4 experimental slopes of linear I-V curves are

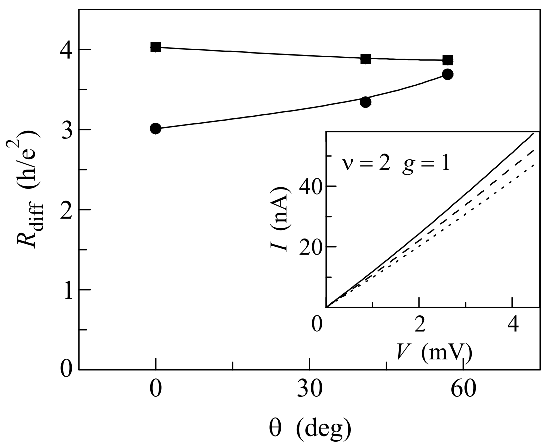

Fig.4. Experimental slopes of linear $I-V$ curves for the sample A for filling factor combinations $\nu = 1$ and $g = 1/3$ (squares) and $\nu = 1$ and $g = 2/3$ (circles) as functions of tilt angle. Error bars are within the symbol size. The equilibrium Buttiker value is $4.5h/e^2$ for both filling factor 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), $\theta = 41^\circ$ (dashed line), $\theta = 57^\circ$ (dotted line). $I-V$ curves are independent of the cooling cycle and well reproducible

shown in dependence on the sample tilt angle in magnetic field. The slopes for $\nu = 1, g = 1/3$ behaves like in the integer case: they are practically independent of the in-plane field. Experimental values for $\nu = 1, g = 2/3$ differ significantly from ones for $\nu = 1, g = 1/3$ in normal field and are approaching to them with increasing the in-plane field component, see Fig.4. It can be also seen from the inset to Fig.4, where the original $I-V$ curves for different tilt angles are shown for filling factor combination $\nu = 1, g = 2/3$. Let us stress that $I-V$ curves 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 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 ES α, corresponding to the fractional filling factor ν_α and connected to a contact with electrochemical potential μ_α; e, h are the electron charge and the Plank constant repectively, $T_{\alpha\beta}$ are the Buttiker coefficients for the transmission from contact β to contact α.

This formulas 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 in the assumption of full equilibration between all ES in the gate-gap:

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

Correspondingly, we can expect that like for integer ES (i) linear $I-V$ curve means the full equilibration between ES in the gate-gap (ii) experimental slopes should coincide with calculated ones within 10%, as it was discussed above; (iii) these slopes should be independent of the in-plain magnetic field component, like presented in Fig.2. Moreover, we can expect from the calculation that $I-V$ slopes 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 in 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 other parameters of the sample edge (potential profile, disorder, etc). The only difference is the incompressible stripe, which separates ES from inner and outer contacts in the gate-gap: it correspond 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 can not 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 very special character in the model of sharp edge potential profile of MacDonald [10]. Here $\nu = 2/3$ is regarding as the electron ground state of the filling factor 1 and the Laughlin hole fractional one with positive fractional charge 1/3. Both ones give their contributions into the ES formation, leading to two counterpropagating ES at one edge: the outer integer for electrons and the inner fractional for holes. This model can not be directly applied to our experiment, because the electrostatical edges in any case are not sharp and even etched ones are very doubt. It was predicted [16, 17] that while smoothing the edge profile, edge reconstruction occurs and quantum Hall "puddles" are forming with local fractional filling factors, see Fig.5. Each boundary of the

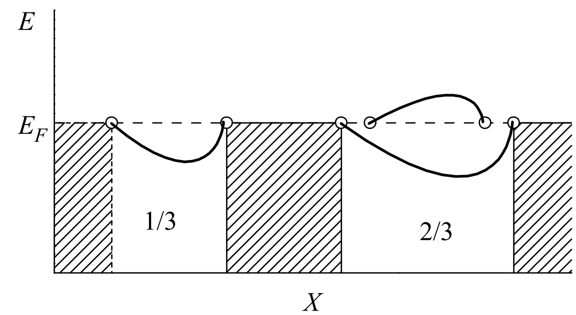

Fig.5. Schematic energy diagram of the sample edge in the fractional quantum Hall effect regime. Hatched regions represent compressible stripes with electrons at the Fermi level. In the incompressible "puddles" between them the energy of the fractional ground state is sketched (it is asymmetric because 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

fractional quantum Hall puddle is still can be regarded as a sharp boundary of quantum Hall system with 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 depend on the bulk filling factor only, so in our experiment the detailed structure of 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 temperature 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 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 $g_c = 1/3$ forms the incompressible stripe along the etched edge like it 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 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 tunnelling 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 tunnelling 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 hole fractional with current $-\frac{1}{3}\mu_\alpha \frac{e}{h}$, 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 in 1.5 times smaller than it would be if all ES in the gate-gap mixed their electrochemical potentials and is in fact observing in the experiment in normal magnetic field, see Fig.4. The in-plane magnetic field increases the fractional gaps (it was verified for our samples by usual magnetocapacitance spectroscopy), transforming fractional quantum Hall puddles into the stripes of significant width. It makes the proposed mechanism to be ineffective and the only way is to mix the electrochemical potentials of all present ES in the gate-gap, like in Beenakker model. As a result, the differential resistance increases to the value of $9/2\ h/e^2$. As about the other fillings under consideration, $\nu = 1, g = 1/3$ and $\nu = 2/3, g = 1/3$, tunnelling should occur between ES in the $\nu_c = 1/3$ quantum Hall puddle. There is no complex ES structure in this case and ES are far away from each other. The proposed mechanism is ineffective and mixing between all 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 study 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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