Edge channels and the role of contacts in the quantum Hall regime

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The vanishing voltage drop U_{xx} in the quantum Hall regime is destroyed if barriers with reduced filling factors are introduced between the potential probes. We investigated a system with two barriers created by Schottky gates that are separated by up to 200 μm. Two metallic contacts could be electrically connected or disconnected to the system in the region between the barriers. The change from adiabatic to equilibrated transport demonstrates the importance of Ohmic contacts as energy and phase-randomizing reservoirs. The experiments show strong evidence for current-carrying edge states.

Recently the Landauer-Büttiker picture[1,2] was successfully applied to the quantum Hall effect (QHE) (Ref. 3) explaining the quantized resistance values.[4,5] Within this picture the transport in strong magnetic fields and at low temperatures is governed by one-dimensional channels at the boundaries of the two-dimensional electron gas (2D EG). These channels are formed by the intersection of the Fermi energy with the bent-up (due to the confining potential) Landau levels (LL) at the edges of the device. Classically these edge states correspond to skipping orbits moving along the edges in opposite directions on opposite sides of the sample. In the QH regime the number of occupied edge channels is given by the filling factor in the 2D EG. A net current I flows due to the difference in the electrochemical potential $\Delta\mu$ between the two sides of the Hall bar.[6] Backscattering from one side of the sample to the other is the reason for dissipation and therefore finite resistance in this model.[5] Currents and voltages between the different contacts in the system are determined by transmission probabilities $t_{i\to j}$ from reservoir i to reservoir j and reflection probabilities $r_{i\to i}$ (from reservoir i back to the same reservoir). The incoming net carrier flux at contact i is given by[5]

$$\frac{h}{e}I_i=(\nu-r_{i\to i})\mu_i-\sum_{j\neq i}t_{j\to i}\mu_j \ , \qquad (1)$$

where ν is the number of edge channels and μ_j stands for the electrochemical potential of the different contacts.

Within this picture an ideal contact has the property of equally populating these edge channels up to its electrochemical potential μ_i. A nonideal contact, on the other hand, populates the outgoing channels unequally and reflects part of the incoming channels. While moving along the boundaries equilibrium may be established due to interchannel scattering. The corresponding equilibration length is surprisingly long; deviations from the quantized resistance values have been observed over a distance of 100 μm (Ref. 7) from the disturbed contacts. One can also use point contacts to selectively populate the edge channels.[8] The observation of the anomalous QHE and the suppression of the Shubnikov–de Haas oscillations is a striking manifestation of the nonequilibrium edge channel occupation in these systems.[8–10]

In this Brief Report we shall demonstrate experimentally the important role of contacts for edge-channel equilibration by connecting and disconnecting metallic contacts to the sample and therefore switching between equilibrated and adiabatic transport. Here equilibrated means that all available edge channels are occupied up the same electrochemical potential (at one side of the sample), each of them carrying the same amount of current. Transport with a nonequal distribution of the current among the edge channels is denoted as adiabatic. We demonstrate for the first time the ability of Schottky gates to selectively populate edge channels and investigate adiabatic transport between such selector gates. Gates of this type have been used previously to investigate magnetotransport across a single barrier.[11]

The layout of our devices is sketched in Fig. 1. We have evaporated two gates (NiCr/Au) across the Hall bar separated by a distance d ($d=20$ and 200 μm on the same device) as is sketched in Fig. 1(a). Applying a negative voltage to both gates reduces the carrier density underneath and allows the filling factor ν to be adjusted under the gates ($\nu=g$) independently of the ungated bulk ($\nu=b=hN_s/eB$). The magnetic field B is perpendicular to the 2D EG. Using contact 1 and 4 as current source and sink and contacts 2 and 3 as voltage probes, respectively, one can easily express the injected current, e.g., for contact 1, as $I_1=I=e/h[b\mu_1-(b-g)\mu_2-g\mu_4]$. Writing down the equivalent equations for all the other contacts, one finds

$$R^{\rm ad}_{14,23}=\frac{h}{e^2}\left[\frac{1}{g}-\frac{1}{b}\right] . \qquad (2)$$

Equation (2) is valid as long as purely adiabatic transport

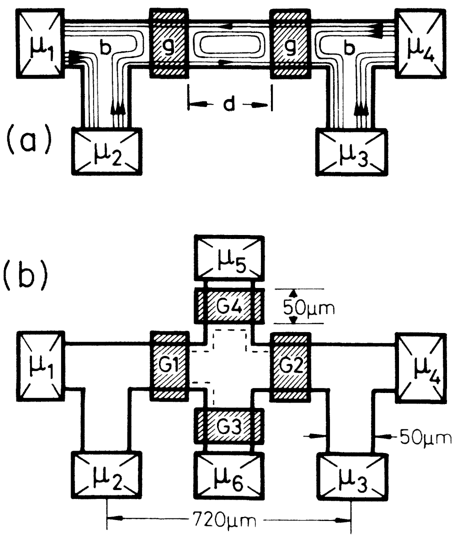

FIG. 1. Schematic layout (not to scale) of the samples investigated. Adiabatic transport over a distance d ($d=20$ and 200 μm) is investigated using structure (a). The edge channels for a high magnetic field are sketched for a filling factor $g=1$ under both gates and $b=3$ in the bulk. The four gates (b) $G1,G2,G3,G4$ with corresponding filling factors g_1,g_2,g_3,g_4 underneath are used to demonstrate experimentally switching between adiabatic and equilibrated transport. Relevant length (dashed line): $G1\rightarrow G2=110$ μm, $G1\rightarrow G3=45$ μm.

occurs between the two gate fingers. This means that there is no coupling between the g current carrying edge states and the $b-g$ remaining edge channels. Interchannel scattering processes as well as contacts establish equilibrium among the circulating and transmitted states.[5] Full equilibration can be achieved by incorporating reservoirs between the two gate fingers ($G1,G2$) as shown in Fig. 1(b). Two additional gates ($G3,G4$) can be used to connect or disconnect these Hall probes electrically. With the Hall probes (and therefore the metallic reservoirs) connected ($V_g=0$ at $G3$ and $G4$, $g_3=g_4=b$, $g_1=g_2=g$) the corresponding four-point resistance is given by

$$R^{\rm eq}_{14,23}=2\frac{h}{e^2}\left[\frac{1}{g}-\frac{1}{b}\right], \tag{3}$$

which is twice as much as the "adiabatic resistance" $R^{\rm ad}_{14,23}$ given by Eq. (2). Thus by connecting or disconnecting the reservoirs to the Hall bar the resistance measured between contact 2 and 3 should change by a factor of 2. This is demonstrated later on experimentally. An intermediate resistance value between $R^{\rm eq}$ and $R^{\rm ad}$ is expected for partial equilibration between initially populated and nonoccupied edge channels. Using one gate as a current injector and a second as edge channel detector (e.g., $g_1<g_3<b=g_2=g_4$ with edge states running counterclockwise) one can realize the geometry used previously to investigate the degree of equilibration among the edge channels by measuring the Hall resistance $R_{14,56}$.[12]

Our devices are $GaAs/Al_xGa_{1-x}As$ heterojunctions with carrier densities N_s between 1.7×10^{11} cm^{-2} and 2.0×10^{11} cm^{-2} and mobilities ranging between 1.1×10^6 cm^2/V s and 1.4×10^6 cm^2/V s at liquid-helium temperature. The shape of the device, the contacts, and the Schottky gates have been defined by usual photolithographic techniques. The alloyed AuGe/Ni contacts have contact resistances of typically 400 Ω. The experiments are carried out in a $^3He/^4He$ dilution refrigerator at temperatures as low as 30 mK.[13] The resistances are measured by applying an ac current (10 nA,10 Hz) and measuring the corresponding voltage drops by lock-in techniques (the accuracy of the corresponding resistance values is within 3%).

In Fig. 2 we demonstrate the use of Schottky gates [using the device geometry of Fig. 1(a)] to selectively populate the edge channels between the two gate fingers. We have measured the resistance $R_{14,23}$ as a function of the gate voltage V_g for $d=20$ and 200 μm, where d is the distance between the two gate fingers. In the bulk we have set the filling factor $b=3$. Applying the same negative voltage to both gates results in a resistance plateau when the filling factor under the gates is around 2. The plateau value is determined by Eq. (2) ($b=3,g=2$) indicating that only the two selectively populated edge channels carry the current between the gates. No difference of the plateau for $d=20$ and 200 μm is found, in agreement with recent experiments where an effective decoupling of the edge states corresponding to the topmost occupied LL in the bulk from the remaining edge channels has been noted.[12] By adjusting the filling factor $g=1$ under the gate [the situation sketched in Fig. 1(a)], one observes nearly full adiabatic transport over a distance of 20 μm but not over 200 μm. Here some of the injected current is now also redistributed into the next higher channel which is, however, only separated by the Zeeman energy $g\mu_B B$ (≈ 60 μeV) from the lowest edge channel. We conclude that one can observe "true" adiabatic transport at low-enough temperatures and for high mobility samples over macroscopic distances. Here "true" is used to characterize that interedge channel scattering is not only

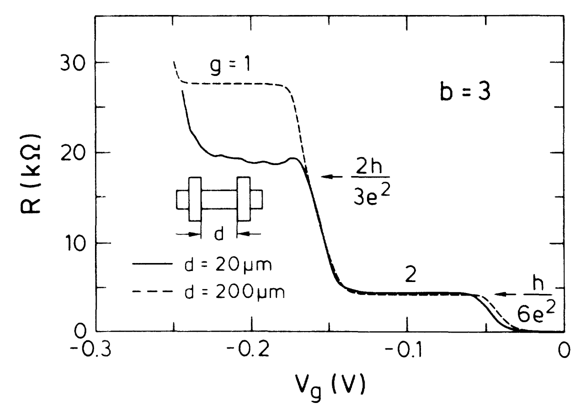

FIG. 2. $R_{14,23}$ as function of selector gate voltage. The expected plateau values for complete adiabatic transport between the two gates are marked by arrows.

suppressed for a situation where the topmost Landau level is decoupled but also for other nonequilibrium edge channel populations, however with a smaller characteristic equilibration length. If the claim of Alphenaar *et al.*[12] that the lack of equilibration observed over macroscopic distances is due to the decoupling of the highest Landau level only, whereas all the other edge channels carry the same amount of current would be generally valid, we would expect a plateau value of $7h/6e^2$ (≈ 30.1 kΩ) for both curves at $g=1$ in Fig. 2.

Adiabatic transport is destroyed if the edge channels become equilibrated (equally distributed current among all edge channels), e.g., by scattering processes. This situation can be realized experimentally by incorporating metallic reservoirs in between the two gate fingers, as is sketched in Fig. 1(b). The results with the Hall probes connected ($g_1=g_2<b=g_3=g_4$) are displayed in Fig. 3 (solid lines), where $R_{14,23}$ is plotted as a function of the negative gate voltage applied to $G1$ and $G2$ for filling factor $b=4$ (upper curves) and $b=6$ (lower curves) in the bulk. The quantized resistance steps appearing in the solid curve in Fig. 3 (arrows indicate the quantized values for the equilibrated case) are described exactly by Eq. (3), thus demonstrating that the edge channels become equally populated within the metallic contacts. Disconnecting these metallic reservoirs by negatively biasing gate $G3$ and $G4$ we can switch to adiabatic transport. To disconnect the reservoirs effectively it is sufficient to adjust the filling factors $g_3=g_4$ equal to $g_1=g_2$ since the injected edge channels are already occupied up to the same electrochemical potential. Adiabatic transport is demonstrated convincingly by the plateau value around -0.15 V in the upper curve (dashed line) of Fig. 3. Here exactly (within the experimental error) one-half of the resistance value $R^{\mathrm{eq}}_{14,23}$ is measured, indicating that transport between $G1$ and $G2$ (distance = 110 μm) takes place only via two selectively populated edge channels ($g=2$) which do not couple to the two remaining edge channels "circulating" between the gates. For filling factor $b=6$ in the bulk, nonequilibrium transport can also be observed (dashed line) but we could not switch completely between $R^{\mathrm{eq}}_{14,23}$ and $R^{\mathrm{ad}}_{14,23}$, indicating that partial equilibration occurs even without metallic contacts.

The geometry sketched in Fig. 1(b) also allows experiments to deduce the degree of equilibration. Using gate $G1$ as current injector and gate $G3$ as edge channel detector ($g_2=g_4=b$), we have in principle the same arrangement as has been used previously,[12] however, with a relevant length of only 45 μm [see Fig. 1(b)]. If one now measures the Hall resistance $R_{14,56}$ as a function of V_{G3} (Fig. 4), one expects [according to Eq. (1)] steps at h/g_3e^2 ($g_1 \le g_3$) for purely adiabatic edge currents running counterclockwise. Reversing the magnetic-field direction and thus reversing the rotation of the edge channels gives h/be^2 independent of V_{G3} (dashed line in Fig. 4). No steps are expected ($R_{14,56}\equiv h/be^2$) either, if the current injected into g_1 edge channels (each channel j carries the current $I_j=I/g_1$) is completely redistributed among all available edge channels (now $I_j=I/b$) before reaching the detector gate $G3$. The actually observed plateau value can therefore be used to estimate the distribution of the total current among the edge channels incoming at gate $G3$.[12] For filling factor $b=4$, $B=1.75$ T, $T=30$ mK in the bulk, and injecting all the current into the lowest edge channel ($g_1=1$) we found that at $G3$, 65% of the total current is still in the lowest edge channel, 28% is in the second, 5% is in the third, and 2% is in the fourth edge channel. The actual degree of equilibration depends on the temperature (as is deduced from the experiment and displayed in the inset of Fig. 4) and the mobility of the samples. This experiment also demonstrates strong nonequilibrium transport over macroscopic distances, not only decoupling of the topmost edge channel from the remaining ones carrying all the same amount of current, as was suggested recently.[12] For filling factor $b=6$ ($B=1.2$ T) in the bulk (dotted line in Fig. 4), we observe a similar result to that of Alphenaar

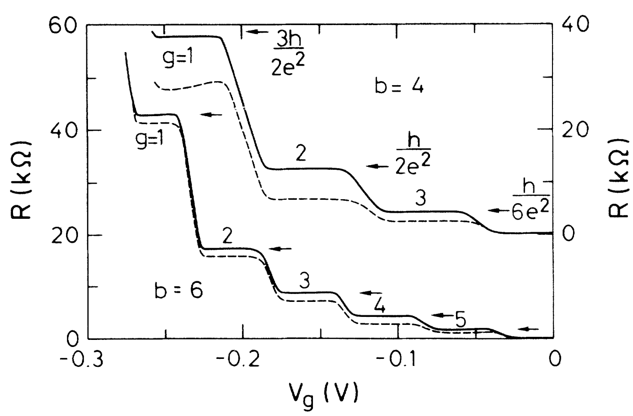

FIG. 3. $R_{14,23}$ for connected (solid line) and disconnected (dashed line) Hall probes [contacts 5 and 6 in Fig. 1(b)] as a function of the gate voltage V_g applied to $G1$ and $G2$ ($g_1=g_2=g$) for filling factors $b=4$ (upper curves) and $b=6$ (lower curves) in the bulk. The arrows indicate the expected plateau values for equilibrium transport [Eq. (3)].

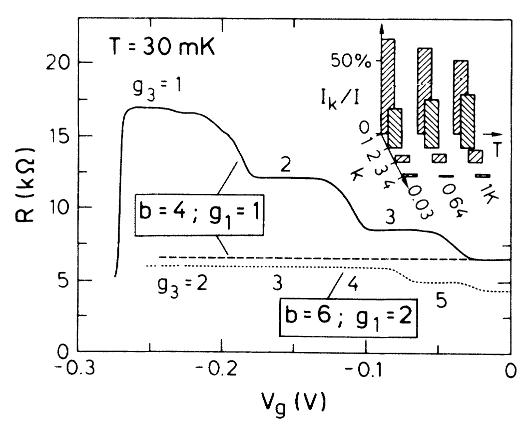

FIG. 4. Hall resistance $R_{14,56}$ for two ($g_1=2$) and one ($g_1=1$) selectively populated edge channels as a function of V_{G3}. The distribution of the injected current among the four edge channels for $b=4$ is displayed for three temperatures in the inset.

et al.,[12] however with the spin-split edge channels resolved. This demonstrates again that a nonequilibrium occupation between the highest available LL and the (equilibrated) remaining others is the most stable one (see Fig. 2, $g=2$ plateau where there is no difference between transport over 20 and 200 μm). This behavior is in qualitative agreement with the theories of Martin and Feng[14] and Palacios and Tejedor,[15] where the scattering rates depend mainly exponentially on the spatial separation Δy_0 between neighboring edge channels for Δy_0 larger than the magnetic length describing the spatial extent of an edge-channel wave function. Since Δy_0 is largest between the two innermost edge channels (for fixed energy gaps), this may explain that the most prominent suppression of the interedge channel scattering is observed for a nonequilibrium occupation between these edge channels.

In summary we have demonstrated nearly ideal adiabatic transport in a spin-polarized edge channel over distances up to 20 μm by selectively populated edge channels using Schottky gates. By electrically connecting or disconnecting incorporated Hall probes we are able to switch between equilibrated and adiabatic edge-channel transport, emphasizing the important role of contacts and giving strong experimental evidence for current-carrying edge states.

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