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Tunnelling between edge channels in the quantum hall regime manipulated with a scanning force microscope

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Abstract

The tunnelling conductance between edge channels in the quantum Hall regime was measured. The tunnelling coupling is locally enhanced by a local repulsive potential induced by the conducting tip of a scanning force microscope. This allows mapping the enhanced tunnelling coupling along the sample edge and, in this sense, visualizes the presence of edge channels.

Keywords: Scanning probe techniques; Quantum Hall effect; Local spectroscopy

1. Introduction

Soon after the discovery of the quantum Hall effect [1] it was realized that the sample edge plays an important role for its understanding. Halperin suggested a model for the quantum Hall effect based on non-interacting electrons [2]. Later, self-consistent descriptions of the sample edge were suggested which accounted for the unusual screening properties of the perturbed Landau levels near the edge and led to the prediction of compressible and incompressible stripes (see Fig. 1) [3]. Many experimentalists were stimulated by these predictions and there has been a series of measurements which set out to verify the local edge channel structure in high magnetic fields. Electron–phonon interaction was used in first experiments [4]. Optical techniques with a spatial resolution of about 1 μm in the best case also supported the notion of edge channels [5]. Later experiments tried to detect the edge currents inductively, but evidence for bulk currents was found [6]. Capacitance experiments were used to detect the width of edge channels in the integer and fractional quantum Hall regime [7]. Recently, edge strips were imaged using a metallic single electron transistor fabricated near the edge of a 2-dimensional electron gas (2DEG) [8].

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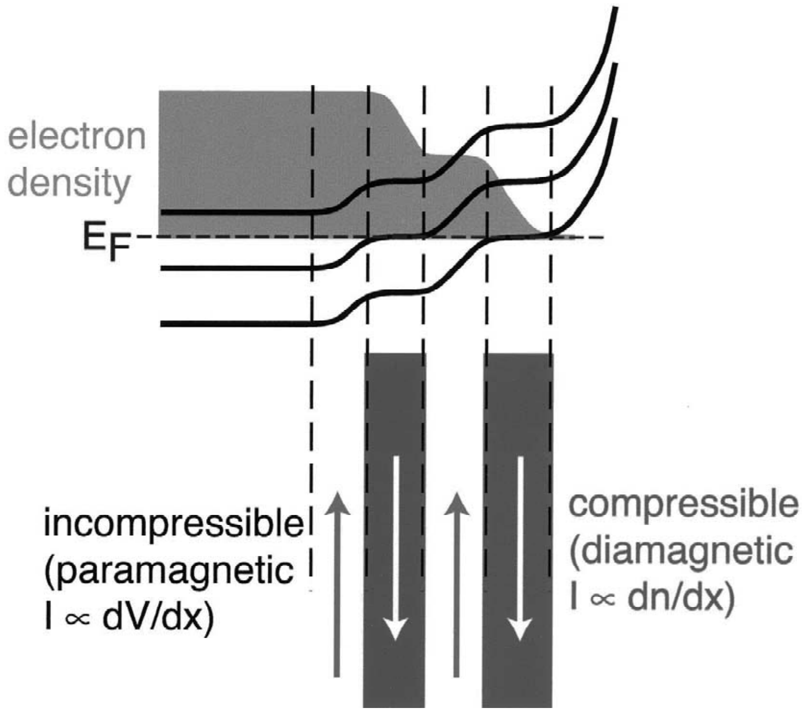

Fig. 1. Present notion of the potential and density profile at the sample edge in the quantum Hall regime. The step-like increase of the potential leads to the formation of compressible and incompressible stripes which accommodate equilibrium currents [3] in opposite directions. The electron density decays step-like as well.

Scanning probe techniques appear to be well suited for the investigation of edge channels due to their excellent spatial resolution. In the past few years a number of experiments have been reported utilizing a scanning single-electron transistor [9], scanned potential microscopy [10], Kelvin probe techniques [11] and local capacitance measurements [12].

In this paper we report the measurement of the tunnelling current between edge channels that are in equilibrium with separate Ohmic contacts. The tunnelling coupling between the edge channels can be locally modified with the help of a metallic tip of a scanning force microscope operating at a temperature of 1.9 K in a magnetic field of up to 8 T.

The tip essentially acts as a local gate electrode coupling capacitively to the electron gas thereby changing the local potential landscape. The measured tunnelling current senses the presence of the tip-induced potential and the edge channels become visible with spatial resolution.

2. Samples and structures

The samples used for this study are based on a GaAs/AlGaAs heterostructure with the heterointerface being 34 nm below the sample surface. Along this interface a 2DEG forms with a density of 5×10^{11} cm^{-2} and a mobility of 10^6 cm^2/V s at 1.7 K. Such a shallow electron gas was

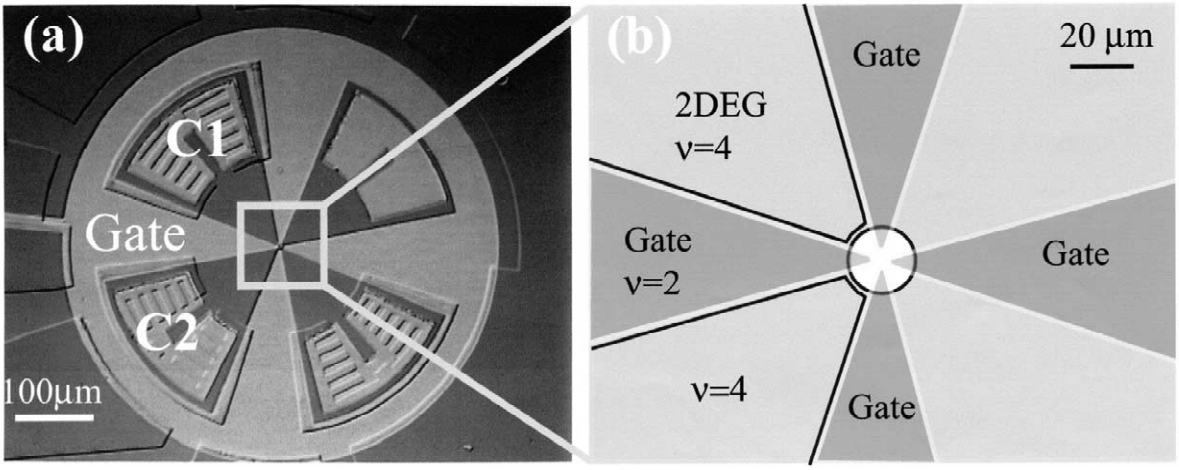

Fig. 2. (a) Photography of the structure used in the experiments. See text for details. (b) Schematic representation of the sample interior at a magnetic field and gate voltage suitable for the experiment. Filling factor $\nu = 4$ is set in the ungated regions, while under the gate, filling factor $\nu = 2$ is set.

chosen in order to keep the spatial resolution with optimum tips of the order of the Fermi-wavelength of the electrons.

The gated mesa structure depicted in Fig. 2a was fabricated with photolithographic techniques. A circular mesa with a diameter of 500 μm was prepared with a central 20 μm hole. Two internal Ohmic contacts C1 and C2 connect to the 2DEG. A star shaped gate electrode splits the 2DEG into gated and ungated sectors.

3. Setup and principle of the experiment

For the experiment we mount the sample in a home built scanning force microscope operated at a temperature of 1.9 K and in magnetic fields up to 8 T in the variable temperature insert of a standard ^{4}He cryostat. The microscope utilizes piezoelectric quartz tuning fork sensors [13] with PtIr tips attached to one prong. Details about the microscope can be found in Ref. [14].

Fig. 2b illustrates the basic concept of our measurement. The experiment was performed with a voltage of 10 μV applied between contacts C1 and C2 (see Fig. 2a) while measuring the current with a current–voltage converter. A magnetic field was applied with the ungated region of the 2DEG at filling factor of $\nu = 4$. The gate voltage was then chosen such that the gated region of the 2DEG has filling factor $\nu = 2$. Therefore the gated regions support only one spin degenerate edge state (outer channel), while in the ungated regions two spin degenerate edge states exist (outer channel and inner channel). The outer channel is allowed to circulate around the central hole of the sample while the inner channel is forced to travel from the Ohmic contacts along the edges of the gates. Non-equilibrium electrons in any channel can tunnel into the other channel along the circular arcs close to the edge of the internal hole where the two run parallel, i.e., the current through the structure is dominated by tunnelling between edge channels. The basic idea of the measurement is to modify the tunnelling coupling between the edge channels locally by using the tip induced potential perturbation of the scanning force microscope.

4. Measurement results

For the measurement the tip is kept at a constant tip-sample voltage $V_t = 0$ V and scanned across the sample surface near the edge of the central hole. The work function difference between PtIr and the heterostructure of several hundred mV leads to the depletion of the electron gas below the tip even if no gate voltage is applied. In Fig. 3a we show a 5 μm × 5 μm topographical image of the edge of the central hole. The tunnelling current which was simultaneously measured is depicted in Fig. 3b.

The presence of the tip in a stripe of about 700 nm width along the curved edge of the hole enhances the tunnelling current by slightly more than a pA. Closer inspection of the image even shows that there exists some internal structure in bright stripe of enhanced conductance. We argue, that although the conductance of a sample in the quantum Hall regime is non-local [15,16], the self-consistent formation of edge channels will only allow the local manipulation of the tunnelling coupling. The tip potential will change the run of the equipotential lines near the sample surface as depicted in Fig. 4 which obviously leads to a local rearrangement of the edge channels and thereby to a change in their coupling.

5. Conclusions and outlook

In this paper we have demonstrated how a scanning force microscope with a conducting tip can be used for the investigation of edge channels in the quantum Hall regime. The local nature of the presented conductance contrast makes this imaging method a promising tool for the local investigation of edge channel coupling and edge channel scattering.

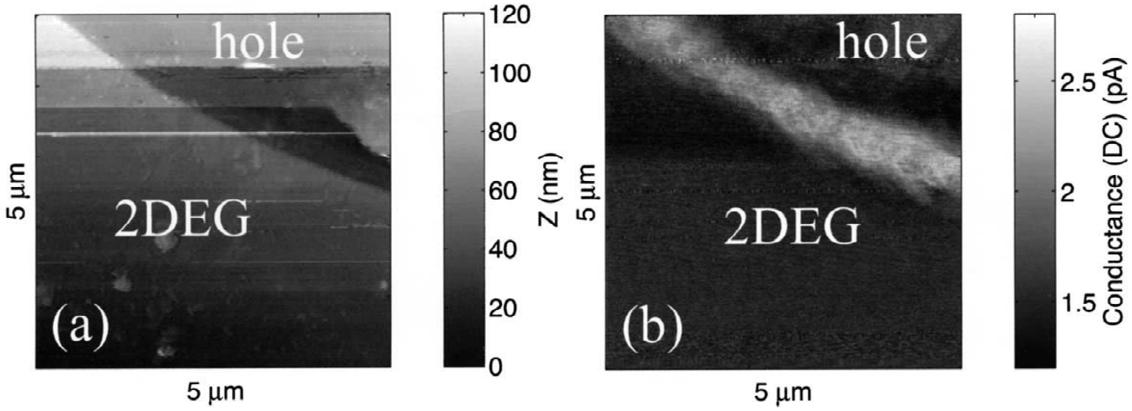

Fig. 3. (a) Topographical image of the edge of the central hole of the structure. (b) Simultaneously measured (DC) tunnelling conductance as a function of tip position. The tip induced local potential enhances the tunnelling coupling between the outer and inner edge channels and thereby increases the conductance.

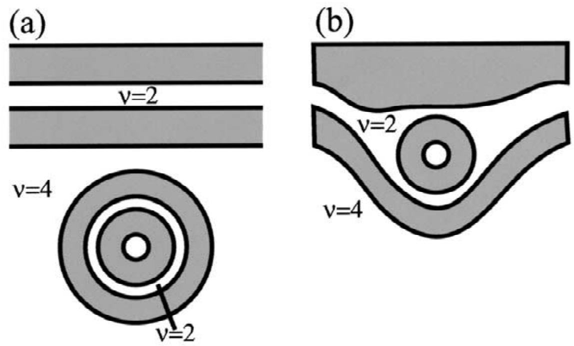

Fig. 4. (a) Tip far away from the edge. Two edge states encircle the tip-induced potential hill. States at the sample edge are not affected. (b) Tip close to the edge of the sample. The tip induced potential locally changes the run of the edge currents and thereby modifies the tunnelling coupling between them.

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