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Potential screening in the integer quantum Hall effect: evidence for bulk currents

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Abstract

The current distribution in the integer quantum Hall regime was studied by inductive coupling technique and transport measurements. Using an inductive coupling method we were able to study the screening properties of a two-dimensional electron gas (2DEG). We found that having gates in the vicinity of the 2DEG influence the distribution of the non-equilibrium Hall current injected into the sample. From the inductive measurements we proved that the non-equilibrium Hall current is carried by bulk states. We also demonstrated the role of externally applied electric fields. 2DEG V-grooved samples allowed us to realize a configuration at which the normal component of the magnetic field to the plane of the 2DEG alternates in sign. We showed that for such a magnetic field configuration, the quantum Hall effect survives although the magnitude of the quantized Hall coefficient is multiplied by the number of the grooves. This observation can easily be explained by the alternation of the current direction in each subsequent sidewall of the groove, and therefore implies the current flow in the bulk of the sample.

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The spatial distribution of current across a Hall bar sample in the Integer Quantum Hall Effect (IQHE) was an open question since the discovery of the effect. Over the years, people tried to describe the current distribution by two models. The first one is a model which considers the edges of 2DEG samples to be of no importance. According to this model the current distribution is not confined to the edges of the sample. This is known as the bulk-state picture [1,2]. In contrast, the edge-state picture [3–7] suggested that the Hall voltage (and therefore the current density) drops over a narrow region in the vicinity of the physical boundaries of the sample. During the last decade, experiments aimed to probe the current distribution and the electrostatic potential profile of a 2DEG in the IQHE, used various measuring techniques [8–14].

In the presence of an external applied magnetic field, the current in the sample contains two parts. The

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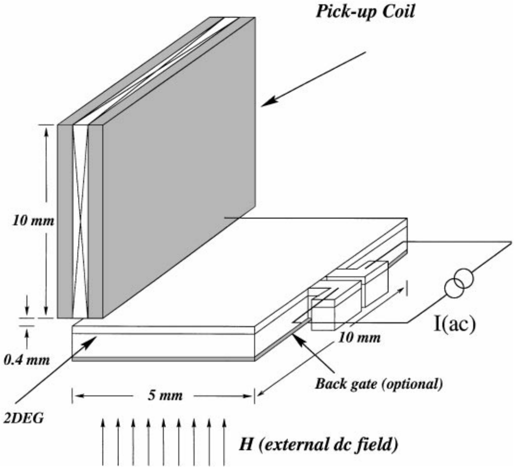

Fig. 1. Setup of the inductive coupling experiment.

first part is a diamagnetic current, i.e., an equilibrium current, which exists in a closed Hall bar sample. The second part is a Hall current which is generated or injected into the sample. This is a non-equilibrium component and its spatial distribution could be very different from the distribution of the equilibrium part. The spatial distribution of the non-equilibrium component of the current is the much debated subject.

In the following paper we discuss the problem of current distribution in the IQHE by means of two experimental techniques. The first one, the inductive coupling technique, was proposed by the authors recently. This method, which couples a tiny pick-up coil to a 2DEG, was aimed to probe the spatial current distribution at the IQHE conditions [15]. The second technique uses magnetotransport measurements on a V-grooved 2DEG.

Fig. 1 shows a schematic view of the experimental setup of the first technique. It includes a pick-up coil and a 2DEG sample. The 2DEG samples were fabricated from $GaAs_x/Al_{1-x}GaAs$ heterostructure, and had the typical dimensions of 10×5 mm^2. The current Ohmic contacts were alloyed along the edge opposite to the coil, in order to increase the experimental sensitivity of the pick-up coil signal to changes in the spatial current distribution.

An alternating current, driven between the Ohmic contacts, produced a time-dependent alternating magnetic flux at the pick-up coil. The latter, induced an electro-motive force (emf) at the pick-up coil circuit. The calibration constant was 180 ± 10 nV/μA at 26 kHz, when the total injected current flows underneath the pick-up coil.

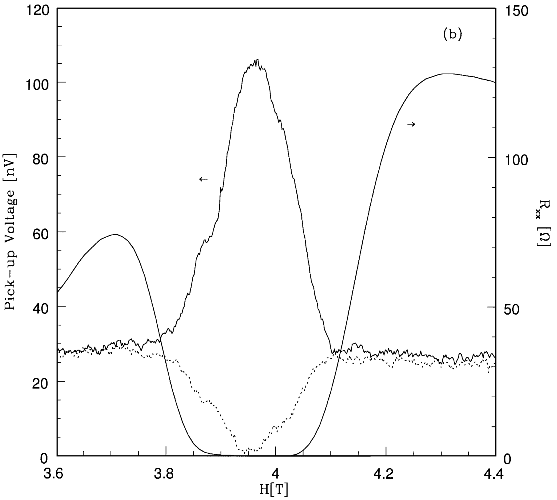

Fig. 2. The pick-up voltage (left axis) and longitudinal resistance (right axis) versus the external magnetic field. Solid line: +H, +V. Short dashed line: +H, −V. The traces correspond to $\nu = 2$.

At first, we measured the current distribution in a back gated Hall bar sample. The sample had carrier concentration of 1.8×10^{11} cm^{-2} and mobility of 2×10^6 cm^2/V s. The amplitude of the injected current was 0.5 μA at a frequency of 26 kHz at all experiments.

Fig. 2 shows traces of the pick-up coil voltage (left axis) and the longitudinal resistance (right axis) versus the external magnetic field, for a fixed direction of the magnetic field and two polarities of the applied voltage. The trace for (+H, +V) gives the maximum signal at the pick-up coil according to our calibration constant. It means that the entire Hall current flows along the edge underneath the pick-up coil. The measurement was done at 2.17 K. The curve corresponding to (+H, −V) in Fig. 2 shows zero pick-up signals. It means that the entire Hall current flows along the short edge opposite to the coil (cf. Fig. 1). According to the edge-state picture, half of the injected current should flow along each edge. This in turn means that the voltage across the coil should have been about 45 nV, which is half of the full signal expected for 0.5 μA of injected current at 26 kHz.

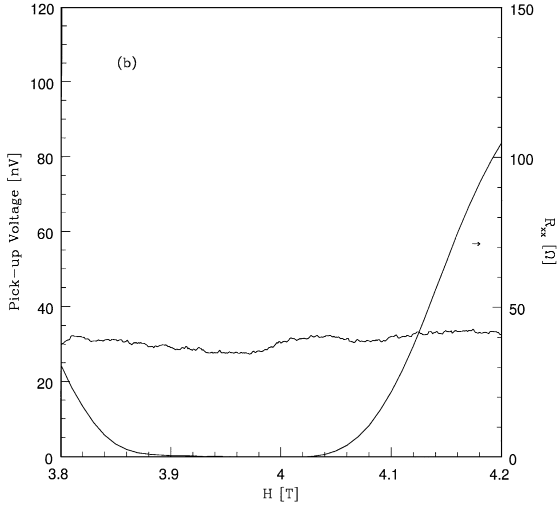

Fig. 3. The pick-up voltage and longitudinal resistance versus external magnetic field at $\nu = 2$. The sample was attached to the holder by an insulating paste which prevented gating by a back gate.

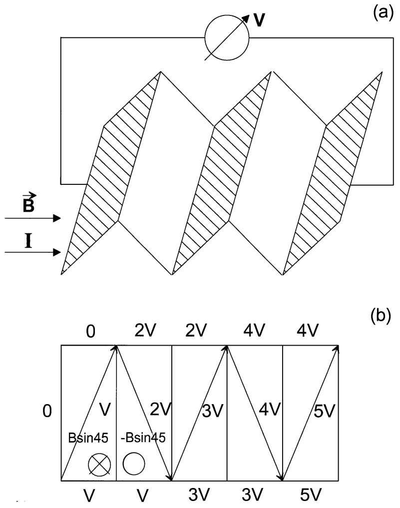

Fig. 4. (a) The experimental setup for the V-grooved 2DEG; (b) The analogy for a plannar 2DEG; potential and schematic current distribution for the bulk picture.

The explanation for the observed signal is based on the screening properties of the 2DEG. In the IQHE, the edges are conducting and are at source (±V) and drain (ground) potentials correspondingly [15]. The potential at a given point in the bulk 2DEG approaches the ground potential of the back gate, as the distance between this point and the edge becomes larger than the distance between this point and the back gate. Therefore, the Hall voltage drops over a region ($\sim$ 350 μm) at one edge, which is biased by the source voltage. Since both the bulk and the second edge are at ground potential, the electrical field is zero at this edge. Therefore, the entire Hall current flows only along one edge. This Hall current, flowing at the edge in a gated 2DEG Hall bar sample, should not be confused with the so-called "edge" currents, discussed above.

In order to study the spatial current distribution it is necessary to reduce undesired gating effects of the 2DEG. The same kind of inductive measurements were carried on a sample without a back gate, and the results are presented in Fig. 3. From the figure, it can be concluded that the pick-up signal remains constant at the value corresponding to the current distribution at the dissipative regime ($\rho_{xx} \neq 0$), which is a bulk current. This experiment proves that non-equilibrium Hall current in a Hall bar geometry sample, is carried by bulk states.

Transport experiments on standard Hall bar geometry samples at uniform magnetic field cannot provide any information on the spatial distribution of the Hall current. In this part of the paper we present a magnetotransport experiment, which gives an additional evidence for the validity of the bulk current picture in the IQH regime. This experiment is done on a 2DEG with a magnetic field varying periodically in space, resulting in a redistribution of the Hall current through the bulk of the sample. The sample studied in this experiment is a 2DEG grown on a V-grooved prepatterned GaAs substrate, which is usually used for producing one-dimensional wires [16].

An application of a uniform magnetic field parallel to the substrate and perpendicular to the V-grooved 2DEG allows us to realize a configuration at which the normal component of the magnetic field to the sidewalls of V-grooves alternates in sign. Fig. 4 shows this configuration and the experimental setup (a), and its analogy for a planner 2DEG (b). The results of two-terminal magnetoresistance measurements at 4.2 K are presented in Fig. 5. The wide curve corresponds to 60 grooves (120 sidewalls) and the narrow one corresponds to 30 grooves (60 walls). The figure shows that the quantum Hall effect in a periodic in sign

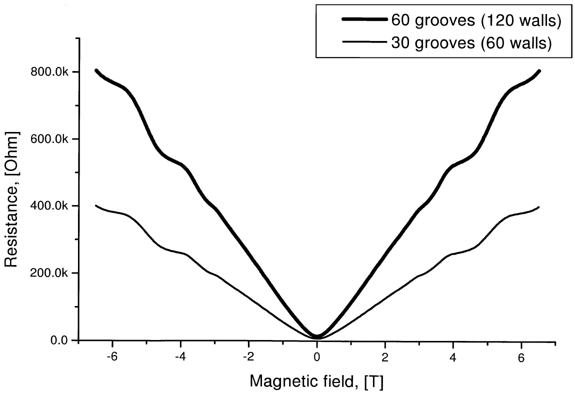

Fig. 5. Two-terminal magnetoresistance measurements on V-grooves.

magnetic field survives although exactly the number of sidewalls (twice the number of grooves) multiplies the magnitude of the Hall resistance. This observation can easily be explained by the alternation of current direction in each subsequent sidewall of the groove, implying bulk current distribution. This is schematically shown in Fig. 4(b).

The edge current approach fails to explain the observed experimental results, unless one assumes that the tops and bottoms of the grooves could be regarded as electronic reservoirs at zero magnetic field. It is a hardly plausible assumption since the width of the bottom, where the normal component of the field reverses its sign, is of order of 100 Å which is much smaller than the magnetic length even for the highest field in the experiment.

To conclude, we performed inductive coupling measurements on a plannar 2DEG Hall bar samples and magnetotransport studies on a V-grooved 2DEG. We found that under the conditions, where the surrounding of the 2DEG contained no gate, the current distribution in the IQHE plateaus remained the same as in the dissipative regime. These measurements prove that the Hall current at the IQHE plateaus is carried mostly by extended bulk states, located below the Fermi level. Results of magnetotransport measurements provide a valuable complementary proof for the existence of bulk current carrying states.

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