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Gate controlled separation of edge and bulk current transport in the quantum Hall effect regime

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Abstract It is generally accepted, that the plateau regime of the integer quantum Hall effect (QHE) can be explained in terms edge channels (EC) , which are separated by so called incompressible regions. However, the fundamental question where the current flows is answered differently by different models. While the already mentioned edge EC picture associates the sample current with the ECs, the bulk current picture attributes the current to the incompressible regions between the ECs, which may cover the whole bulk region in the plateau regime. On the basis of a non-equilibrium network model for magneto transport we propose an approach for creating a quite narrow incompressible stripe far from the sample edges without creating ECs at it's boundaries. This is achieved by an appropriate biasing of a narrow stripe like gate electrode, which is aligned to the longitudinal direction of the sample and covers only a vanishing small part (few percent) of the bulk region. By adjusting the magnetic field in order to tune the bulk region to the vicinity of a plateau transition, the bulk gets resistive (dissipative). In this way we create 3 distinguishable possibilities for current flow: (i) The original ECs at the real edge of the sample; (ii) the dissipative bulk region which covers nearly all of the sample area and (iii) the narrow incompressible stripe in the middle of the bulk region. Our calculations clearly demonstrate, that there exists a dissipation-less current in the narrow incompressible stripe, which dominates the sample behaviour, while the edge channels as well as the bulk region loose their importance.

Keywords Network model, quantum Hall effect

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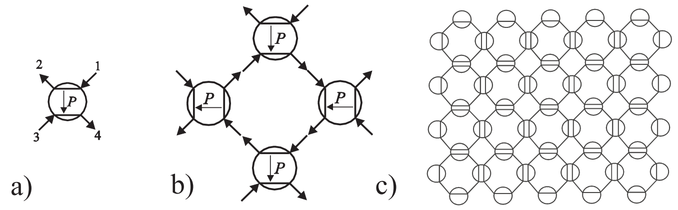

Fig. 1 a) Node of the network with two incoming and two outgoing channels. The channels $1 \rightarrow 2$ and $3 \rightarrow 4$ are treated like ECs with back scattering, where $P = R/T$ corresponds to the relation between reflection and transmission coefficients according to the Landauer- Büttiker formalism. b) Arrangement of the nodes for building the minimal physical element of a network, which is the closed loop of a so called magnetic bound state. c) The complete network is composed by putting together a sufficient number of such adjacent loops.

1 Introduction

The integer quantum Hall effect (IQHE) is well understood in terms of quantum localization within the framework of scaling theory[1]. While the localization problem is theoretically well investigated, the modeling of the current flow is still a challenging problem. The ongoing discussion in terms of 'edge versus bulk current' is based on the general believe, that the so called edge channel (EC) picture attributes the current to the edges, while the bulk current picture attributes the current to the bulk region even in the plateau regime. Chklovskii et al made clear, that the ECs are not geometrically narrow one-dimensional channels, but stripes of up to more than $100\mu m$ width[2]. These so called compressible stripes are formed at steps of the electrostatic edge potential, which result from a re-distribution of free carriers at the Fermi level. However, an answer how these wide stripes keep the quantization like 1D- channels was not given. Weis et al conclude, that the dissipation-less current flows in the so called incompressible regions between the edge stripes[3]. This seems in serious conflict with the EC picture.

2 The non-equilibrium network model

The layout of our network looks similar to the well known Chalker-Coddington (CC) network[4]. However, the CC network has been setup to study quantum localization, while our model aims directly at modeling non-equilibrium currents. Consequently our handling of the nodes as well as the association of the channels with currents and potentials is substantially different from the CC model. The main facts are given below and for further details refer to the cited papers[5,6].

Fig.1a shows a single node of our network, which transmits potentials from the incoming to the outgoing channels, Figs.1b-c demonstrate, how the network is composed. The potentials transmitted by a node are calculated as follows:

$$u_2 = (u_1 + P \cdot u_3)/(1 + P) \tag{1}$$

$$u_4 = (u_3 + P \cdot u_1)/(1 + P) \tag{2}$$

In contrast to the CC-network, we attribute the non-equilibrium currents to channel pairs, like e.g. the current from the right to the left $I = (e^2/h) \cdot (u_1 - u_4)$ (see

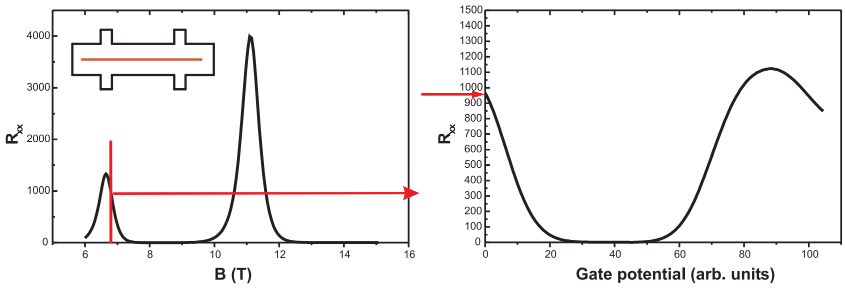

Fig. 2 Left: R_{xx} versus magnetic field B with inactive gate. The vertical line marks the fixed magnetic field B at which the gate voltage sweep on the right has been made. The horizontal line marks the initial R_{xx} value for the gate sweep. Insert: schematic sample geometry, the bold line in the middle indicates the position of the gate stripe. Right: R_{xx} versus gate voltage at fixed magnetic field as marked on the left.

Fig.1a). It is important to realize, that in this way our nodes provide a handle to both, the injected currents and the potentials. P results from tunneling across saddle points of the potential landscape in the bulk[5]: $P = \exp\left[-\frac{L^2 E_F}{e\tilde{V}} \frac{eB}{h}\right]$, E_F is the Fermi energy relative to the saddle energy which corresponds to the center of the Landau level (LL), eB/h is the number of LL states, L is the period and $\tilde{V}$ the amplitude of a representative two-dimensional Cosine-potential modulation, which has the same Taylor expansion like the actual saddle potential. Therefore the ratio $L^2/\tilde{V}$ can be understood as a measure of the ”smoothness” of the potential modulation near the saddle.

The design of the sample is managed by shaping the lateral confining bare potential and using a self consistent Hartree type approximation to calculate the Fermi energy and the lateral carrier distribution. On this basis a gate electrode can be easily modeled by biasing the bare potential of the designated gate region.

3 Results and Discussion

For the numerical study in Fig. 2 we designed a Hall bar with a narrow stripe shaped gate electrode in the middle of the bulk region. The Hall conductor is represented by 165x20 grid periods, the voltage probes are 5 grid periods wide and 5 grid periods long and are 20 grid periods apart from each other, the gate stripe is 2 grid periods wide and 140 grid periods long and is placed in the middle of the bulk, the bulk carrier density was chosen to be $n = 4x10^{11} cm^{-2}$

The key point is, that on the one hand the gate region should become insulating, on the other hand no ECs should be created at the boundaries of the gate. This is only achievable in a very limited gate voltage interval. The magnetic field is kept fixed in a regime of non-zero R_{xx} (see Fig. 2). When the gate is activated by sweeping the gate voltage towards depletion, R_{xx} starts to decrease and finally reaches zero. Sweeping further leads again to an increase of R_{xx}. In order to understand this behavior more easily, another simulation has been performed by using a pure rectangular Hall conductor without potential probes, but plotting the whole

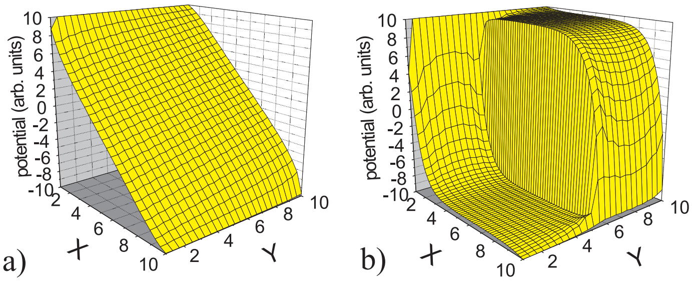

Fig. 3 a) 3D plot of the lateral potential distribution of a rectangular Hall conductor in the resistive regime without active gate b) 3D plot for the same condition but with active gate. All the transverse potential appears within the gate stripe, where x is the longitudinal and y the transverse direction.

lateral potential distribution. Fig.3a shows the lateral potential distribution without active gate, while Fig.3b shows it with activated gate in the zero resistance regime according to Fig. 2 on the left. Almost the complete longitudinal voltage drop turns to a purely transverse voltage because of the gate. In this way the bulk on both sides of the gate starts to act like extremely wide edge stripes, which are no longer distinguishable from the ECs at the real edges. Since we know, that at this magnetic field the bulk is resistive, the vanishing potential gradient in the bulk in Fig.3b indicates that all the bulk current must have vanished too, but leaving as the only possibility the dissipation-less current flow in the gate region.

4 Summary

By using a stripe shaped narrow gate electrode in the bulk region we have demonstrated the possibility, to re-distribute the sample current from the compressible resistive bulk to the incompressible gate region. This gives direct evidence of dissipation-less currents in incompressible regions. Experimental verifications of this numerical results are encouraged.

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