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Local spectroscopy of edge channels in the quantum Hall regime with local probe techniques

T. Ihn[a, *], J. Rychen[a], T. Vančura[a], K. Ensslin[a], W. Wegscheider[b], M. Bichler[c]

[a] *Laboratory of Solid State Physics, ETH Zürich, CH-8093 Zürich, Switzerland*
[b] *Angewandte und Experimentelle Physik, Universität Regensburg, 93040 Regensburg, Germany*
[c] *Walter Schottky Institut, Am Coulombwall 3, 85748 Garching, Germany*

Abstract

We present measurements of the tunnelling conductance between edge channels in the quantum Hall regime. By using a local potential perturbation induced by the tip of a scanning force microscope we are able to enhance the tunnelling coupling and map its strength along the edge of the two-dimensional electron gas. It is suggested that the presented method is promising for the local investigation of inter-edge-channel scattering and edge-channel equilibration. © 2002 Elsevier Science B.V. All rights reserved.

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The importance of the sample edge for the quantum Hall effect [1] has been pointed out soon after its discovery on the basis of a model of non-interacting electrons [2]. Later on interactions were considered by using self-consistent descriptions of the sample edge [3]. Since the theoretical prediction of the existence of self-consistent edge-channels and compressible and incompressible stripes in the quantum Hall regime there has been a series of experimental attempts to measure local properties at sample edges in high magnetic fields [4]. It is obvious to employ scanning probe techniques with their unprecedented potential of spatial resolution for such investigations and several experiments have been reported during the past few years using a scanning single-electron transistor [5], scanned potential microscopy [6], Kelvin probe techniques [7] and local capacitance measurements [8]. In this paper we report a novel type of local edge state imaging in the quantum Hall regime which is also based on low-temperature scanning probe techniques. In our approach we measure the tunnelling current between edge channels that are separately contacted. The tunnelling current is locally modified using a potential perturbation induced by the conducting tip of a scanning force microscope.

The samples are based on a GaAs/AlGaAs heterostructure with the two-dimensional electron gas residing 34 nm below the sample surface. Fig. 1a shows a photography of the structure which was prepared using photolithographic techniques. The structure is essentially a circular mesa with a diameter of about 500 μm with a central hole of 20 μm in diameter. The sample is connected to the measurement setup via the internal Ohmic contacts C1 and C2. A star-shaped gate electrode splits the two-dimensional electron gas into four ungated sectors. The sample is mounted in

* Corresponding author. Laboratorium für Festkörperphysik, ETH Hönggerberg, CH-8093 Zürich, Switzerland. Tel.: +41-1-633-22-80; fax: +41-1-633-11-46.
E-mail address: ihn@phys.ethz.ch (T. Ihn).

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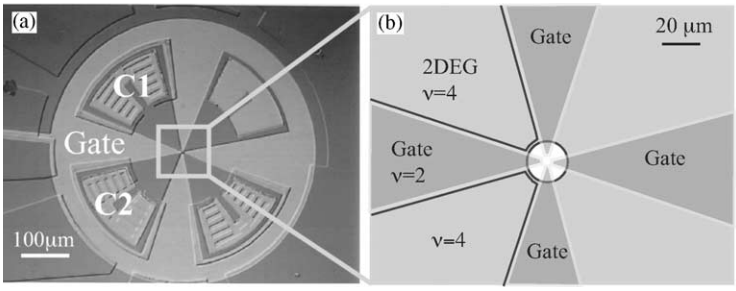

Fig. 1. (a) Photography of the circular mesa structure with the internal contacts C1 and C2. A small circular hole is etched into the center of the structure. (b) Schematic blow-up of the central part of the sample. For appropriate choice of V_G and B the indicated filling factors can be realized leading to the distribution of edge channels as indicated by the black lines.

a home-built low-temperature atomic force microscope utilizing a piezoelectric quartz tuning fork force-sensor. The basic principle of the microscope and the characteristics of the tuning fork sensors can be found in Ref. [9]. Experiments were performed in the variable temperature insert of a standard ^{4}He cryostat at a temperature of 1.9 K. A voltage of 10 μV was applied between C1 and C2 and the two-terminal conductance was measured with a current-voltage converter.

Fig. 1b shows a schematic magnification of the central part of the structure for illustrating the basic concept of our experiment. Using the appropriate combination of gate-voltage, U_G, and magnetic field, B, we are able to set up a situation in which the bulk of the ungated electron gas has a Landau-level filling factor $\nu=4$, i.e. two spin-degenerate edge channels exist, while the gated regions have a filling factor of $\nu=2$ supporting only one spin-degenerate edge channel. The latter will be able to circulate around the central hole of the structure as shown in Fig. 1b. The other edge channel is not allowed under the gate. It will therefore come from C1 (or C2) along the edge of the gate, run in parallel with the $\nu=2$ edge channel along the edge of the central hole and then return to contact C1 (or C2) along the other edge of the gate. Since under these conditions the bulk regions of the gated as well as of the ungated 2DEG are insulating, the current from C1 to C2 involves tunnelling processes between the two edge channels. Spatially, tunnelling has to occur in regions where both edge channels run in parallel, i.e. in the vicinity of the edge of the central hole. Conceptually, this tunnelling transport is somewhat related to recent experiments on

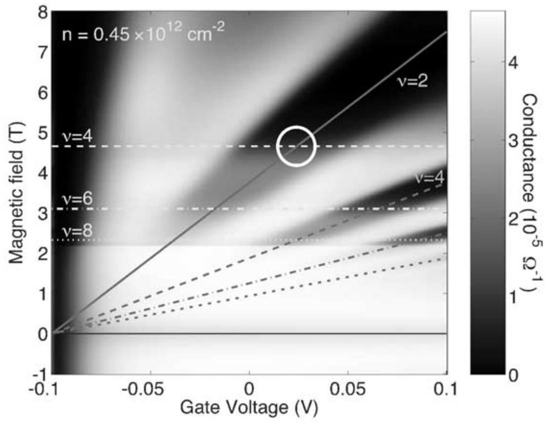

Fig. 2. Conductance measured as a function of magnetic field and gate-voltage. The white horizontal lines (dashed, dash–dotted, dotted) indicate the filling factors in the ungated regions of the 2DEG. The gray Landau-fan indicates filling factors in the gated regions of the 2DEG.

tunnelling through the edge-states around an antidot [10], however, the quantization of edge states around the central hole (the 'antidot') plays no role in our structure. The central idea of the present experiment is that the tunnelling current between the two edge channels can be locally enhanced (or suppressed) by applying a local potential perturbation capacitively induced by the conducting tip.

In order to find the appropriate settings for V_G and B we characterized the structure by measuring the two-terminal conductance between contacts C1 and C2 as a function of these two parameters with the tip withdrawn from the surface of the structure. The result is shown as a grayscale image in Fig. 2.

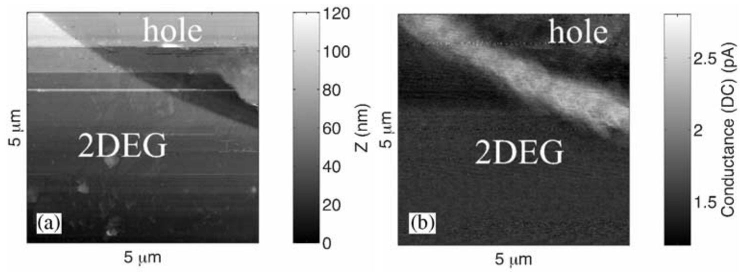

Fig. 3. (a) Topographic image of the mesa edge defining the central hole etched into the 2DEG. (b) Conductance as a function of the tip position. The tip-induced local potential leads to an enhanced tunnelling coupling of the two parallel edge channels and thereby to an increase in the conductance.

It can be seen that at $V_G < -0.08$ V the regions under the gate are completely pinched off and the conductance vanishes. At $V_G > -0.05$ V the grayscale plot is dominated by the Landau fan given by the 2DEG under the gate. The conductance oscillates as a function of B due to the Shubnikov–de Haas effect. The contribution of the ungated 2DEG can barely be seen in this range of V_G. However, in a very small range of gate voltage around $V_G \approx -0.07$ V vertical cuts through the plot reveal $1/B$-periodic oscillations which are independent of V_G but can hardly be seen on the grayscale plot, i.e. we observe the Shubnikov–de Haas oscillations of the ungated regions. They lead to the bright horizontal lines in the figure where the filling factors for the ungated regions are indicated. It can be seen from the figure that at $B \approx 5$ T and $V_G \approx 0.02$ V we achieve the desired $\nu = 2$ under the gate, while in the ungated regions we have $\nu = 4$.

While keeping the sample under these conditions the tip is now scanned across the sample surface near the edge of the inner hole. The tip was kept at a constant voltage $V_t = 0$ V, but due to the work function difference between the tip material PtIr and the sample there exists an effective electrostatic potential drop between tip and 2DEG which locally depletes the electron gas. Fig. 3a shows a 5 μm × 5 μm topographical image of the edge of the central hole of the sample. In Fig. 3b the conductance image can be seen measured simultaneously with the topography. The conductance of the sample is enhanced along a stripe of about 700 nm width which follows the curvature of the edge of the 2DEG. The image proves in a direct way that we can indeed enhance the tunnelling coupling between the two parallel edge channels by applying a local potential perturbation.

It is well established that the conductance or resistance of a sample in the quantum Hall regime is highly non-local [11,12] and the phase-coherence length of electrons in edge channels can be macroscopically large. Therefore, it is not a priori clear that the local perturbation induced by the presence of the tip will change the tunnelling coupling of the edge channels *locally*. Yet we argue that the self-consistent nature of the edge channel formation may well lead to a local enhancement of the tunnelling coupling. According to the adiabatic edge channel description [13] edge channels will follow equipotential lines along the sample edge. The local perturbing potential will affect the spatial run of the equipotential lines locally (i.e. on the scale of the screening length) and, therefore, we expect the edge channels to follow this perturbation on a local scale. The tunnelling coupling between the edge channels depends on the exponential overlap of the wave functions and therefore on the width of the incompressible stripe separating them. We suggest that the *local* change of the tunnelling coupling creates the observed conductance contrast in Fig. 3.

The local nature of the conductance contrast makes the presented imaging method a promising tool for the local investigation of edge channel coupling and inter-edge-channel scattering (for a review see [14,15]). As a matter of fact it can already be observed in Fig. 3b that the bright stripe is not homogeneous but exhibits some internal structure. In order to illustrate this further we show in Fig. 4 the conductance image obtained in the course of the same cooldown

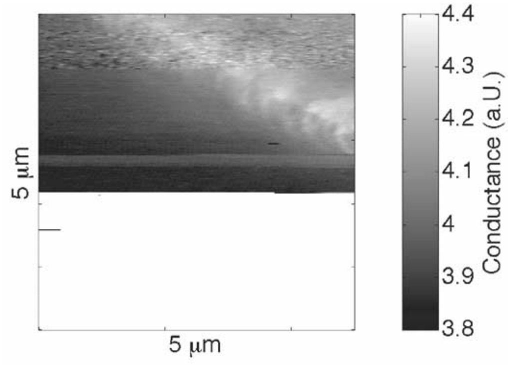

Fig. 4. Image of the edge-channel coupling at enhanced spatial resolution.

of the sample but with the tip in better condition. Unfortunately, the tip shape can change during a cooldown, e.g. due to contaminations picked up from the sample surface. In some fortunate cases, however, the spatial resolution of the images is improved. In Fig. 4 it is clearly visible that the extent to which the edge channel coupling can be enhanced depends strongly on the position of the tip even within the stripe of enhanced conductance. The image shows fringes leading away from the center of the stripe reminding of the fascinating fine structure observed with other methods in the bulk of 2DEGs in the quantum Hall regime [16]. More investigations will help to further establish the presented imaging technique and to deepen our understanding of its interpretation.

In conclusion, we have presented a low-temperature scanning probe experiment which aimed at the local investigation of edge channels in the quantum Hall regime. We could show that a local potential perturbation leads to a measurable enhancement of the tunnelling coupling between parallel edge channels. We suggest that the tunnelling coupling is enhanced locally under the influence of the perturbation and that the method is therefore promising for the local investigation of inter-edge-channel scattering.

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