On the current domain picture of the microwave induced zero-resistance of high mobility quantum Hall systems

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Abstract:

Numerical simulations of the current domain picture, which is frequently used to describe the microwave induced zero resistance state of high mobility 2-dimensional electron systems, are shown. We demonstrate that we obtain a situation which is equivalent to the current domain picture by introducing an artificial domain wall into our network model for magneto transport. However, in contrast to the current domain picture the current in our simulations is insensitive to the width of the domains. Finally we propose an alternative picture where we use several domain walls, which are distributed along the current path. These serve as current filaments and lead also to a vanishing longitudinal resistance, while the Hall resistance remains unchanged.

Keywords: Quantum Hall Effect; Current domain; Zero resistance state; Network model

1. Introduction

The experimental observation of a zero resistance state [1,2] which occurs by irradiating a very high-mobility 2D electron gas with microwaves at low magnetic fields attracted immediately after its discovery a great deal of attention and a lot of theoretical papers followed [3,4,5,6]. An often used picture is that one of current domains (CDs) [5], where the sample is separated in two domains in which dissipation less currents flow parallel and anti parallel to the domain wall. The position of the domain wall inside the sample is determined by the net current flowing in the circuit. Since the current is assumed to be loss-free no longitudinal voltage drop occurs. The sample is considered to be infinitely long, meaning that the boundary problem at the contacts is neglected. It is not the purpose of this paper to give a physical explanation how such CDs could be generated by the microwaves, but we want to demonstrate that we are able to simulate a situation, which is equivalent to the domain wall picture, including the boundary problem at the metallic contacts. We use a network approach, which was successfully used for modeling the integer quantum Hall effect (QHE) for realistic geometry and contact configurations [7]. It gives exact quantization of R_{xy} and zero resistance of R_{xx} even for macroscopically wide edge stripes, which we therefore consider as good candidates for representing current domains in our network model.

2. The network model

In this section we want to give a brief introduction to the network model. For more details see reference [7]. The network consists of a matrix-like arrangement of interconnected nodes (see Fig. 1 left), where each node represents something like an elementary quantum Hall sample with two incoming and two outgoing channels.

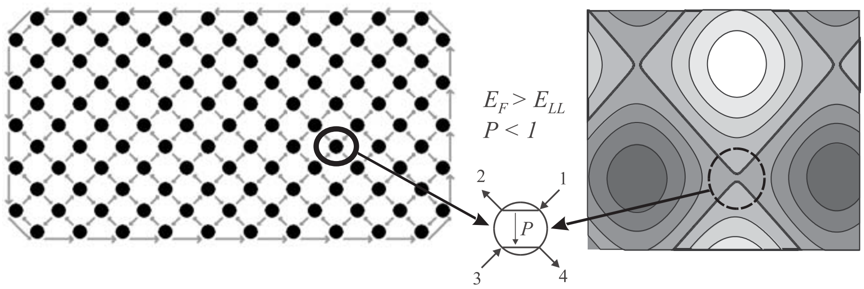

Fig. 1: The network consists of interconnected nodes indicated by black dots. Each node represents something like an elementary quantum Hall sample with two incoming and two outgoing edge channels. This network is based on the idea of transport across magnetic bound states via tunneling, as schematically shown on the right side. P represents a back scattering function, which is associated with the tunneling process.

The key-point in our model is that the coupling at the nodes is handled as a back scattering process in the EC picture. On this basis we have introduced a back scattering function P, which is formally equivalent to the ratio R/T of the Landauer-Büttiker formalism, with R and T being the reflection and transmission coefficient respectively. P depends on the position of the Fermi level and hence, on the filling factor (P = P(υ)). The shape of the sample is defined by the lateral distribution of the carrier density on the network. The lateral carrier density profile itself is calculated from the distribution of lateral electrostatic bare potential, which is used as a tool for designing the shape of the sample. At this point it should also be mentioned, that each involved LL is represented by its own complete network and all these networks contribute in parallel. Contacts are defined within the network by interconnecting all channels of the different layers of the network (which are associated with the different LLs) at the designated location of the contact. For representing current domains we use macroscopically wide edge stripes, which are created by half filling of the top LL. The domain wall is defined by preventing a mixture of the opposite currents in the two domains. In our network model this means a suppression of the coupling across the designated domain wall. It is important to know that such a suppression of the coupling cannot be simply realized by cutting the sample (network) along the current path, since this generates automatically counter flowing ECs. Instead, we achieve this by rounding the filling factor to the next higher integer value inside the domain wall.

3. Results:

The calculations shown in Fig. 2 have been done for a half filled LL. However, half filling in the bulk leads to the ohmic regime of a standard QHE sample (Fig. 2 (a)). With domain wall the situation changes completely. As shown in Fig. 2 (b) the whole potential drop appears only in a narrow region close to the current contacts. For voltage probes far from the current contacts this results in a vanishing longitudinal voltage drop like expected from the CD picture. However, our simulations don't show any dependence of the sample current on the width of the two CDs. In Fig. 3 (a) and (b) the corresponding 2D gray scale picture of the potential distribution is shown.

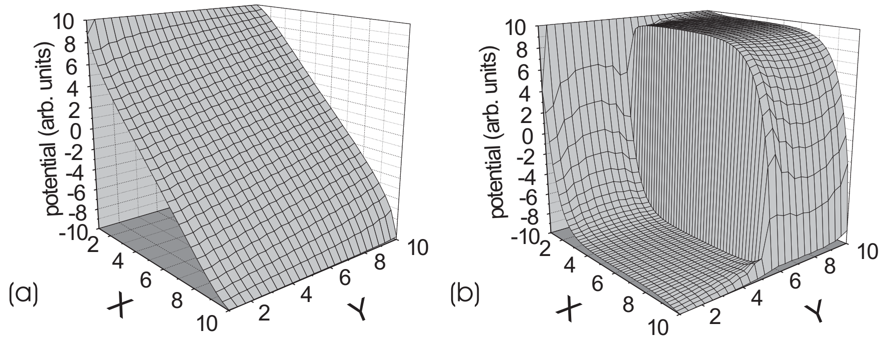

Fig. 2: 3D plot of the simulated lateral potential distribution without (a) and with (b) domain wall.

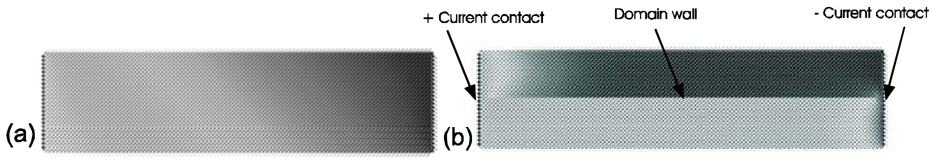

Fig. 3: Corresponding 2D gray scale picture of the potential distribution without (a) and with (b) domain wall.

4. Discussion and conclusion

On one hand we obtain the major agreement with the CD picture that our model calculations show a vanishing R_{xx} also at non integer filling. On the other hand there is a major disagreement because in our simulation the net sample current is independent of the CD widths. For the standard QH situation it has been shown, that the dissipation less current flows in the incompressible regions between the so-called edge stripes [8]. For our case this means that at some distance from the current contacts the current gets concentrated within the domain wall, which is physically equivalent to an incompressible stripe of the normal QH situation. However, it appears quite unlikely that just a single domain wall should be present in a macroscopic sample carrying the whole sample current. On this background we propose the idea of having several domain walls distributed across the whole current path, which act as some sort of current filaments. The very first simulation of such a situation (Fig. 4) shows indeed a drastic reduction of R_{xx} by nearly 3 orders of magnitude. In real samples one can expect that there are much more filaments achieving indeed zero resistance. All the above shown calculations have been done for a single LL. For the real case at large filling factors we have a large number of overlapping LLs. In this case the sample current is distributed over all involved LLs and their number is determined by the filling factor. On this background we get a Hall voltage, which continues to increase normally with magnetic field (decreasing filling factor) while R_{xx} remains at zero. Without the artificial domain wall the simulations show the normal SdH-oscillations.

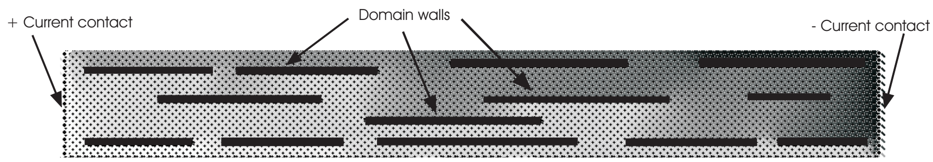

Fig. 4: Sample layout as used for the simulations. Several domain walls (current filaments) are distributed along the current path (black bars). The gray scale indicates the lateral potential distribution.

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