

Inductive Probing of the Integer Quantum Hall Effect

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We investigated the integer quantum Hall effect (IQHE) using an inductive method. The following conclusions can be derived from our study: (i) When the Fermi energy is located between Landau levels the only extended states at the Fermi energy are located at the physical edges of the sample. (ii) The extended states located at the bulk of the sample below the Fermi energy are capable of carrying a substantial amount of Hall current, but cannot screen an external electrostatic potential.

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Since the discovery of the integer quantum Hall effect (IQHE) [1], the role of bulk [2–5] versus edge [6–9] states has been discussed theoretically. The results of many experiments [10–15] addressing this issue seem to favor the edge picture over the bulk one. However, recent experimental studies [16–18] revived this controversial question by giving evidences supporting the bulk picture. In these studies it has been shown that the electrostatic potential varies in the bulk of the sample. It implied the existence of Hall current carried by the bulk states.

The magnetic coupling between a SQUID magnetometer and a two dimensional electron gas (2DEG) has been suggested for studies of current distributions [19]. However, this method is extremely difficult to realize experimentally since it requires the critical field H_c of the SQUID to be higher than the typical magnetic fields used in IQHE experiments. Another variation of inductive coupling has been employed in a recent experiment [20] where an external solenoid was used in order to induce azimuthal electric field in 2DEG samples patterned in a Corbino geometry. Although the authors observed well-defined Hall plateaus, they did not provide any information about the spatial distribution of the extended states at the Fermi energy.

In order to address the questions concerning the role of edge versus bulk states in the IQHE we employed an inductive coupling, different from those mentioned above. Our method utilizes a pickup coil in order to measure time-dependent magnetic fields induced by alternating currents in the sample. Although the sensitivity limitations of this method do not allow for a precise determination of the current's spatial distribution, a quantitative analysis of our data allows us to reaffirm the following important statements: (i) In the plateaus of the IQHE, the extended states at the Fermi energy are located at the edges of the sample. (ii) In this regime the bulk states at the Fermi energy are localized. However, the bulk states, at the Landau levels below the Fermi energy, may carry a substantial amount of the Hall current. The contribution of these bulk states to the Hall current depends on the details of the electrostatic potential. The latter is strongly

influenced by the geometry of the sample and by the attached contacts.

The 2DEG samples used in this study were fabricated from $\text{GaAs}_x/\text{Al}_{1-x}\text{GaAs}$ heterostructures. The electron carrier concentration and the mobility of the samples were $n = 2.1 \times 10^{11} \text{ cm}^{-2}$ and $\mu = 6.4 \times 10^5 \text{ cm}^2/\text{Vs}$ at 1.4 K, respectively. Rectangular shaped samples with typical dimensions of $10 \times 5 \text{ mm}^2$ were cleaved from the wafer and Ohmic Au/Ge/Ni contacts were alloyed at opposite sides. A 3000 turn pickup coil was placed 0.4 mm above the sample's physical edge. The effective area of the pickup coil was $5 \times 5 \text{ mm}^2$. A schematic view of the geometrical setup is shown in Fig. 1.

An alternating current at frequency ω , driven through the sample, produced an electromotive force at the same frequency in the pickup coil circuit. A grounded metallic shield made of brass foil was used to screen any direct electrostatic coupling between the pickup coil and the sample.

The voltage which develops across the pickup coil depends on the distribution of the currents in the bar and on geometrical factors of the setup. Although the value of the pickup voltage can be estimated theoretically [19] for any given distribution of the current, we have performed an experimental calibration of the response of our pickup coil. We have found that for homogeneous current distribution, at a frequency of 6.4 kHz, the voltage response of the pickup coil was $25 \text{ nV}/\mu\text{A}$. In order to demonstrate the sensitivity of the pickup coil to changes in the current distribution, we have deposited a 1000 \AA thick and $500 \mu\text{m}$ wide Au film along the periphery of a sample having the same geometry. In this case, the pickup response increased to $45 \text{ nV}/\mu\text{A}$ at the same frequency. Although this calibration gives smaller pickup response values than those calculated theoretically, the relative change of the signals between uniform and edge distributions of currents is consistent with the theoretical estimate. We believe that the discrepancy between the theoretical and experimental absolute values of the pickup response is due to partial screening of the inductive coupling by eddy currents in the

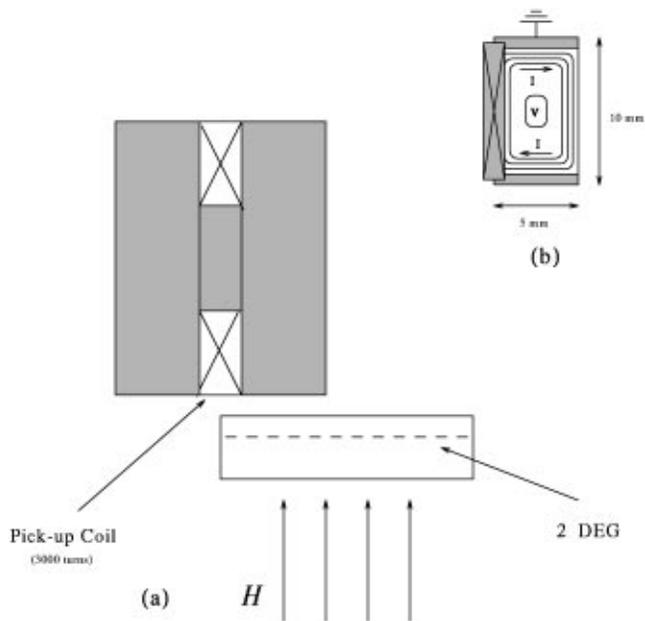


FIG. 1. The experimental setup. Lateral (a) and top (b) views of the 2DEG and the pickup coil.

metallic shield. These currents were found to be sensitive to the conductivity of the shield and varied with temperature. The calibration values mentioned above are given for low temperatures where the pickup response was found to be temperature independent. Since the distance of the shield from the sample is relatively large ($\sim 400 \mu\text{m}$) and because the dielectric constant of the media is an order of magnitude smaller than that of GaAs, we do not expect the shield to significantly alter the potential distribution in the sample.

A standard four probe measurement of the IQHE in our Hall bar samples resulted in the experimental curve for the longitudinal resistivity ρ_{xx} shown in the inset of Fig. 2. Since the lowest temperature of our experimental setup was 1.4 K and the highest magnetic field was 5.5 T, only the plateaus with $\nu = 2, 4$ showed experimentally zero values of the longitudinal resistivity ρ_{xx} .

In the first part of our investigation a metallic gate has been deposited on the bottom surface of the sample (back gate), $250 \mu\text{m}$ from the 2DEG. We have applied an alternating voltage V_g between the back gate and the 2DEG and monitored the signal in the pickup coil V_{pc} as the magnetic field H was swept in the range between -5 and 5 T. The results of this measurement are shown in Fig. 2. The amplitude and frequency of the applied gate voltage were varied in the range of 0.05 – 0.5 V and 0.2 – 30 kHz, respectively.

The peaks in V_{pc} are clearly observed for values of H for which the longitudinal resistivity vanishes. According to our calibration, the values of the peaks correspond to a current $V_g \nu e^2/h$ flowing around the periphery of the sample, where ν is the number of occupied Landau levels below the Fermi energy.

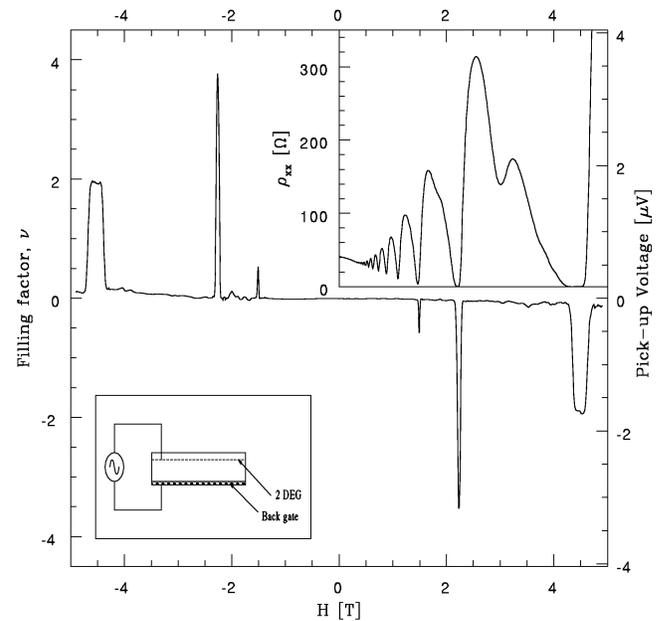


FIG. 2. Inductive voltage in the pickup coil for a back gate voltage $V_g = 0.5$ V at a frequency of 6.4 kHz. The left axis depicts the number of filled Landau levels needed to produce the same signal, assuming that the current flows within a distance of $500 \mu\text{m}$ from the edge. V_{pc} clearly shows well-resolved picks in the middle of Hall plateaus. Plateaus with $\nu = 2, 4$ are already saturated, whereas $\nu = 6$ still has nonzero longitudinal resistance. The insets show a schematic view of the sample and the longitudinal resistivity measured on the same wafer.

At first, this result seems to be surprising since for the estimated values of the capacitance of our samples such values of V_g cannot produce or modulate a Hall current of the observed magnitude. Indeed, there is no signal at the pickup coil at the entire range of the magnetic field besides the regions corresponding to Hall plateaus. The resolution to this apparent “mystery” becomes clear when one assumes that at the Hall plateaus the entire bulk of the sample becomes an insulator, while the edges are conducting. In such a situation, the electric potential of the sample should approach the value of V_g as the distance from the edge becomes larger than the distance to the back gate. Applying V_g under such conditions is equivalent to the application of Hall voltage to a Corbino geometry sample. It results in a Hall current of the observed magnitude, circulating along the sample’s boundaries. Since the direction of the current should be reversed when the polarity of the magnetic field is changed, the pickup signal should also reverse its sign under such an operation as indeed one finds by inspecting Fig. 2.

The existence of extended states in the bulk of the sample at the Fermi energy is equivalent to introducing extra edges to the sample. Furthermore, it would increase the distance from the edge at which the electric potential attains its maximal value V_g . In addition, if the extended states below the Fermi energy were able to partially screen the external voltage, the Hall voltage developed in the

sample would have been smaller than V_g . All of these effects would tend to diminish the signal measured by the pickup coil. The measured signal, however, is the largest possible since the Hall voltage cannot exceed V_g and the current cannot flow any closer to the pickup coil than along the sample's edge. This observation leads us to two important conclusions: (i) *At the Hall plateaus the only extended states at the Fermi energy are located along the sample's edges.* (ii) *The extended states below the Fermi energy, though capable of carrying Hall current, as will be shown later, cannot screen the external electric field.* This is the first direct observation of this property which is implicit in the bare existence of the IQHE. Our experimental resolution provides us with an upper bound of 0.5 mm (10% of the sample's width) to the distance from the edge in which the current flows.

Within the measuring range of applied voltages and frequencies, the signal was found to depend linearly on these parameters. However, at voltages exceeding 1 V, deviation from linearity was observed and the dependence of the signal on the applied voltage was weaker (not shown). A possible source for this nonlinearity could be the onset of the breakdown of the IQHE. Such a breakdown is expected to result in a current distribution which is extended into the bulk. This, in turn, decreases the signal measured by the pickup coil.

Although the experiment described above indicates that the Hall current flows in the vicinity of the edge, it should not be concluded that such a nonuniform distribution between the bulk and the edges is an inherent property of the IQHE. On the contrary, it is the proximity of the back gate to the 2DEG (their separation is much smaller than the dimensions of the sample) that causes the electrostatic potential to be flat far from the edges and to change by V_g in the vicinity of the sample's edges. Therefore we cannot resolve questions concerning the contribution of bulk states to the current based on this experiment.

In order to address this issue we fabricated two samples in which the back gate was replaced by additional Ohmic contacts which were alloyed in the interior of the 2DEG. In the first sample, the inner contact occupied almost its entire area, thus defining a strip of 2DEG along the edges. Such a geometry is usually referred to as Corbino geometry. The experimental setup is presented in Fig. 3. We applied a source voltage and measured the current flowing in the circuit and the voltage drop across the shunt resistor. An alternating voltage drop V_r , which developed between the inner contact and the Ohmic contact located at the sample's edge, resulted in a pickup signal that corresponded to a Hall current of the same value as in the previously described experiment, namely, $I = V_r v e^2 / h$. Figure 3 shows the pickup coil response and the Hall current calculated using

$$I_H = \frac{V_r - R_{xx} I_r}{R_{xy}} = \frac{V_{\text{source}} - V_{\text{shunt}} [1 + (R_0 + R_{xx} / R_{\text{shunt}})]}{R_{xy}}, \quad (1)$$

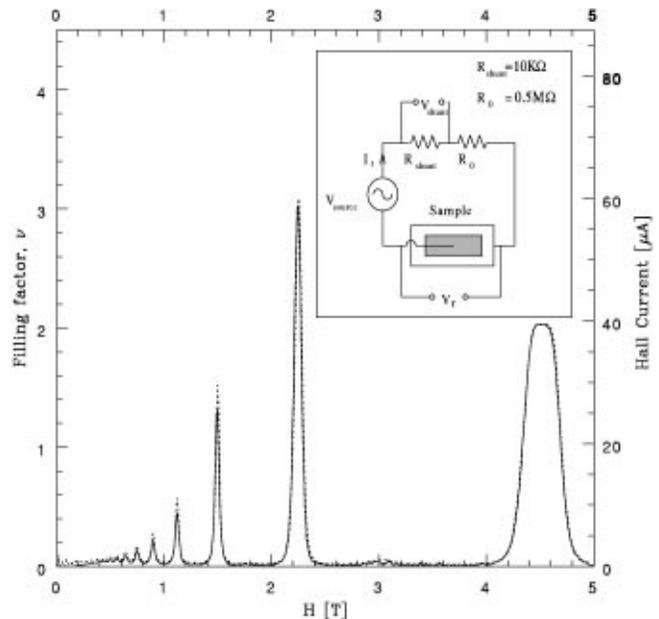


FIG. 3. Solid line—Hall current in a sample having a Corbino geometry as deduced from the pickup signal. The source voltage is 0.5 V at a frequency of 26 kHz. Dotted line—Hall current calculated according to Eq. (1). The inset shows a schematic view of the experimental measuring circuit.

where I_r is the dissipative current that flows between the inner contact and the edge. This current vanishes for Corbino geometry samples at the IQHE plateaus, and the expected value of the Hall current is $I_H = V_r / R_{xy}$. At these regions V_r equals V_{source} (cf. Fig. 3). In the dissipative regimes, namely, in between plateaus and at small values of magnetic fields, the Hall current is practically independent of R_{xx} as long as the latter is much smaller than R_0 . Since $R_0 = 0.5 \text{ M}\Omega$ and R_{xx} is of the order of ρ_{xx} , measured in Hall bar geometry, we expect this inequality to hold. Accordingly, we also expect V_r in these regions to be much smaller than V_{source} , thus resulting in a smaller signal in the pickup coil. For R_{xy} , we use the values obtained from the four probe measurement. The good agreement between the pickup signal and I_H given by Eq. (1) indicates that indeed the pickup coil measures the circulating current in the sample. One should note that the latter consists of a constant diamagnetic current and a time-dependent Hall current induced by V_r . The pickup coil is sensitive, of course, only to the second component. This measurement also provided us with an additional calibration of the pickup response, which was consistent within a few percent with the previous calibration procedure.

A second sample with two inner contacts having dimensions of $100 \mu\text{m} \times 100 \mu\text{m}$ (see inset of Fig. 4) has been measured using the same technique. The pickup signal versus the magnetic field when an alternating voltage V_{source} was applied to the device is shown in Fig. 4. The pickup coil signal at integer filling factors in this case dropped significantly relative to the value measured for the sample shown in Fig. 3. Since the total Hall current

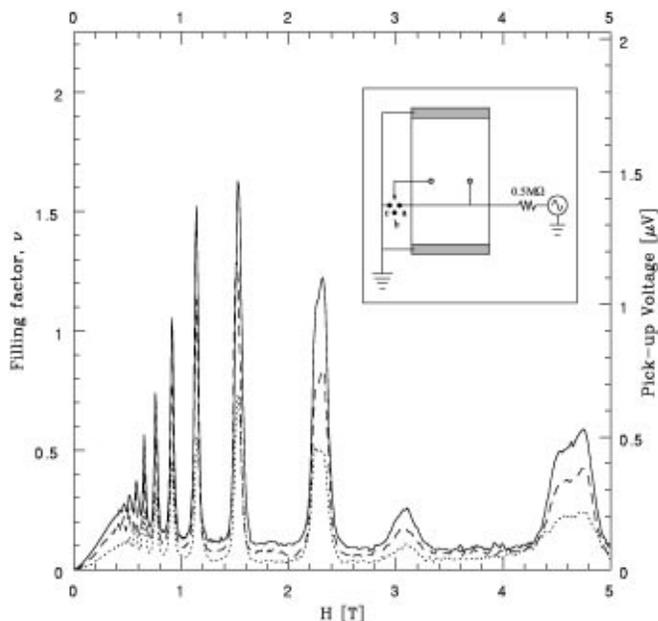


FIG. 4. Pickup coil signal for various contact configurations as shown in the inset. The source voltage is 0.5 V at a frequency of 26 kHz. (a) Solid line—voltage applied to both point contacts. (b) Dashed line—one contact left floating. (c) Dotted line—one contact grounded.

in this configuration should be the same in both cases, the only possible explanation is a spatial redistribution of the current. Moreover, the signal detected by the pickup coil varies considerably for different realizations of the circuit as depicted in Fig. 4. For configuration (c) the signal is smaller by an order of magnitude relative to the signal measured in the case of the sample with the large inner contact. This undoubtedly proves that Hall current is carried by bulk states. As far as we know, this is the first direct experimental evidence for bulk current in the IQHE. Although the spatial resolution of our technique does not allow for a precise determination of the current distribution, we can set an upper bound for the edge current. Under the assumption that the only contribution to the pickup signal is due to edge states, we find that, at most, 10% of the total Hall current is carried by the edge. However, it is more reasonable to conclude that the actual fraction carried by the edge is much smaller (if not zero [21]) and the entire signal in the pickup coil is due to bulk current. The results for the different configurations of contact connections indicate that the current distribution in the sample depends on the details of the electrostatic potential, which can be strongly influenced by the geometry of contacts, the presence of gates, etc.

We would like to emphasize that our conclusions about the role of edge versus bulk states apply to Corbino

geometry samples, and further investigation addressing this problem for the Hall bar geometry is required. The main difference between the two geometries, at the IQHE regime, is the necessity to inject external current from the Ohmic contact into the 2DEG for the Hall bar geometry. The current injection mechanism could significantly enhance [22] the role of the edge currents.

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