Evidence of Inter-Landau-Level Tunneling in the Integral Quantum Hall Effect

B. E. Kane and D. C. Tsui
Physics Department, Princeton University, Princeton, New Jersey 08544

and

G. Weimann
Forschunginstitut der Deutschen Bundespost, D-6100 Darmstadt, Federal Republic of Germany

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We have investigated conduction across electron density discontinuities induced by a front gate on GaAs/Al$_x$Ga$_{1-x}$As single-interface heterostructures in the integral quantized Hall regime. When the gate is biased so that the Fermi level must cross between adjacent Landau levels at the gate edge, the boundary between higher- and lower-density regions behaves like a backward diode, suggesting the presence in these devices of inter-Landau-level tunneling.

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While electronic transport in the integral quantized Hall regime has by now been thoroughly studied,[1] most work has been confined to systems in which the carrier density is uniform. Nevertheless, density inhomogeneities in the two-dimensional electron gas (2DEG) can have important consequences. Recently, we have shown[2] that current can flow chiefly along the edges of 2DEG channels in the integral quantized Hall regime, probably because of the large density gradients occurring there. Woltjer *et al.*[3] have proposed an explanation for the integral quantized Hall effect in which electron density fluctuations, not localization, account for the presence of Hall plateaus. Syphers and Stiles[4] undertook an investigation of the potential distribution in contiguous regions of differing electron density, but failed to address the question of conduction across the density discontinuity.

We have investigated the current-voltage (*I*-*V*) characteristics of abrupt density discontinuities in the integral quantized Hall regime. We have found that when the Fermi level ($E_{\rm F}$) must cross between adjacent Landau levels at the discontinuity, the *I*-*V* characteristic of the discontinuity is similar to that of a backward diode: When the device is forward biased (electrons flow from the high-density to the low-density region), conduction is small until a temperature-dependent threshold voltage is reached, when the current rapidly increases. When the device is reverse biased, the magnitude of *I* gradually increases with *V*, and is temperature independent. The similarity of our devices to backward diodes suggests that the conduction mechanisms are the same in both, implying the existence of inter-Landau-level tunnel currents across the discontinuity.

Our experiments were performed on a GaAs/Al$_x$Ga$_{1-x}$As single interface heterostructure with a 2DEG density of $5.1\times10^{11}/\text{cm}^2$ and a 4.2-K mobility of 300000 cm^2/V s. On portions of the heterostructure, an Al front gate was evaporated to enable the variation of the electron density beneath it. In the material used in our experiments, the GaAs/Al$_x$Ga$_{1-x}$As interface where the 2DEG occurs is 815 Å beneath the top surface on which the gate is evaporated. Thus, the density change in the 2DEG must occur at the edge of the gate in a comparable distance.

To determine the *I*-*V* characteristics of the boundary between regions of different electron density, a Corbino-geometry device was fabricated in which the density discontinuity encircles the interior contact. Such a device is optimal for *I*-*V* measurements of the discontinuity because the voltage drop across the discontinuity can be made uniform, and the current flowing through the discontinuity is just the current flowing to the interior contact. The mesa pattern used in our experiments (Fig. 1) is an annulus of width 100 μm and diameter 1600 μm fed by six equally spaced current leads on its interior and exterior. At the magnetic fields at which the experi-

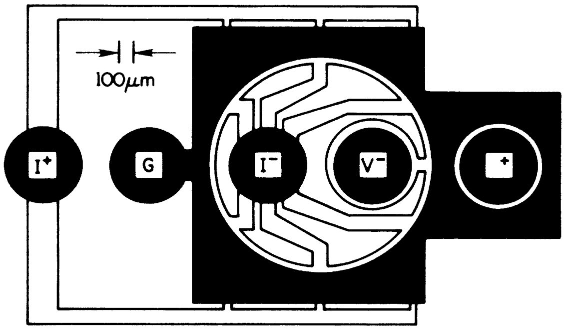

FIG. 1. Representation of the device used in the experiments. Lines delineate mesa region where 2DEG is present. Shaded region defines the area where the Al gate is evaporated. Blackened circles are the In contacts. The interior edge of the gate is centered in the annular mesa region. In the experiments I^- is grounded and the current flowing from I^+ to I^- is plotted as a function of the potential difference $V^+ - V^-$. The gate is held at a constant potential referred to ground.

ments are performed, the ratio of the Hall resistivity, ρ_{xy}, to the magnetoresistivity, ρ_{xx}, is large compared to the ratio of the separation between current leads to the width of the annulus; consequently, the electric field within the annulus is nearly uniform around its circumference. The interior edge of the gate is centered in the annular mesa region. Voltage probes are positioned on the interior and exterior of the annulus so that the voltage across the gate edge can be measured.

To fabricate the devices the mesa pattern is first defined by wet etching. Subsequently, 3000 Å of In is evaporated to create contacts. The device is then alloyed in H_2 at 400 °C for 5 min. Finally, 1000 Å of Al is evaporated to form the gate. In our device, gate leakage current is negligible (< 1 nA) when the gate bias with respect to the 2DEG, V_g, is between 0.0 and -0.7 V, and so all data were taken within this range.

In our experiments the interior current contact is grounded and the current I flowing from the exterior to the interior of the annulus is measured as a function of the potential difference V between its outside and inside edges, measured between the contacts V^+ and V^-. Thus, in our data, V is positive when electrons are flowing outward. During each I-V measurement, V_g is held at a constant value to regulate the density beneath the gate. When $V_g < 0$, the gate reduces the electron density beneath it, so that electrons are flowing from a higher-density to a lower-density region (the boundary is forward biased) for positive V. Two Hall bar mesas, one of which is beneath a gate, are placed adjacent to the Corbino structure, enabling ρ_{xx} and ρ_{xy} in both the gated and ungated regions to be directly measured.

Typical I-V characteristics when $T=4.2$ K and $B=8.5$ T are shown in Fig. 2(a). At this value of B, the Landau-level filling factor is $\nu \cong 2.5$ in ungated regions of the device. When $V_g=0$, the density in both the gated and ungated regions is the same. (We observed no density difference induced purely by the presence of the gate.) The I-V characteristic of the annulus is linear, and its resistance is about 3 kΩ. As V_g is reduced from zero, the electron density beneath the gate diminishes and approaches the value where $\nu=2$. When $V_g=-0.25$ V, the conductance under the gate vanishes, and the resistance of the annulus approaches infinity. If V_g is further lowered, then $\nu<2$ beneath the gate while $\nu>2$ in the ungated region, and E_F at the edge of the gate must cross between Landau levels. It is in this regime that we observe interesting behavior: For forward biases of a few millivolts the resistance approaches 1 MΩ. This resistance is roughly constant until a threshold voltage of about 8 mV is reached, when the current rises rapidly. By comparison, at 8.5 T the Landau-level separation, $\hbar\omega_c$, is 14.6 meV in GaAs. Once E_F is in different Landau levels on opposing sides of the gate edge, the forward-bias behavior is almost independent of V_g.

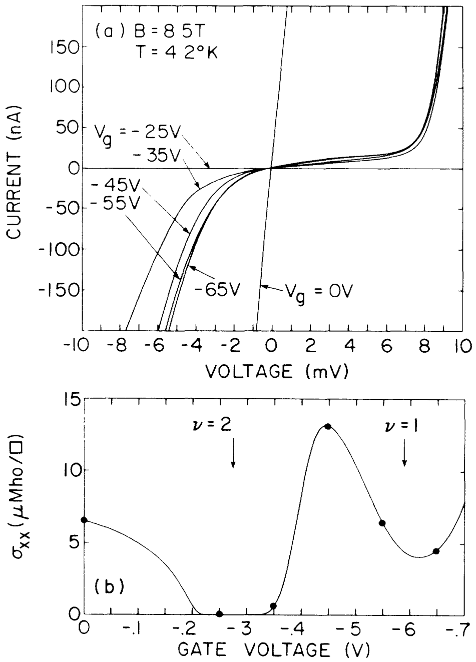

FIG. 2. (a) I-V characteristics of the device at various gate voltages. In this data $\nu=2.5$ in ungated regions of the sample, while in gated regions ν is set to various values in the range $1 \leq \nu \leq 2.5$. When E_F must cross between Landau levels at the gate edge, the device exhibits diode behavior. (b) σ_{xx}, calculated from transport measurements on an adjacent gated bar-geometry device as a function of V_g. Dots are drawn at points where I-V traces were made.

In contrast, the magnitude of I increases gradually when the boundary is biased negatively. Reverse-bias conduction does depend on V_g: It increases when V_g is reduced from -0.35 to -0.45 V, but does not change substantially when V_g is reduced further. Reduction of ν beneath the gate to less than 1 has no effect on the I-V characteristic. Because the spin-splitting energy is comparable to kT in these experiments, it is unlikely that structure associated with odd-integral filling factors would be observable.

We note that when finite current travels through a 2DEG beneath a gate, the potential of the 2DEG, and consequently its density and conductivity, will not be uniform. While this property of these devices is capable of causing nonlinearities in their I-V characteristics, the total voltage drop across the 2DEG in our measurements never exceeded 35 mV, far less than the magnitude of V_g when nonlinear behavior is observed. Thus, conductivity variation under the gate is small and is not the source of the I-V behavior that we have described.

To determine the effects of the magnetic field on the I-V characteristics, B was varied between 6.7 and 10.3 T, corresponding to Landau-level filling factors in the ungated region in the range $2<\nu<3$ [Fig. 3(a)]. At each value of B, V_g was adjusted so that $\nu \cong 1.5$ in the

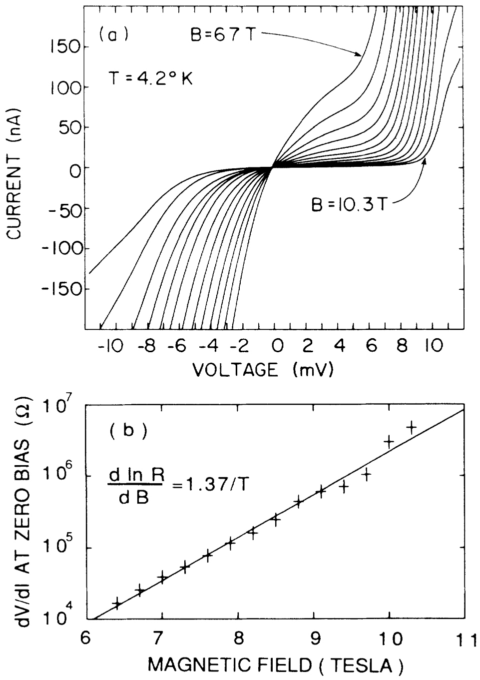

FIG. 3. (a) I-V characteristics of the device at 0.3-T intervals of B in a range in which $2 < \nu < 3$ in ungated regions of the device. For each trace the density under the gate was adjusted to $\nu = 1.5$. (b) The zero-bias values of dV/dI, determined from the data in (a), plotted as a function of B. The line is a least-squares fit of the data by an exponential function.

gated region. The threshold voltage, when it is easily resolved, is linear in B, and is somewhat more than half of $\hbar\omega_c/e$ at 4.2 K. The most noticeable feature of the data is that the conductance at forward bias below threshold and at reverse bias increases rapidly when B is reduced, and, at low fields, almost completely obscures the threshold structure. The value of dV/dI at $V=0$ appears to be exponential in B [Fig. 3(b)].

The temperature dependence of the I-V characteristics was also measured at fixed values of B and V_g (Fig. 4). Data were taken at small currents (when conductance across the boundary is small) so that contributions from temperature-dependent series resistances would be minimized. These data show that the forward-bias threshold voltage increases linearly as T is decreased from 4.2 to 1.2 K. The threshold voltage, extrapolated to $T=0$, would be 13.8 mV, still less than $\hbar\omega_c/e = 16.7$ mV. While the subthreshold conductance diminishes when T is reduced, the reverse-bias conductance of the device has virtually no T dependence in the temperature range studied.

The strong similarity of the I-V characteristics that we have observed to those of backward diodes suggests that the mechanisms of conduction in both devices are the same. A backward diode is a tunnel diode in which E_F lies close to the band edges on both sides of a semiconductor p-n junction. When a backward diode is reverse biased, a temperature-independent tunnel current can flow across the depletion region. Because E_F lies near the band edge, tunnel currents cannot occur when the device is forward biased, and forward-bias currents are small until thermal diffusion currents can flow.

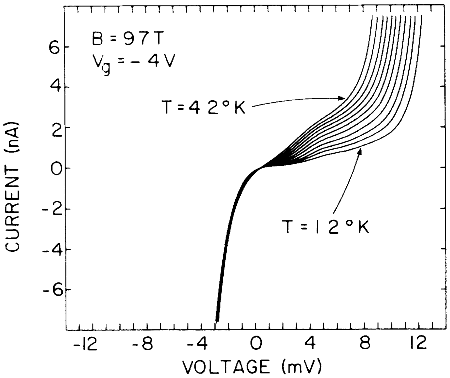

FIG. 4. I-V characteristics of the device at different temperatures. Data were taken at 0.3-K intervals.

In our devices the role played by the semiconductor band gap in the backward diode is played by the Landau-level separation. When the electron density beneath the gate is reduced sufficiently, E_F at the edge of the gate must cross between Landau levels, and a depletion region is formed. For forward biases, a diffusion current, $I_{\text{dif}} = I_0 \exp[e(V - V_{bi})/kT]$, can flow across the depletion region,[5] with the electrostatic potential difference across the boundary at equilibrium $V_{bi} \cong \hbar\omega_c/e = \hbar B/m^* c$. The voltage required to generate a given diffusion current is linear in both B and T, as is seen in our data, and should equal the Landau-level spacing when $T=0$. The fact that the temperature-dependent threshold voltage, when extrapolated to $T=0$, is about 25% less than $\hbar\omega_c/e$ in our data is probably attributable to Landau-level broadening.

In analogy with the backward diode, we believe that inter-Landau-level tunneling is responsible for the current flow when the device is at zero bias or is reverse biased. If this hypothesis is to be valid, then the width of the depletion region at the edge of the gate must be comparable to the magnetic length, $l_B = (\hbar c/eB)^{1/2}$, a measure of the spatial extent of the electron wave function in a magnetic field. We have calculated[6] the depletion width, W, in two-dimensional systems using the depletion approximation for a symmetric abrupt junction and find

$$W = \epsilon V_{bi}/\pi \Delta n e \, ,$$

where ϵ is the dielectric constant, and Δn is the density difference across the junction. If we again assume that $V_{bi} = \hbar\omega_c/e$, and assume that Δn equals the maximum density of a single Landau level, $eB/2\pi\hbar c$, then

$$W = 2\frac{\hbar^2}{me^2}\frac{m}{m^*}\epsilon = 180 \text{ Å} \quad (\text{in GaAs}) \, .$$

Because this distance is small compared to the separation between the gate and the 2DEG, the assumption of an abrupt junction is not valid. It is more appropriate to use the linear-graded-junction approximation to calculate the depletion width. Within this approximation, if we assume that the density changes over a distance = 800 Å, we find $W=420$ Å.

The magnitude of tunnel currents will depend on the overlap of electron wave functions on opposite sides of the depletion region. With use of expressions for the wave functions in the Landau gauge,[7] the overlap is

$$\langle \Psi(x)\Psi(x+W)\rangle^2 \propto \exp(-eBW^2/2\hbar c),$$

where we have neglected all terms outside the exponential. At $B=10$ T, when $l_B=81$ Å, the value of the overlap is about 10^{-6} with the value of W calculated above. Thus, tunneling processes can be significant.

Since the overlap is exponential in B, the tunneling hypothesis leads naturally to an explanation of the similar exponential dependence of the zero-bias resistance on B observed in the data. If the zero-bias resistance is inversely proportional to the overlap, then $d\ln R/dB = eW^2/2\hbar c$. Using this expression, we obtain from the data a value for W that is in excellent agreement with the value estimated above.

If the electrostatic potential in a two-dimensional system varies in only one dimension, then wave functions of electrons in separate Landau levels are strictly orthogonal, and no coupling between Landau levels is possible. Nevertheless, we anticipate that disorder will introduce coupling, and allow tunneling to occur.

Further experiments are contemplated in the fractional quantized Hall effect regime. Naive application of the depletion-width formula above gives depletion widths much smaller than l_B for typical fractional-quantized-Hall-effect energy gaps. Thus, it is not clear whether a depletion region even exists in the fractional regime. Also, it is uncertain what effects density discontinuities will have on the fractional-quantized-Hall-effect ground state. Theoretical work in these directions is eagerly anticipated.

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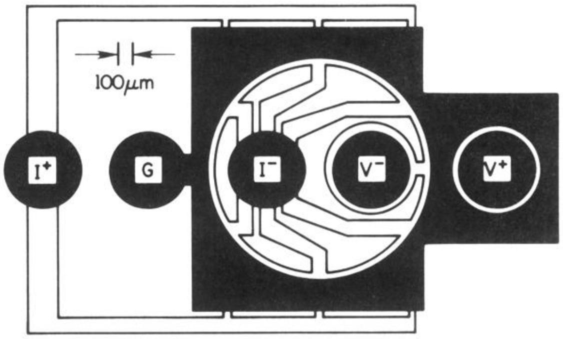

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