Evidence for Edge Currents in the Integral Quantum Hall Effect

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In high-mobility GaAs/As$_x$Ga$_{1-x}$As heterostructures at magnetic fields below well-developed integral quantum Hall-effect plateaus, we have observed that the magnetoresistance is independent of the device channel width in sufficiently small channels. Additionally, the current distribution within the channel depends on the total current magnitude and direction. We interpret our observations with a model in which current flows primarily along the edges of the sample when small currents are applied.

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The integral quantum Hall effect (IQHE) is generally understood to be a bulk phenomenon that is independent of the boundaries and the shape of the region in which the two-dimensional electrons are confined. Nevertheless, some observations are in conflict with this view. Zheng *et al.*[1] have reported that the shape of the Shubnikov–de Haas (SdH) oscillations in high-mobility samples becomes strongly asymmetric in narrow channels, with ρ_{xx} suppressed below well-developed Hall plateaus. The onset of this asymmetry is observable at channel widths much larger ($w=1$ mm) than any microscopic scale relevant to the problem. Woltjer *et al.*[2] have observed that in regions where ρ_{xx} is suppressed, it is also strongly current dependent. While Haug, Klitzing, and Ploog[3] have developed a theory of the SdH asymmetry based on an asymmetric bulk density of states, they have been unable to account for the size effect.

Another observation difficult to reconcile with a bulk picture of the IQHE is the appearance of structure at anomalously low voltages seen by Kirtley *et al.* in the breakdown of the IQHE dissipationless state.[4] While these measurements were primarily conducted on samples with constrictions a few micrometers wide, the authors reported seeing similar structure in samples where the current was not confined to a narrow region. It is difficult to understand these observations unless most of the voltage drops across small regions within the sample and the current flow is highly nonuniform. Recently, measurements of the low-frequency noise in the IQHE regime have also suggested that the current distribution is nonuniform below Hall plateaus.[5]

In order to understand better the apparent deviations from uniform bulk behavior in the IQHE, we have investigated the dependence of the magnetoresistance, R_x, on channel width and current in high-mobility GaAs/Al$_x$Ga$_{1-x}$As single-interface heterostructures. We find that in channels narrower than 100 μm, R_x is independent of channel width at magnetic fields below plateaus where $R_x \rightarrow 0$ when small currents are passed through the channel. When the channel current is increased, R_x increases abruptly in a manner similar to the dissipationless breakdown behavior observed by Kirtley *et al.* We have also measured in larger samples the dependence of the internal current distribution on the total channel current using internal contacts. Our data indicate that the current distribution is sensitive to the direction of the Hall electric field. We believe that nearly dissipationless currents traveling along sample edges, where the carrier density is substantially depleted, can provide a natural explanation for the observations we have discussed.

Our experiments were performed on n-type devices with mobility $\mu=290000$ cm^2/V s and carrier density $n=5.8\times10^{11}$/cm^2. All data were taken at 4.2 K. To measure dV/dI an ac modulation technique was used: A 10-nA ac current at 425 Hz was added to a dc bias current and the sum was passed through the sample. Voltage differences between contacts at the modulation frequency were measured with a lock-in amplifier. For magnetic-field–dependent data, the dc bias current was held constant while the magnetic field was swept. For current-dependent data, the superconducting magnet was placed in persistent mode and the bias current was swept. For all measurements, the contacts were made of indium alloyed at 400 °C for 5 min in hydrogen.

To observe the width dependence of R_x, a device was fabricated containing several channels of differing widths in series with one another (Fig. 1). The data show strikingly that there exist two mechanisms of conduction in these devices: At low magnetic fields and at magnetic fields immediately above Hall plateaus, R_x scales inversely with channel width, consistent with bulk conduction in the channel. Immediately below plateaus where $R_x \rightarrow 0$, however, R_x is independent of channel width, indicating that the current travels along a fixed number of "filamentary" paths. When 10 μA is passed through the channels, bulk conduction occurs at all magnetic

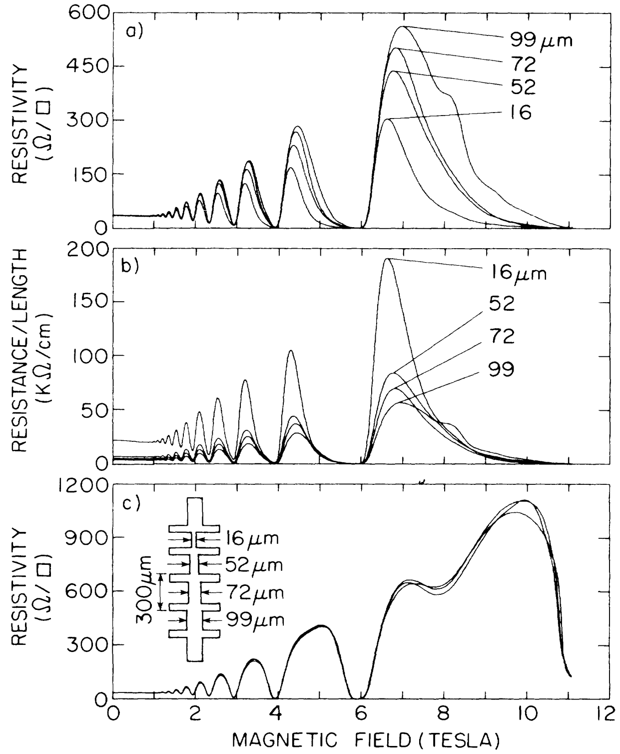

FIG. 1. Differential magnetoresistance of channels of varying width as a function of magnetic field. (a) The zero-current resistivity, (b) the zero-current resistance/length, and (c) the resistivity at $I = 10\ \mu$A. The $\nu = 4$ plateau occurs at 6 T in this sample.

fields.

When the channel current is increased, the transition from filamentary current flow to bulk current flow is abrupt and strongly reminiscent of the breakdown of the dissipationless state observed by Kirtley *et al.* (Fig. 2). While the critical current we observe is comparable to $I_c = \hbar\omega_c/eR_{\rm H}$ (about 1.5 μA in our sample; $\hbar\omega_c$ is the cyclotron energy and $R_{\rm H}$ is the Hall resistance), we find that I_c depends significantly on magnetic field. At higher currents, R_x approaches a constant, bulk value, although structure like that seen in Fig. 2 is not uncommon. R_x can also have multiple minima, as is seen in Fig. 3(a). While repeatable within a given run, magnetoresistance structure is not generally the same if the sample is warmed to room temperature and cooled again subsequently.

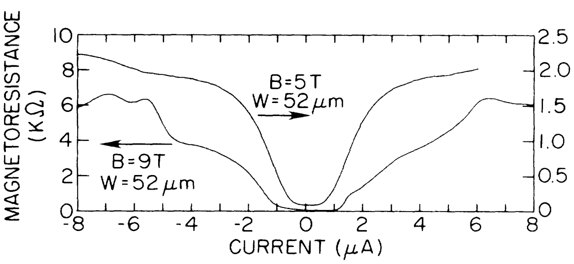

FIG. 2. Current-dependent differential magnetoresistance below the $\nu = 2$ plateau. R_x rises abruptly at a critical current and eventually approaches a constant value at about 10 μA.

If current is not flowing evenly within a device below Hall plateaus, it is of interest to know the current distribution within the device. Previous measurements[6-8] were conducted on large samples with $I \cong 10\ \mu$A, where the effects of filamentary current flow are unlikely to be observed. Unfortunately, to make current-distribution measurements with internal contacts in samples small enough ($w \cong 100\ \mu$m) for the effects to be large is difficult technically, and the placement of the internal contacts is liable to affect the current distribution significantly. Instead, we have attempted to observe small current-dependent effects in internal potentials in a large sample. Contacts were made on the edges and in the center of a 1-mm-wide piece of unetched material [see Fig. 3(a)]. The measurements were made far enough from the plateau region so that the impedance of internal contacts was not large enough to affect the results.

Figure 3 shows the current dependence of R_x, $R_{\rm H}$, and

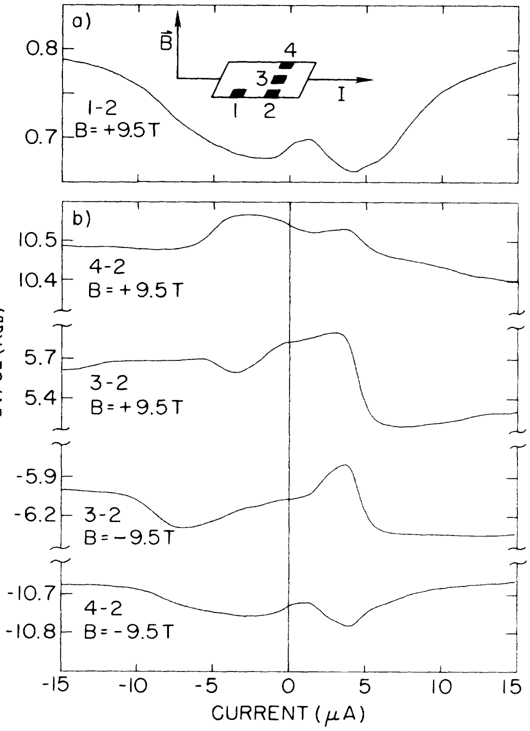

FIG. 3. Current-dependent dV/dI below the $\nu = 2$ plateau for various pairs of probes on a sample of width 1 mm. The separation of the contacts on the edge is 1 mm. The arrows designate the directions of positive I and $\mathbf{B}$. Conditions for the top traces and the bottom traces of (b) are identical except that the magnetic field is approximately reversed.

the internal potential, dV_{32}/dI, for both polarities of **B** at 9.5 T. While irregular structure is visible in all three quantities, its magnitude is largest in dV_{32}/dI. Also, the approximately symmetric structure seen in R_x and R_H is accompanied by antisymmetric structure in dV_{32}/dI. Since terms proportional to either R_x or R_H could not produce a larger, antisymmetric term, we conclude that structure seen in dV_{32}/dI is a consequence of a varying current distribution. The current distribution appears to depend on the Hall electric field: between $I=-3$ and $+3$ μA, dV_{32}/dI increases for both polarities of **B**, implying that the current distribution shifts toward the negative edge of the sample.

We believe that the most likely explanation of the data is that nearly dissipationless currents can flow along the channel edges at magnetic fields below well-developed Hall plateaus. Most theoretical work[9-11] on edge currents in the IQHE was focused on phenomena within a few magnetic lengths $[l_B \equiv (\hbar c/eB)^{1/2} \simeq 100$ Å] of abrupt boundaries. However, experimental evidence is accumulating[12,13] that edge depletion widths of about $\frac{1}{2}$ μm occur in GaAs/Al$_x$Ga$_{1-x}$As heterostructures. We hypothesize that there exist, near channel edges, regions large compared with l_B where the carrier density is significantly less than the bulk value (Fig. 4). Within these regions the Landau-level description of single electron states remains valid, and the existence of energy gaps allows the IQHE to occur. Because of their diminished electron density, however, these regions reach Hall plateaus at magnetic fields below the bulk plateaus. In a long channel where the carrier density is the same along the length of the channel, but the density can depend on the distance from the edge, the component of the electric field in the direction of the channel, E_x, and hence the product $\rho_{xx}J_x$, must be the same everywhere. Below a bulk plateau, ρ_{xx} is very much smaller at the edges than in the interior. Consequently, large current densities will occur near edges, and the edges will effectively short-circuit the interior unless the channel is very wide. When most of the current is traveling along the edges, R_x will not depend on the channel width. Only when large currents are passed through the sample, causing the edges to become dissipative, will the current distribution become uniform.

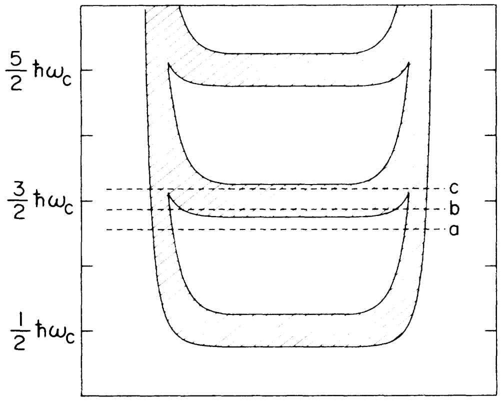

FIG. 4. Schematic representation of the energy levels in an IQHE device with finite width. The effects of spin are neglected. The hatched areas denote extended states. The Fermi level, E_F, moves upwards as **B** is reduced. At *a*, E_F is in an energy gap throughout the device and transport across the device is dissipationless. When E_F is at *b*, dissipation can occur in the interior, but not at the edges. The edges short-circuit the bulk. When E_F is at *c*, dissipation can occur throughout the device and current flow is uniform. Notice that the effective energy gap separating Landau levels must vanish near the edges.

The variation of the current distribution we observed is probably a consequence of the effect of the Hall voltage on the edges. To create the Hall voltage across the sample, carriers must accumulate on one edge and be depleted on the other. Thus, the Hall voltage could induce a difference in the conductivity of the two edges that would appear as an antisymmetric current dependence of the current distribution.

The edge-current model can explain some details in our data we have not yet considered. Asymmetries in the data observable in Figs. 2 and 3 probably result from difference in the current-carrying qualities of the two edges of the channel. The structure in the wide sample (Fig. 3) occurs at higher currents than in narrow samples because only a fraction of the current is traveling along the edges, so that edge-current breakdown occurs at higher total currents. It is noteworthy that phenomena we believe are related to edge currents have been seen in etched and unetched samples, as well as in pseudo-Corbino-geometry samples, where the edge is defined by the indium contacts. Thus, edge effects are not strongly dependent on the exact origin of the edge discontinuity.

We have heretofore neglected spin because we believe that it enters only peripherally into the problem. Presumably, dissipationless edge currents cannot occur unless a dissipationless state associated with the same Landau level can occur in the bulk. At common experimental temperatures and magnetic fields, R_x minima are much less well developed for odd-numbered plateaus than for even-numbered plateaus. Consequently, edge effects are important only below even plateaus, giving SdH data an apparent spin asymmetry.

Haug, Klitzing, and Ploog[3] have shown that the asymmetry in the SdH oscillations reverses itself when the carrier density is increased with a back gate. This is a consequence of the fact that the charge distribution on a finite charged two-dimensional conductor is not uniform. In fact, for a disk, it is singular at the edge.[14] If one increases the charge density with a back gate, the charge density at the edges will begin to exceed the bulk value. At this point the edge effects will begin to be observable above Hall plateaus.

Further experiments will be necessary to understand the nature of the edge states and the mechanisms of their breakdown. Experiments in devices where the number-density discontinuity can be varied with a gate, such as those fabricated by Syphers and Stiles,[15] would be especially interesting. It is also of interest to determine whether the energy gap associated with the fractional quantum Hall effect can survive near such discontinuities.

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