Observation of Chiral Surface States in the Integer Quantum Hall Effect

D. P. Druist,[1] P. J. Turley,[1] K. D. Maranowski,[2] E. G. Gwinn,[1] and A. C. Gossard[2]
[1]*Physics Department, University of California, Santa Barbara, California 93106*
[2]*Materials Engineering Department, University of California, Santa Barbara, California 93106*
(Received 5 June 1997)

We have made experimental studies of low-temperature, high-magnetic field electronic transport in layered, three-dimensional semiconductor structures. In fields that produce the integer quantum Hall effect for transport parallel to the layers, we find deep minima in the vertical conductance G_{zz}. Between these quantum Hall states, the size dependence of G_{zz} indicates that vertical transport is through the bulk. Within quantum Hall states, we find that vertical transport is along the surface of the sample, via a "sheath" of extended surface states. This surface sheath is a novel two-dimensional system that exhibits a metallic conductivity $\ll e^2/h$. [S0031-9007(97)04945-4]

PACS numbers: 73.40.Hm, 73.20.Dx

The combined effects of dimensionality and disorder produce a rich variety of behavior in electronic transport [1]. In two dimensions (2D), it is now well accepted that quantum interference generally eliminates diffusive transport in the limit of low temperatures, so that in the absence of a magnetic field, all electronic states are localized at $T = 0$ [2]. For 2D metals in quantizing magnetic fields, the extended states that lie at isolated energies near the centers of the Landau levels produce diffusive transport, and a temperature-independent dissipative conductivity $\sigma_{xx} \sim e^2/h$, when the Fermi energy E_F lies at these special energies [3]. However, away from these transitions between quantum Hall plateaus, σ_{xx} vanishes at low temperatures, T. Generally, when the conductivity of a 2D system is well below e^2/h, transport is expected to be strongly T dependent, and insulating at $T = 0$.

Recent theoretical studies [4,5] discussed the possibility of creating a novel 2D system in which diffusive transport can coexist with conductivities $\ll e^2/h$. This unusual 2D system forms from the edge states at the sidewalls of three-dimensional (3D), anisotropic conductors in the regime of the integer quantum Hall effect (IQHE). Here, we use multilayer semiconductor structures to look for evidence for this low-conductivity, metallic surface state.

Experimental work on semiconductor multilayers in the 1980s [6] established that the IQHE can occur in anisotropic, 3D conductors. In semiconductor multilayers, the growth parameters determine the coupling between a stack of 2D sheets of electrons. For no coupling, in quantizing magnetic fields perpendicular to the layers, the bulk density of states for each layer is that of a 2D quantum Hall system, with extended states at the center of each Landau level, and localized states in between. Interlayer coupling merges these isolated extended states into bands with widths that depend on the strength of the interlayer coupling, and on the disorder strength [7] [Fig. 1(a)]. If the extended states bandwidth t is smaller than the 2D quantum Hall gap Δ, regions of localized states should lie between the extended states bands. Tuning E_F through the different types of states, by varying the magnetic field, yields a series of phases. For E_F in an extended states band, a 3D metallic state is expected [4]. For E_F between extended states bands, theory predicts a quantum Hall (QH) state, with vanishing bulk diagonal conductivities, and $\sigma_{xy} = ije^2/h$, where i is the Landau level index, and j is the number of layers [4].

Quantization of in-plane transport in QH states has been well documented by Stormer *et al.* [6], using a semiconductor multilayer with relatively strong coupling between the layers. Studies of vertical transport in these multilayers [8], at relatively high T (to $\sim$300 mK), led this early work to conclude that, within the QH states, vertical transport freezes out at low T, consistent with the expectation that the bulk, vertical conductivity $\sigma_{zz} \to 0$ as $T \to 0$.

A vanishing vertical conductivity in the *bulk* does not necessarily imply absence of vertical transport across the multilayer. Although all bulk states at E_F should be localized in QH states, the sidewalls of multilayer samples introduce surface states that must be extended around the perimeter, in order for the in-plane transport to be quantized. For a stack of decoupled 2D electron gases, these surface states are the well-known gapless edge states, and lie at the perimeter of each layer.

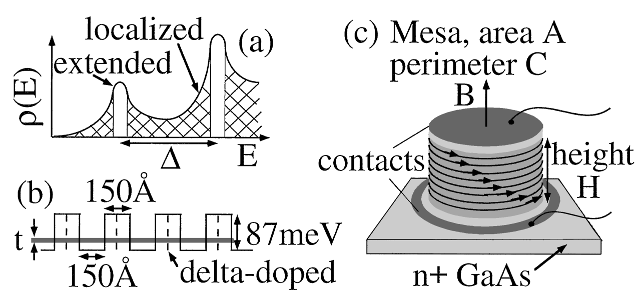

FIG. 1. (a) Density of states for anisotropic, three-dimensional conductors in quantizing fields. Extended states bands exist near the centers of Landau levels, with localized states in between. (b) Multilayer structure used in this experiment. The bandwidth t is $\sim$0.12 meV. (c) Schematic of samples used to probe vertical transport.

Coupling the edge states by interlayer tunneling forms a 2D, chiral sheath of extended states at the sidewalls of the sample. In the IQHE regime studied here, the edge states on decoupled 2D electron gas layers effectively act as 1D Fermi gases, so weakly coupling the layers should yield a 2D Fermi liquid surface phase. In this case, even if the sheath conductivity is much less than e^2/h, the surface sheath may remain conducting to $T = 0$, unlike the case of an "ordinary" 2D system. This qualitatively different behavior of the chiral surface sheath can occur because the ballistic, single-direction transport around the perimeter suppresses localization, allowing diffusive transport perpendicular to the layers [4,5].

To investigate the chiral surface sheath, we use a pair of $GaAs/Al_{0.1}Ga_{0.9}As$ multilayer structures that were grown by molecular-beam epitaxy in the same growth cycle, one immediately after the other. Each structure contains 50 periods of 150 Å GaAs quantum wells that alternate with 150 Å $Al_{0.1}Ga_{0.9}As$ barriers (Si delta doped at their centers), so that the period of the multilayer structure is $d = 300$ Å [Fig. 1(b)], and the height $H = 1.5\ \mu$m. A simple Kronig-Penney analysis of the structure yields a width $t = 0.12$ meV for the lowest band. From the measured sheet density, we estimate $E_F \sim 10$ meV, well below the second band.

The structure used for studies of in-plane transport, wafer A, was grown on a semi-insulating GaAs substrate. We patterned pieces from near the center of wafer A into Hall bars with diffused In contacts. The structure used for studies of vertical transport, wafer B, has degenerately doped $n+$ (2×10^{18} cm^{-3}) GaAs layers above (3000-Å thick) and below (4000-Å thick) the multilayer. Wafer B has 50 Å, $n+$ (2.5×10^{17} cm^{-3}) matching layers directly above and below the outermost, delta-doped 150 Å barriers, to reduce overfilling of the top and bottom layers. As shown in Fig. 1(c), we wet etched a piece from near the center of wafer B into 6 mesas, stopping the etch within the lower 2×10^{18} cm^{-3} $n+$ GaAs layer. A briefly alloyed AuNiGe contact covers the top of each mesa. The bottom, alloyed AuNiGe contact pads rest on the etch-exposed surface of the lower 2×10^{18} cm^{-3} $n+$ GaAs layer.

The six vertical transport mesas have different sizes and shapes, which we use to determine the nature of vertical transport (surface or bulk) through the multilayer. Four mesas are squares, with sides of length 100, 150, 200, and 500 μm. One mesa was a rectangle with dimensions 850 μm $\times$ 150 μm. The sixth mesa had a serpentine shape, with perimeter $C = 7200\ \mu$m and area $A = 422\,000\ \mu$m^2. We made all measurements of vertical transport with the samples in good thermal contact with the mixing chamber of a dilution refrigerator fitted with filters at 300 K and at 1.2 K. The measurements used the same configuration we recently employed to reach electronic temperatures below 50 mK in surface-gated point contact samples in the fractional quantum Hall effect [9]. For all vertical transport measurements on multilayer samples, the excitation was kept below 10 μV (or $<3 \times 10^{-16}$ W in the 100 μm square sample at 50 mK). The 50 mK IV characteristics were linear to more than 10 times this excitation.

Figure 2(a) shows that in-plane transport (wafer A), with the magnetic field perpendicular to the layers, is well quantized at low temperatures. The low-field mobility of the sample is $\mu \sim 15\,000$ cm^2/V s, and the slope of the low-field Hall resistance gives a sheet density $N_s = 1.15 \times 10^{13}$ cm^{-2}, assuming a Hall factor of 1, for an average sheet density of 2.3×10^{11} cm^{-2} per layer over the 50 layers. As shown, plateaus in the Hall resistance R_H accompany minima in the longitudinal resistance R_L. For fields above 3 T, small peaks in R_L flank much larger peaks. These large (small) peaks in R_L accompany large (small) changes in R_H; for example, from 6 to 7.5 T, R_H nearly doubles, while from 8 to 9 T, R_H changes by $\sim 2\%$. We believe that the small peaks in R_L appear where E_F sweeps past isolated, bulk extended states associated with the outermost layers of the multilayer. These end layers can have very different density from the inner layers, and their extended states are not expected to be assimilated into the band of extended states formed from the interior of the multilayer [10]. The change in R_H across the strong peak in R_L near 7 T indicates that for wafer A each extended states band contains 47 states. The arrangement of features in the $\sim 6-8$ T range in Fig. 2(a) suggests that an end-state layer lies near each edge of an extended states band. The numbers above the Hall plateaus in Fig. 2(a) give the number of extended states below E_F, as deduced from the Hall resistance. The prominent QH states, which become well quantized at higher temperatures than the

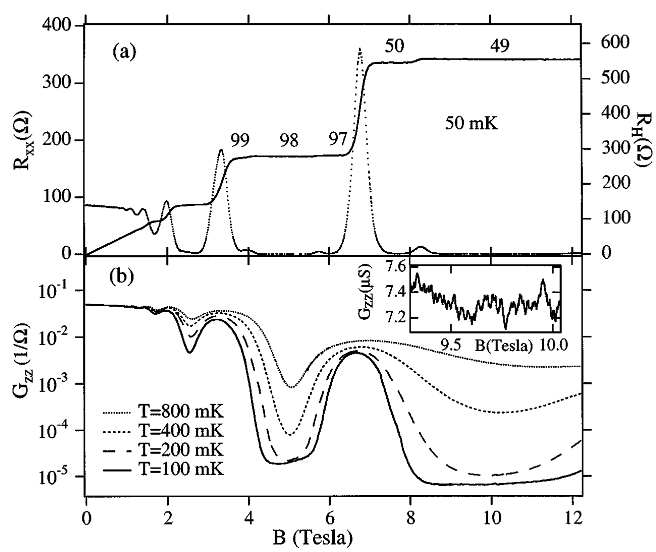

FIG. 2. (a) In-plane transport at 50 mK. Plateaus in the Hall resistance R_H accompany minima in the longitudinal resistance R_L. Numbers above Hall plateaus give the number of extended states below E_F. (b) Vertical conductance G_{zz} of the 150 μm square mesa at different temperatures versus magnetic field. In QH states, G_{zz} saturates to a finite low-temperature value when the surface states dominate transport.

secondary plateaus, appear to be those for which all states of a given Landau index lie below E_F.

Figure 2(b) shows the dependence of the vertical conductance G_{zz} (wafer B) on the magnetic field, which is perpendicular to the layers, at several temperatures, for the 150 μm square mesa (other mesas showed the same field dependence). G_{zz} exhibits pronounced peaks between the prominent QH states that appear in wafer A's in-plane transport, and deep minima within these QH states. Unlike the in-plane transport data, G_{zz} shows no features flanking its strong maxima. Apparently, either G_{zz} is insensitive to the states associated with the end layers, which should not penetrate significantly into the multilayer, or the different boundary conditions in wafer B incorporate the end layer states into the extended states bands (or both). In what follows, we refer to the QH states between peaks in G_{zz} by their Landau index i only.

Figure 3 shows that between QH states the conductance behaves qualitatively as expected for the predicted 3D metallic phase [4]. In Fig. 3(a), we plot the temperature dependence of G_{zz} at 6.7 T, between the $i = 1$ and $i = 2$ QH states, and at 3.2 T, between the $i = 2$ and $i = 4$ QH states. G_{zz} first decreases gradually as the temperature falls, and then is very weakly T dependent, approaching saturation at the lowest temperatures for the 6.7 T data. As shown in Fig. 3(b), measurements at 50 mK of G_{zz} for the six mesas give $G_{zz} \propto A$, where A is the mesa area, indicating transport through the bulk, and a 3D conducting state.

Within QH states, the behavior of G_{zz} is qualitatively different from that in the intervening 3D phases. As the temperature falls, G_{zz} in the QH states initially drops rapidly, as expected if conduction through the bulk of the multilayer is freezing out [Fig. 2(b)]. As the temperature falls below $\sim$200 mK, however, the conductance at the centers of the QH states appears to be approaching a constant value. The Arrhenius plot of G_{zz} for the 100 μm square mesa in the $i = 1$ (10 T) and $i = 2$ (5.0 T) QH states in Fig. 4(a) shows a roughly activated form for G_{zz} at high temperature that settles to a nearly constant, finite value at low T. Larger mesas had similar temperature dependence, as did data taken at different magnetic fields in the QH states.

To investigate the nature of vertical conduction in the QH states, we measured G_{zz} for the six different mesas at 4.75 T ($i = 2$ QH state) and at 10 T ($i = 1$ QH state). For temperatures within the activated region in Fig. 4(a), we find $G_{zz} \propto A$, indicating that transport is primarily through the bulk at high temperature.

Figure 4(b) shows that, in the low temperature nearly constant conductance regime of the QH states, transport is along a sheath of states at the *surface* of the mesas. We plot G_{zz} versus mesa *perimeter* C and find $G_{zz} \propto C$, as indicated by the straight line of slope one on the log-log plot. In contrast, graphing $\log(G_{zz})$ versus $\log(A)$ yields a plot with large scatter, in which the mesas with the same shape (square) have conductances that fall on a straight line with a slope of $\frac{1}{2}$. This dependence of conductance on mesa perimeter C indicates that transport is over the surface, rather than through the bulk, of the multilayer.

The magnitude of the low-T G_{zz} and its lack of strong temperature dependence in the QH states show that the

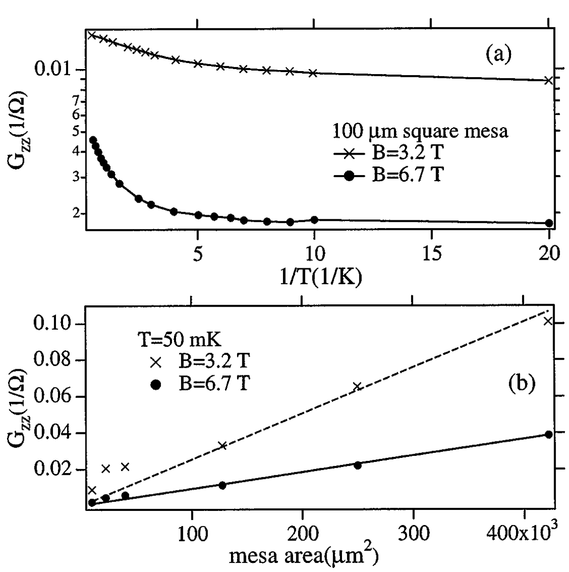

FIG. 3. Behavior of G_{zz} in the transitional phases between QH states. (a) Arrhenius plot of G_{zz} (100 μm square mesa), between $i = 1$ and $i = 2$ QH states (6.7 T) and between $i = 2$ and $i = 4$ QH states (3.2 T). (b) Dependence of G_{zz} on mesa area A at 6.7 and 3.2 T. The linear dependence of G_{zz} on A indicates that the current is flowing through the bulk of the mesa.

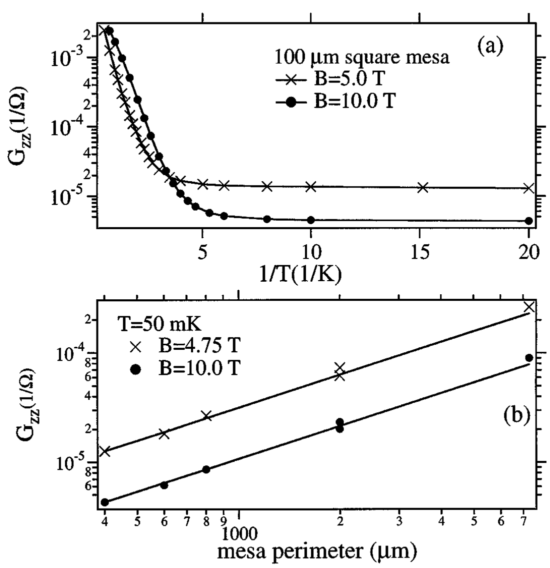

FIG. 4. Behavior of G_{zz} within QH states. (a) Arrhenius plot of G_{zz}. Above $\sim$200 mK, G_{zz} is roughly activated, but at lower temperature it flattens out as the surface sheath dominates transport. (b) Log-log plot of G_{zz} versus mesa perimeter C in the $i = 1$ and $i = 2$ QH states. Good fits to lines with slope = 1 show that G_{zz} is proportional to C, indicating that the current flows on the surface of the mesas.

surface sheath is an unusual 2D system that exhibits metallic conductivity $\ll e^2/h$. Since $G_{zz} \propto C$, the surface sheaths on our mesas all have the same sheet conductivity $\sigma_{zz,\square} = (H/C)G_{zz}$, where $H = 1.5$ μm is the height of the multilayer. We find $\sigma_{zz,\square} \sim 4 \times 10^{-4} e^2/h$ for the $i = 1$ QH state, and $\sigma_{zz,\square} \sim 1.2 \times 10^{-3} e^2/h$ for the $i = 2$ QH state. One might expect the conductivity for $i = 2$ to be twice that at $i = 1$, because two sheaths of edge states contribute to vertical transport at $i = 2$. However, Balents and Fisher [5] have shown that each layer of the sheath has $\sigma_{zz,\square} = (e^2/h)[t^2 \ell d/(\hbar^2 v_{\mathrm{edge}}^2)]$, where ℓ is a mean-free path and v_{edge} is the edge velocity. Because v_{edge} and ℓ may be different for different layers of the surface sheath, and for different fields, it is unclear what to expect for the relative magnitudes of the vertical sheet conductivities in the $i = 1$ and $i = 2$ QH states.

Qualitatively, the suppression of localization on these low-conductivity surface sheaths is due to the handedness of the transport around the sheath. In order to localize, an electron must be able to return to its starting point without losing phase coherence. Because transport around the sheath is in one direction only, localization requires at least one full turn around the perimeter—a macroscopic distance in our samples. Nonetheless, one might expect the onset of localization, and steep T dependence in G_{zz}, for large enough H [4], at low enough T that the phase coherence length around the sheath approaches C [4,11].

Recent theoretical studies show that the sheath's mean conductance $\langle G_{zz}\rangle$ at $T = 0$ should cross over from metallic behavior, with $\langle G_{zz}\rangle = (C/H)\langle\sigma_{zz,\square}\rangle$, to 1D localized behavior, with $\langle G_{zz}\rangle \propto \exp(-H/\xi)$, for H greater than a localization length ξ [4,12–14]. The localization length is proportional to the perimeter C and to the sheath's sheet conductivity: $\xi = 4C\sigma_{zz,\square}/(e^2/h)$ [11–13]. In order of increasing perimeter, the six vertical transport mesas have $\xi/d = 22$, 33, 44, 110, 110, and 380, relative to the height $H/d = 50$ of the multilayer. The largest three samples have $\xi/d > 50$, and should display a metallic size dependence $G_{zz} \propto C$ with G_{zz} tending to a finite, constant value at low T, as observed. For the small samples with $\xi/d < 50$, at sufficiently low temperatures one would expect a crossover to localized size dependence, $G_{zz} \propto \exp(-\mathrm{const}/C)$, with sheet conductivities below that of the $\xi/d > 50$ samples. These expectations disagree with our observation of $G_{zz} \propto C$ and a constant $\sigma_{zz,\square}$ for all samples. This absence of observable localization effects suggests that the phase coherence length around the sheath L_ϕ is much less than C to the lowest temperatures studied [13], which is unsurprising, given that $C = 400$ μm in the smallest sample.

We also observe reproducible fluctuations in G_{zz} as the magnetic field is varied within the QH states, as shown in the inset in Fig. 2(b) (100 μm square mesa at 50 mK). We believe that a field component perpendicular to the sheath causes the interference that produces these fluctuations: The wet etch used to define the mesas yields sidewalls that are not vertical, so that the field applied perpendicular to the layers has a component normal to the sheath. The root-mean-square amplitude of the fluctuations is very small (e.g., $\delta G_{zz} \sim 5 \times 10^{-3} e^2/h$ at 50 mK for the 100 μm square mesa), consistent with $L_\phi \ll C$.

In conclusion, we have explored the transport properties of an anisotropic 3D conductor in the regime of the IQHE. Scaling with sample size and temperature indicates 3D metallic phases between QH states. Within QH states, we find that transport is along a 2D surface sheath with conductivity $\ll e^2/h$ at low temperatures. The surface sheath exhibits small, reproducible conductance fluctuations as the magnetic field is varied within the QH states.

We acknowledge helpful conversations with L. Balents, M. P. A. Fisher, S. J. Allen, and S. Cho. This work was supported by NSF DMR 9314899, and by QUEST, an NSF Science and Technology Center.

[1] P. A. Lee and T. V. Ramakrishnan, Rev. Mod. Phys. **57**, 287 (1985), and references therein.
[2] This is strictly true only in the noninteracting limit. Recent work on Si MOSFETS has found evidence for a zero-field metal-insulator transition. Even in this system, if the conductivity falls well below e^2/h, insulating behavior is found at low T [D. Popovic *et al.*, cond-mat/9704249].
[3] B. Huckestein, Rev. Mod. Phys. **67**, 357 (1995).
[4] J. T. Chalker and A. Dohmen, Phys. Rev. Lett. **75**, 4496 (1995).
[5] L. Balents and M. P. A. Fisher, Phys. Rev. Lett. **76**, 2782 (1996).
[6] H. L. Stormer *et al.*, Phys. Rev. Lett. **56**, 85 (1986).
[7] T. Ohtsuki, B. Kramer, and Y. Ono, J. Phys. Soc. Jpn. **62**, 224 (1993); M. Hennecke, B. Kramer, and T. Ohtsuki, Europhys. Lett. **27**, 389 (1994).
[8] H. L. Stormer *et al.*, in *Proceedings of the 18th International Conference on the Physics of Semiconductors, Stockholm, 1986*, edited by O. Engstrom (World Scientific, Singapore, 1987), p. 385.
[9] P. J. Turley *et al.*, Physica B (to be published). Point contacts are particularly sensitive to heating by stray signals, which can drive very large current densities through the constriction. In our system, the point contact conductance at $\nu = \frac{1}{3}$ showed a steep T dependence to below 50 mK, consistent with theoretical predictions [K. Moon *et al.*, Phys. Rev. Lett. **71**, 4381 (1993)].
[10] S. E. Ulloa and G. Kirczenow, Phys. Rev. B **37**, 8337 (1988).
[11] M. P. A. Fisher (private communication).
[12] L. Balents, M. P. A. Fisher, and M. R. Zirnbauer, Nuc. Phys. **B483**, 601 (1997).
[13] I. A. Gruzberg, N. Read, and S. Sachdev, Phys. Rev. **B55**, 10 593 (1997).
[14] For $H < \xi$, there are small corrections to the leading order result $\langle G_{zz}\rangle = (C/H)\langle\sigma_{zz,\square}\rangle$ that depend on a second, C-dependent length L_0, which is the vertical distance diffused in one ballistic round trip around C [13]. All of our samples have $L_0 < H$.