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Bulk current distribution in Hall bar geometry samples in the integer quantum Hall effect

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Abstract

The problem of current distribution in the integer quantum Hall regime was studied in Hall bar samples of a two-dimensional electron gas (2DEG) by means of an inductive coupling technique. Our results imply that edge states do not carry the total Hall current, injected into the sample. It was found that in the absence of any nearby metallic plates such as gates, the total non-equilibrium Hall current, is carried by 2DEG extended bulk states. © 1998 Elsevier Science B.V. All rights reserved.

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The way current is distributed across a Hall bar in the integer quantum Hall effect (IQHE) [1] was a question in dispute since the discovery of the effect. Two contradictory models have been proposed to describe the spatial distribution of the Hall current. The bulk-state picture [2–8] considered the edges of a two-dimensional electron gas (2DEG) samples to be of no importance, whereas the edge-state picture [9–15] suggested that the Hall voltage drops over a narrow region in the vicinity of the physical boundaries of the sample. The latter means that the Hall current flows in these narrow regions which are called the edge states. During the last decade, experiments aimed to probe the current distribution and electrostatic potential profile of a 2DEG in the IQHE, used various measuring techniques [16–25].

In the presence of an external magnetic field, the current in the sample contains two parts. The first part is a diamagnetic current, which exists in a closed Hall bar sample. This part, which flows near the edges of the sample, is a consequence of the edge confining potential [9]. The width of the edge region is of the order of a few magnetic lengths. It is common belief that the equilibrium current is confined to the edges. The second part is a Hall current which is generated (Corbino disk geometry or injected Hall bar geometry) into the sample. This is a non-equilibrium component and its spatial distribution could be different from the distribution of

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the equilibrium part. The spatial distribution of the Hall current (non-equilibrium component of the current) is the debated subject on which we focus our present research. The experiments described below are sensitive only to the distribution of the non-equilibrium part of the Hall current.

Recently, the authors proposed a new inductive coupling method to probe the spatial current distribution in a 2DEG at IQHE conditions [26].

We showed that, for a Corbino device, the distribution of the Hall current in the bulk depends on the details of the electrostatic potential. The latter is strongly influenced by the geometry of the sample and by the attached contacts and gates. It was found also that the extended bulk states below the Fermi energy cannot screen external applied electrostatic fields in the 2DEG plane.

The role of edge states versus extended bulk states in the IQHE, can be quite different in Hall bar geometry samples. In a Hall bar sample, the electrical current is usually fixed and both the longitudinal and transverse voltages are measured, whereas in a Corbino disk the voltage between the inner and outer Ohmic contacts is kept fixed, and a Hall current is induced along the azimuthal direction. Hence, the current injection mechanism into the Hall bar sample, can enhance the role of the edge states as current-carrying states.

Fig. 1 shows a schematic view of the experimental setup. It includes a pick-up coil and a 2DEG sample with a back gate. The 2DEG samples used in this study were fabricated from GaAs$_x$/Al$_{1-x}$GaAs heterostructures. Rectangular-shaped samples with typical dimensions of $10 \times 5\,\mathrm{mm}^2$ were cleaved from the wafer and Ohmic Au/Ge/Ni contacts were alloyed along the edge, as shown in Fig. 1. The source-drain 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. The back gate, located 350 μm below the 2DEG, was at ground potential in all relevant measurements. Fig. 1 depicts the dimensions of the pick-up coil and the distances between the sample and the coil. The pick-up coil was made from 3000 turns of a copper wire having a diameter of 50 μm, wound around an insulating core. The coil was placed ~400 μm above the physical edge of the sample.

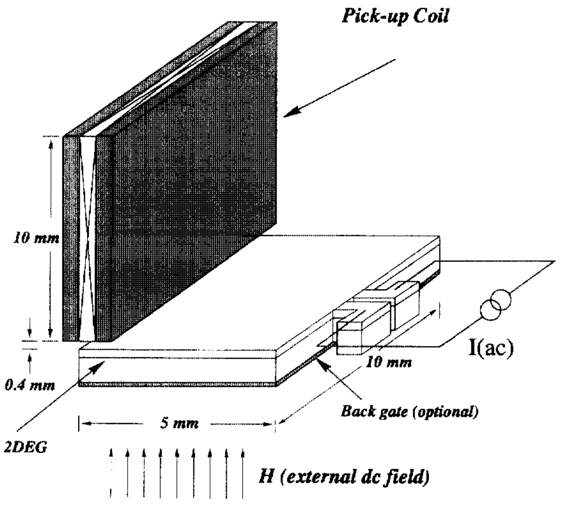

Fig. 1. The experimental setup. The pick-up coil was electrostatically shielded and is coupled to the 2DEG only inductively.

An alternating current at frequency f_0, driven between these Ohmic contacts, produced a time-dependent alternating magnetic flux at the pick-up coil. The latter induced an electromotive force (emf) at the pick-up coil circuit. That emf signal was measured by a standard lock-in technique. The calibration constant was 180 nV/μA at 26 kHz, when the total injected current flows underneath the pick-up coil. The pick-up voltage varied with temperature and saturated at low-temperatures, below 40 K. The calibration constant given above was measured at liquid-helium temperature.

In the IQHE regime the edges of the sample are equipotential ($\rho_{xx} = 0$). The electrostatic potential of the edge is determined by the polarity of the applied voltage source and the direction of the external magnetic field. Note, that although we used an oscillating source, always one of the contacts was grounded whereas the second one alternated with frequency f_0 between $+V$ and $-V$.

Within the framework of the edge-state picture, it is commonly accepted that the current in the sample flows at both edges. The Hall current follows equipotential lines where a potential gradient exists. It was argued [18–20,23] that the Hall current flows within few magnetic lengths at the physical edge of the sample, which is of the order of 1 μm

[23] at magnetic fields corresponding to the IQHE regime. In the bulk of the sample, the current is zero since the bulk Landau levels are flat. If one considers a standard Hall bar sample with symmetrically alloyed source-drain contacts, then according to "edge picture", the two edges suppose to carry the same amount of Hall current, i.e., half of the external injected current at each edge. The Hall current flowing at the edge should not depend on the direction of the external magnetic field.

We measured the current distribution in a back gated Hall bar sample. The role of a metallic back gate located near a 2DEG at the IQHE conditions, was demonstrated for a Corbino-like sample [26]. Fig. 2 shows traces of the pick-up coil voltage (left axis) and the longitudinal resistance (right axis) versus the external magnetic field, in the range between 4.5 T and 6 T, which corresponds to $\nu = 2$, where ν is an integer filling factor. The response of the coil was recorded for all possible configurations of the perpendicular magnetic field and the polarity of the applied voltage source. The amplitude of the injected current was $I = 0.5\,\mu A$ and the frequency was 26 kHz. The sample's carrier concentration was $2.4 \times 10^{11}\,cm^{-2}$ and had a mobility of $3.2 \times 10^5\,cm^2/Vs$ at 4.2 K.

The traces for (+H, +V), and for (−H, −V) give the maximum signal at the pick-up coil according to our calibration constant, for the current and frequency used in the experiment. It means that the *entire* Hall current flows along the edge underneath the pick-up coil. The curves corresponding to (+H, −V), and (−H, +V) show zero pick-up signal, within our experimental resolution. It means that the *entire* Hall current flows along the short edge opposite to the coil (cf. Fig. 1). Note, that according to initial checking of the experimental setup, if the total Hall current flows along the *entire* length of the edge opposite to the coil, the voltage across the coil would be about 50 nV. Since the actual length in more then ten times smaller (less then 1 mm), the signal is practically zero.

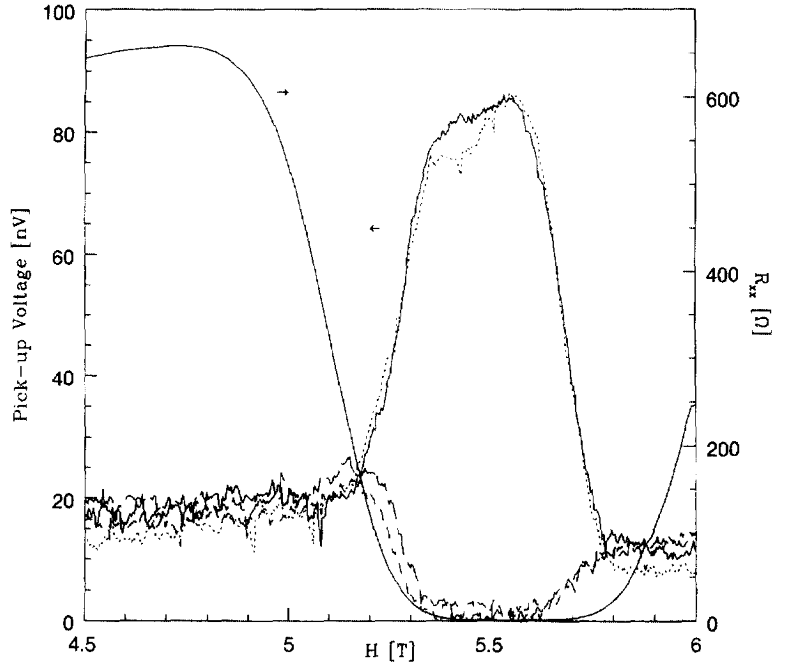

Fig. 2. The pick-up voltage (left axis) and longitudinal resistance (right axis) versus the external magnetic field, in the range between 4.5 T and 6 T, corresponding to filling factor $\nu = 2$. Solid line: + H, + V. Dotted line: − H, − V. Short dashed line: + H, − V. Long dashed line: − H, + V. All configurations were measured in the presence of a grounded metallic back gate.

The explanation for the observed signal is based on the screening properties of the 2DEG. As mentioned before, the 2DEG at the Hall plateaus, cannot screen the external electrostatic field in the bulk of a 2DEG. The edges are conducting and are at source (± V) and drain (ground) potentials correspondingly [26]. 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 narrow region (~ 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. It is only the proximity of a grounded equipotential plate (the back gate) which causes the Hall voltage to drop from the applied voltage to zero within 350 μm distance from the sample's edge. The Hall current, being proportional to the potential gradient, is also expected to flow only at this region.

In order to resolve the question of bulk versus edge states, as current-carrying states, it is therefore necessary to reduce undesired gating effects of the 2DEG. Due to the relatively large dielectric constant of GaAs ($\varepsilon \sim 10\varepsilon_0$), the most effective gating is produced by the back gate. Therefore, the back gate was removed, and the sample was attached to its holder using an insulating paste.

The inductive measurements were performed on an "ungated" sample, and results are presented in Fig. 3. From the plot of Fig. 3, it can be concluded that the distribution of the Hall current at the IQHE regime is not much different from the electrodynamic current distribution at zero magnetic

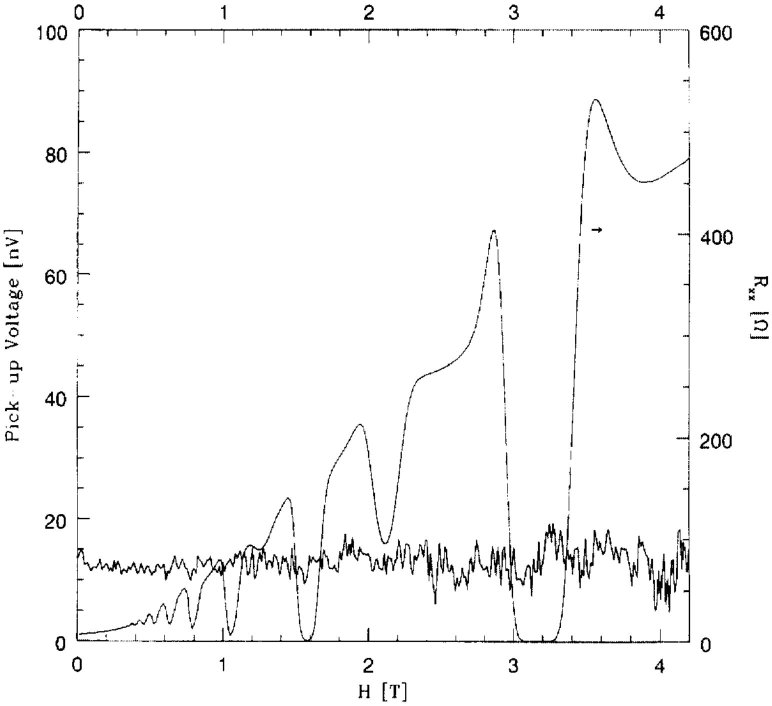

Fig. 3. The pick-up voltage and longitudinal resistance versus external magnetic field. The sample was attached to its holder by an insulating paste which prevented gating by a back gate.

field. The sample used in this measurement, had a carrier concentration of $1.6 \times 10^{11}\,\mathrm{cm}^{-2}$ and a mobility of $7.7 \times 10^5\,\mathrm{cm}^2/\mathrm{Vs}$. The amplitude and frequency of the current was 0.5 μA and 26 kHz, respectively. Within our experimental resolution, the pick-up signal remains constant at the value corresponding to the current distribution at the dissipative regime ($\rho_{xx} \neq 0$), which is governed by the Kirchoff's law, and is distributed in the bulk. Note that the value of the pick-up voltage predicted by the edge-current model should be increased to 45 nV at the Hall plateaus, *but* no change in the pick-up signal was observed.

To conclude, we performed inductive coupling measurements on 2DEG Hall bar samples in the IQHE regime. We found that under (almost) "ideal" conditions, where the surrounding of the 2DEG contained no metallic plates (such as back gate), the current distribution in the IQHE regime remained the same as at zero magnetic field. No redistribution of the current was observed at the Hall plateaus. This measurement proved that the Hall current at the IQHE plateaus is carried by extended bulk states, located below the Fermi level.

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