Evidence for Bulk Current in Hall Bar Samples and Potential Screening in the Integer Quantum Hall Effect

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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. It was found that in the absence of nearby metallic plates, such as gates, the total nonequilibrium Hall current is carried by 2DEG extended bulk states. The effects of potential screening on the current distribution are demonstrated. The spatial distribution of the Hall current, as monitored by the voltage developed across a small pickup coil, resembles the electrodynamic current distribution at zero magnetic field. [S0031-9007(98)07888-0]

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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 [2–6] considered the edges of a two-dimensional electron gas (2DEG) sample to be of no importance, whereas the edge-state picture [7–13] 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 past decade, experiments aimed to probe the current distribution and electrostatic potential profile of a 2DEG in the IQHE used various measuring techniques [14–23].

In the presence of an external applied magnetic field, the current in the sample contains two parts. The first part is a diamagnetic current, i.e., an equilibrium 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 [7]. The width of the edge region is of the order of a few magnetic lengths. It is a common belief that the equilibrium current is confined to the edges. The second part is a Hall current which is generated or injected into the sample. This is a nonequilibrium component and its spatial distribution could be very different from the distribution of the equilibrium part. The experiments described below are sensitive only to the distribution of the nonequilibrium 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 [24]. This experimental technique couples a tiny pickup coil to a 2DEG. We monitored variations of the pickup coil voltage, induced by an alternating Hall current in the sample. The pickup signal depends on the amplitude and frequency of the current and on its spatial distribution.

Using the inductive coupling technique, we have shown [24] that for a Corbino geometry in the IQHE regime the current distribution is extended into the bulk of the sample. The conclusions from that research included the following: (i) in the IQHE plateaus, the extended states at the Fermi energy are located only at the edges of the sample; (ii) in this regime, the bulk states at the Fermi energy are localized. However, the extended bulk states, at the Landau levels below the Fermi energy, carry a substantial amount of the Hall current. 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 a Hall bar geometry sample. 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 (usually it is not measured). Hence, the current injection mechanism into the Hall bar sample can enhance the role of the edge states as current-carrying states. Figure 1 shows a schematic view of the experimental setup. It includes a pickup coil and a 2DEG sample. The back gate shown in Fig. 1 was present only in the relevant experiment. The 2DEG samples used in this study were fabricated from $\mathrm{GaAs}_x/\mathrm{Al}_{1-x}\mathrm{GaAs}$ 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 pickup coil signal to changes in the spatial

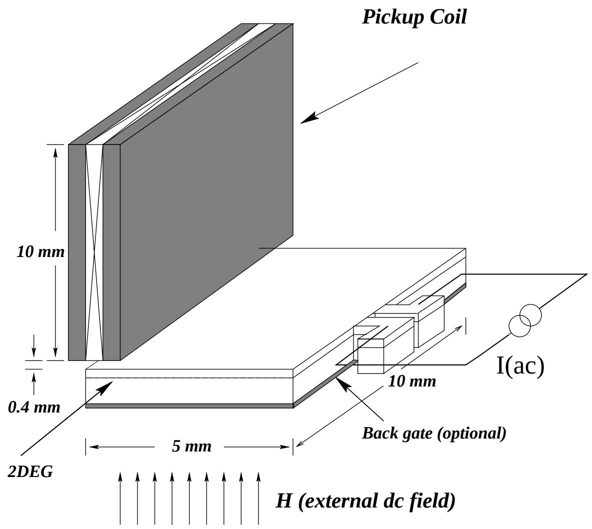

FIG. 1. The experimental setup. The pickup coil was electrostatically shielded and is coupled to the 2DEG only inductively.

current distribution. The back gate, located 350 μm below the 2DEG, was at ground potential in all relevant measurements. Figure 1 depicts the dimensions of the pickup coil and the distances between the sample and the coil. The pickup coil was made from 3000 turns of a copper wire having a diameter of 50 μm winded around an insulating core. The coil was placed ~400 μm above the physical edge of the sample. The schematic drawing of the sample represents a typical Hall bar sample used in this study.

An alternating current at frequency f_0, driven between these Ohmic contacts, produced a time-dependent alternating magnetic flux at the pickup coil. The latter induced an electromotive force (emf) at the pickup coil circuit. That emf signal was measured by a standard lock-in technique. The calibration constant was 180 ± 10 nv/μA at 26 kHz, when the total injected current flows underneath the pickup coil. The error bar is due to small variations of the sample's size and its position relative to the coil. The pickup voltage varied with temperature and saturated at low temperatures below 40 K. The calibration constant given above was measured at liquid helium temperature.

At first, we measured the current distribution in a back gated Hall bar sample. Two samples were measured. The first sample (denoted as sample *A*) had carrier concentration of 2.4×10^{11} cm^{-2} and mobility of 3.2×10^5 cm^2/V s. The second sample (*B*) had carrier concentration of 1.8×10^{11} cm^{-2} and mobility of 2×10^6 cm^2/V s. These numbers were measured at 1.5 K.

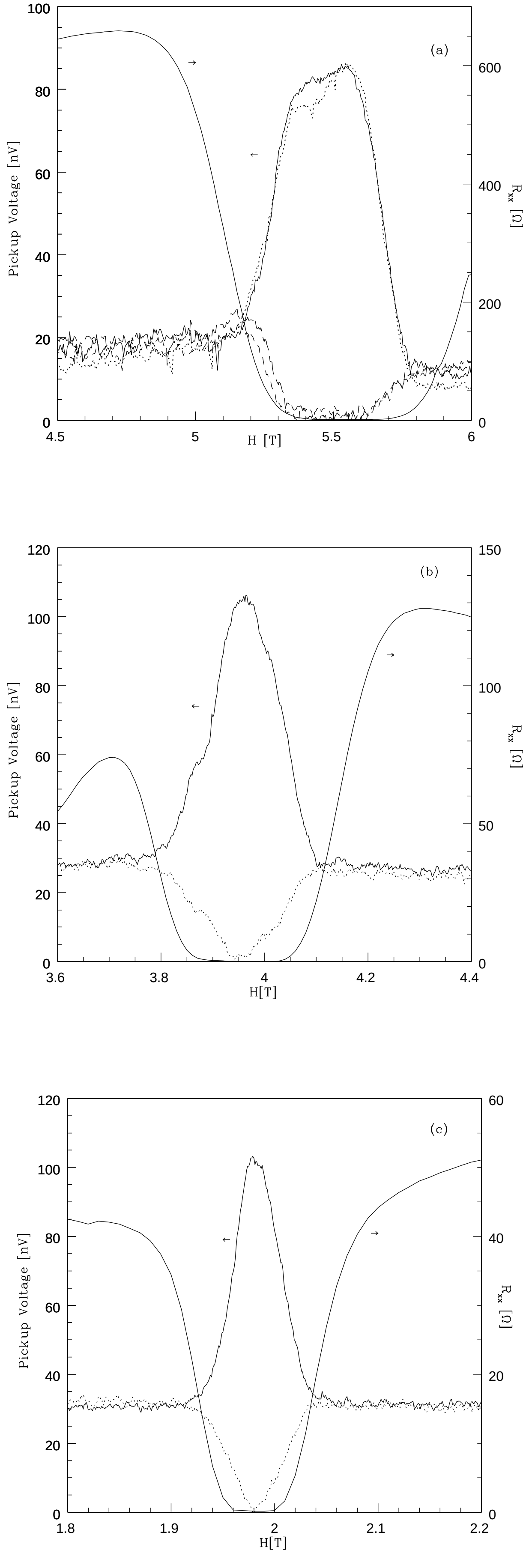

FIG. 2. The pickup voltage (left axis) and longitudinal resistance (right axis) versus the external magnetic field. (a) sample *A*: solid line, $+H, +V$; dotted line, $-H, -V$; short dashed line, $+H, -V$; long dashed line: $-H, +V$. All configurations were measured in the presence of a grounded metallic back gate and correspond to $\nu = 2$. (b) Sample *B*: solid line, $+H, +V$; short dashed line, $+H, -V$. Both traces correspond to $\nu = 2$. (c) Sample *B*: solid line, $+H, +V$; short dashed line, $+H, -V$. Both traces correspond to $\nu = 4$.

The amplitude of the injected current was $I = 0.5\ \mu$A at a frequency of 26 kHz at all experiments.

Figure 2 shows traces of the pickup coil voltage (left axis) and the longitudinal resistance (right axis) versus the external magnetic field for various directions of magnetic field and polarities of the applied voltage. Figure 2(a) presents traces measured for integer filling factor $\nu = 2$ at 4.2 K. The traces for $(+H, +V)$ and $(-H, -V)$ give the maximum signal at the pickup coil according to our calibration constant. It means that within our experimental resolution the *entire* Hall current flows along the edge underneath the pickup coil. Note that $+V$ and $-V$ mean to change the grounded contact. The same result is demonstrated for the high mobility sample (sample *B*) for $\nu = 2$ [Fig. 2(b)] and $\nu = 4$ [Fig. 2(c)] at 2.17 K. The curves corresponding to $(+H, -V)$ and $(-H, +V)$ in Fig. 2(a) show zero pickup signal, within our experimental resolution. It means that the *entire* Hall current flows along the short edge opposite to the coil (cf. Fig. 1). The same result is shown to occur in the high mobility sample (sample *B*) in Figs. 2(b) and 2(c). Note that according to the edge-state picture, half of the current injected into the sample 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. The fact that the Hall current flows along *one* of the edges only contradicts the edge-state picture.

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 external electrostatic field in the bulk of a 2DEG. The edges are conducting and are at source $(\pm V)$ and drain (ground) potentials correspondingly [24]. 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 ($\sim 350\ \mu$m) 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. Because of 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.

Inductive measurements were performed on samples without a back gate. The results are presented in Fig. 3. We tested two samples with different mobilities in order to verify that the results are sample independent. The samples used in this part of the research were sample *C* [Fig. 3(a)] and sample *B* [Fig. 3(b)]. The former sample had carrier concentration of 1.6×10^{11} cm^{-2} and mobility of 7.7×10^5 cm^2/V s.

From both plots 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 field. Within our experimental resolution, the pickup signal remains constant at the value corresponding to the current distribution at the dissipative regime ($\rho_{xx} \neq 0$), which is governed by Kirchoff's law and is distributed in the bulk. Note that the value of the pickup voltage predicted by the edge-current model should be increased to 45 nV at the Hall plateaus, *but no*

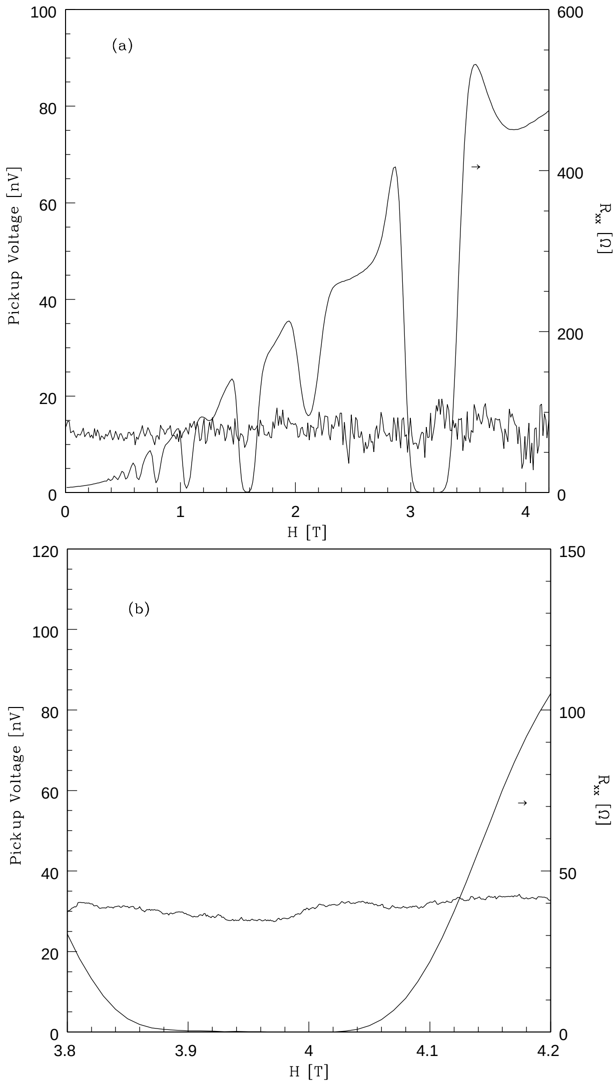

FIG. 3. The pickup voltage and longitudinal resistance versus external magnetic field at $\nu = 2$. The samples were attached to the sample's holder by an insulating paste which prevented gating by a back gate. (a) Sample *C*. (b) Sample *B*.

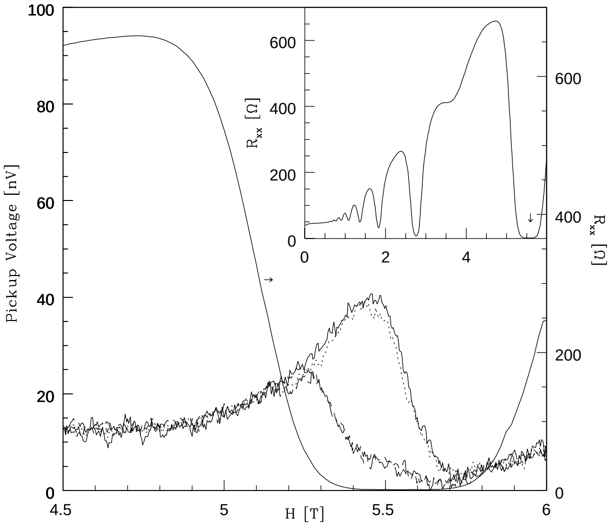

FIG. 4. The pickup voltage (left axis) and longitudinal resistance (right axis) versus the external magnetic field for sample *A*. The range of the magnetic field corresponds to $\nu = 2$. Solid line, $+H, +V$; dotted line, $-H, -V$; short dashed line, $+H, -V$; long dashed line, $-H, +V$. The inset shows a trace of the longitudinal resistance versus the magnetic field up to 6 T. The sample was "partially" gated due to the presence of a floating "back gate" formed by a silver paste.

change in the pickup signal was observed. Our resolution provides us with an upper bound of 5 nV (the noise) to the relative change in the pickup voltage. Therefore, we can state that no more than 5% of the total injected current flows at the edge. This experiment proves that the nonequilibrium Hall current in a Hall bar geometry sample is carried by bulk states located below the Fermi level.

We have also performed experiments on the sample with the metallic back gate (sample *A*) which was left floated (the potential at the back of the sample attained undefined constant value). The experiment presented in Fig. 4 used a silver paste to hold the sample to its holder. The paste covered roughly half of the sample's area at its center. Figure 4 indicated that as one enters the IQHE regime the current density is indeed weighted towards the edges. Figures 2 and 4 are instructive since they demonstrate that any metals connected to a defined potential or left floating, in the close vicinity of the GaAs substrate, significantly affect the electrostatic potential profile in the 2DEG. We would like to draw the attention of the reader to the fact that almost all experimental setups in which IQHE has been observed do not meet the requirement of having no gates or metallic holders, and therefore the conclusions extracted from these experiments, regarding the electrostatic potential profile in the sample, should be taken with reservation.

To conclude, we performed inductive coupling measurements on a 2DEG Hall bar sample in the IQHE regime. We showed that the gating effects completely change the electrostatic potential profile of the 2DEG, and as a result the Hall current distribution is distorted. We also found that under the conditions, where the surrounding of the 2DEG contained no metallic plates (such as the back gate), the current distribution in the IQHE regime remained the same as in the dissipative regime. No redistribution of the current was observed at the Hall plateaus. These measurements prove that the Hall current at the IQHE plateaus is carried mostly by extended bulk states located below the Fermi level. In view of our results, we believe that special care has to be taken in all experiments which aim to probe the current distribution in the dissipationless regime of the IQHE.

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