Quenching of the Hall Effect in a One-Dimensional Wire

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We report the first observation of the complete quenching of the Hall effect in a one-dimensional conductor. In our narrowest wires at low temperatures and for small magnetic fields, where the 1D subband splittings exceed both k_BT and $\hbar\omega_c$, we observe striking departures from the 2D Hall effect, characterized by an unexpected low-field plateau and a precipitous, complete suppression of the Hall resistance. We believe these to be unambiguous manifestations of one-dimensional electrical transport; they appear to provide a *direct* measure of the number of quantum conduction channels that participate.

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Electrical transport ceases to display behavior characteristic of the bulk when probed over very short distances. Conceptually, one expects that naive scaling of macroscopic properties down to small dimensions will fail at length scales on which the intrinsic physics of the system is determined. Three distinct small size regimes have emerged; these are demarcated by the electron's phase-coherence length $l_\varphi=(D_{el}\tau_\varphi)^{1/2}$, its mean free path $l=v_F\tau$, and its Fermi wavelength $\lambda_F=2\pi/k_F$. Here D_{el} is the elastic diffusion constant ($v_F^2\tau/3$ in 3D), τ_φ and τ are the phase-coherence and total electron lifetime, respectively, and v_F and k_F are the Fermi velocity and wave vector.

Solid-state Aharonov-Bohm oscillations and universal conductance fluctuations are observed at lengths of order l_φ. In this regime, although the electron propagates diffusively, it retains phase memory and, consequently, can exhibit quantum interference. At length scales of order l, transport becomes strongly nonlocal. Scattering events outside a region of this size determine its "resistance"—within it electrons propagate ballistically. In this Letter, as in the very recent work by Berggren *et al.*,[1] Hansen *et al.*,[2] and Timp *et al.*,[3] we focus upon a newly accessible and entirely different size regime, that of *quantum transport*. It is entered when high-mobility structures are scaled down to dimensions approaching λ_F, which characterizes the spatial extent of the electron wave function. Here the boundaries of the structure confining the electron gas determine the eigenstates participating in transport.

We report here the first observation of the quenching of the Hall effect in conducting paths of width $w\simeq\lambda_F$. When a macroscopic conductor is subjected to a magnetic field normal to the direction of the current flow, a transverse electric field arises to balance the Lorentz force on the electron. In the quasi-1D regime, however, the development of this Hall field may be impaired by discreteness in the transverse-mode spectrum. Since each transverse eigenstate has a specific density profile, arbitrary charge distributions may not be constructed until many such states are energetically accessible. At very large magnetic fields, when $\hbar\omega_c$ greatly exceeds the level spacing, 2D behavior should be recovered. Here, $\omega_c=eB/m^*$ is the cyclotron frequency and m^* is the (2D) effective mass of the electron. It is the quasi-1D regime at small magnetic fields that we investigate in this work.

Our wires are laterally patterned from high-mobility, modulation-doped GaAs-AlGaAs heterojunction material, with use of electron-beam lithography and ion-beam-assisted etching. A complete description of our new technique of defining narrow conducting paths by selective ion etch damage is presented elsewhere.[4] At 4.2 K, the measured mobility and carrier density in the unpatterned material are 5.4×10^5 $cm^2/(V\ s)$ and 5.3×10^{11} cm^{-2}, respectively, yielding $l\simeq7$ μm. These values are essentially preserved in our small wires. The experiments are performed at 4.2 K in an environment carefully shielded against electromagnetic interference. We make four-terminal magnetoresistance measurements

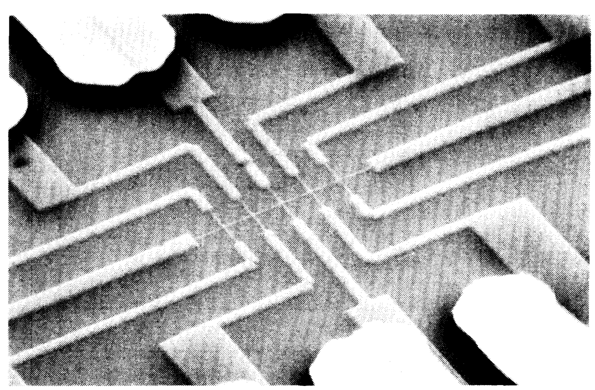

FIG. 1. Scanning electron micrograph of 75-nm quantum-well wires. Current flows along the long wire; five pairs of transverse voltage probes placed on $\simeq$2-μm spacing permit four-terminal Hall measurements.

with a $\leq$ 1-nA constant ac drive current at 17 Hz. Four separate channels of electronics allow simultaneous measurement of structurally identical, single wires fabricated on the same chip connected and cooled at the same time. In this way we have obtained magnetoresistance measurements on *many, nominally identical*, quantum-well wires. This allows us to isolate and ignore artifacts arising from spatially inhomogeneous electron density and focus on the systematic effects which arise from lateral confinement.

We have studied quantum-well wires having structural widths, w_{str}, ranging from 1100 nm downward to roughly 75 nm (see Fig. 1). All conduct without illumination at 4.2 K. We determine w_{str} by scanning electron microscopy; the *electrical* widths of the conducting paths, w_{el}, however, are much more difficult to determine precisely. We note that, as our wire width is reduced, the longitudinal resistance roughly scales with geometry and that the region of anomalous R_H grows monotonically. We believe that these indicate that $w_{el} \simeq w_{str}$. We also observe Aharonov-Bohm oscillations in a $\simeq$250-nm-diam loop of $\simeq$75-nm "wire." This evidence for a multiply connected geometry of very small dimensions precludes a gross "sloshing" out of carriers from beneath the mask.[4]

In Fig. 2 we display magnetoresistance data obtained from a 100-nm sample, taken at 4.2 K. The well-defined integral quantum Hall plateaus stay centered about the line defining the ordinary Hall effect ($R_H = B/n_s e$). Here, n_s is the sheet (2D) carrier density. These features, representative of the data obtained at all widths, indicate that the current paths follow well-defined geometries, that the electron density is spatially homogeneous, and that conduction paths in parallel with the 2D electron gas are negligible.

The inset in Fig. 2 shows the low-field Hall resistance of a 75-nm wire at 4.2 K, and also at $\simeq$50 K. The low-temperature curve shows that R_H is strongly quenched in the region between $\pm$100 mT. We note that R_H is antisymmetric in B when it breaks out of the quenched region. In the narrowest of our wires we occasionally observe offsets in R_H at zero field; these are always less than one percent of R_{xx}. On a given sample of constant wire width < 200 nm, each of the five pairs of transverse voltage probes (see Fig. 1) generally shows a quenching of R_H below the same value of B, whereas the small offsets at $B=0$ show no such systematic behavior. These offsets may therefore arise from secondary considera-

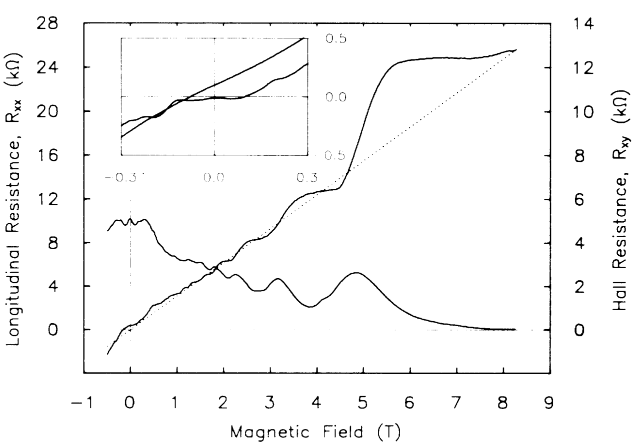

FIG. 2. Longitudinal and Hall resistance for a 100-nm-wide Hall bar at 4.2 K. Dotted line is classical Hall resistance for reference. Inset: Quenched Hall resistance near $B=0$ for a 75-nm wire at 4.2 K, and behavior at $\simeq$ 50 K.

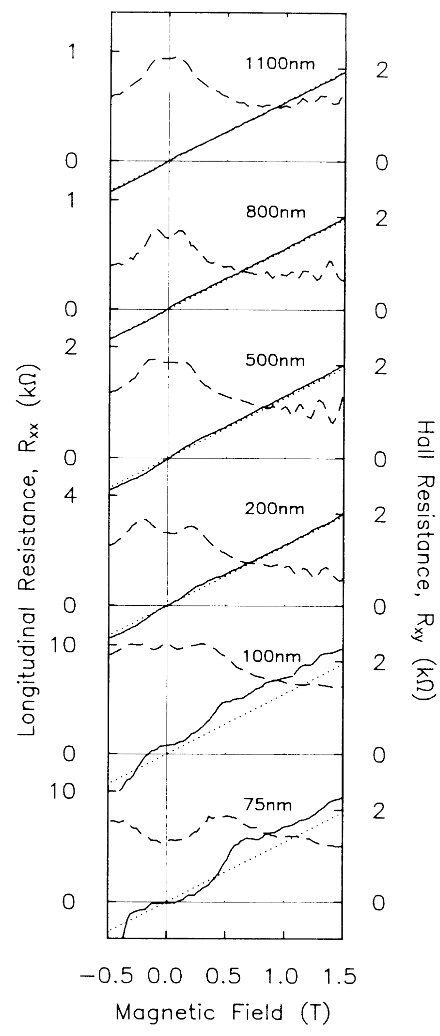

FIG. 3. Systematic development of the low-field structure as the wire width decreases from 1100 to 75 nm. A barely perceptible change in the slope of the Hall resistance (solid lines) evolves into a complete quench and plateau for the smallest wire, 75 nm. The peaks in the longitudinal resistance (dashed lines), symmetrically displaced about $B=0$, correlate with the Hall anomalies. The dotted lines correspond to the classical Hall resistance. Zero-field offsets resolved in these magnified R_{xy} plots always amount to $\leq$1% of R_{xx}.

tions specific to each probe pair, such as slight transverse misalignment or nonlocal impurity-scattering effects. Dependence upon longitudinal current is negligible. Only after we increase the drive level by 3 orders of magnitude (to $J \simeq 0.13$ A/cm in the 75-nm wire) does measurable slope at zero field appear. We attribute this behavior simply to electron heating.

We have systematically investigated the width dependence of these effects in numerous quantum-well wires. Six representative low-field curves are presented in Fig. 3. The progressive development of the low-field anomalies in the Hall resistance, R_H, are evident. Quenching is observed for $w \lesssim 200$ nm. We also note strong low-field features in longitudinal magnetoresistance concomitant with those in R_H. Simmons, Tsui, and Weimann[5] suggest such a correlation. The data indicate that the low-field region of anomalous R_H, bounded by $\pm B_{crit}$, approximately follows a $B_{crit} \simeq w^{-3/2}$ relation. If only one transverse subband contributed, one might expect a w^{-2} dependence. The multiple-subband nature of the real physics, compounded with the unknown transverse potential determining the exact level spacings, makes the finite-temperature problem much less trivial. Simple effects occurring when the cyclotron diameter equals the wire width, however, would display a w^{-1} dependence in the low-field regime.

To help us gain a qualitative understanding of the anomalies in R_H at low fields, we construct the energy-level diagram for electrons subjected to both a magnetic field and a transverse confinement potential. We model the confinement by a harmonic potential, $U_0(x) = \frac{1}{2} m^* \omega_0^2 x^2$. This leads to simple eigenvalues,

$$\epsilon_n(X) = (n + \tfrac{1}{2})\hbar\omega + \tfrac{1}{2} m^* (\omega^2 \omega_0^2 / \omega_c^2) X^2. \qquad (1)$$

Here, x and y are transverse and longitudinal coordinates, ω_0 characterizes the potential, n is the level index, and $\omega^2 = \omega_0^2 + \omega_c^2$. X, the guiding-center coordinate for the Landau states,[6] is linearly related to the longitudinal momentum, $X = (\omega_c/\omega^2 m^*)\hbar k_y$. In Fig. 4(a) we plot the Landau-level energies for orbits centered on the wire, $X = 0$, as functions of magnetic field.

Halperin[6] and MacDonald and Streda[7] describe the Hall effect for 2D systems in terms of "edge states." If a chemical potential difference is imposed between two sides of a sample, it is these edge states that determine the longitudinal current. It is assumed that the Fermi level lies between Landau levels within the conductor, but that it crosses them at the edges. Each crossing provides one state to support the longitudinal current at the edge.

In large magnetic fields, 2D magnetic confinement will dominate the 1D electrostatic confinement. Expecting a smooth crossover to the quasi-1D regime when the field is reduced, we apply the edge-state theory and investigate its implications when the transverse confinement potential becomes appreciable compared to $\hbar\omega_c$. In the following discussion we assume spin degeneracy; thus each state is twofold degenerate. At zero temperature, on the assumption of a continuous manifold of longitudinal states, each Landau level intersecting the Fermi level contributes two "quantum conduction channels",[8] at $\pm k_y^{(n)}(E_F)$, to electrical transport.

The longitudinal current induced by a chemical potential difference imposed between the two edges of the sample is then given by[7]

$$I = 2ne\Delta\mu/h, \qquad (2)$$

where $\Delta\mu$ is the chemical potential difference and we assume $2n$ channels contribute per edge.

The issue is to understand this picture for small B where confinement effects become important. Taking Fig. 4(a) at face value, we conclude that the essential feature of magnetotransport in 1D is that *at small magnetic fields the number of channels does not become arbitrarily large but hangs up at a value controlled by the confinement potential. This implies that the Hall resistance does not fall to zero in continuously diminishing steps, but stops at a "last plateau" determined by the number of conduction channels in the quasi one-*

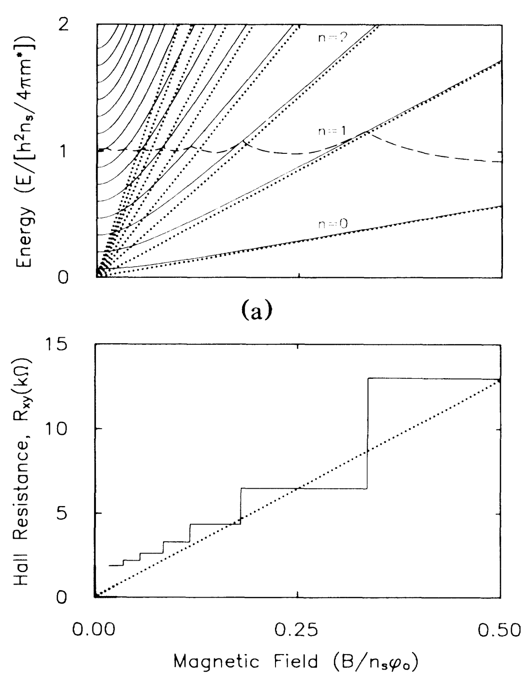

FIG. 4. (a) Nonlinear fan diagram for the simple 1D model. Dotted lines show several 2D Landau levels, solid lines are for the hybrid electric-magnetic confinement potential. The dashed line displays the calculated E_F. For $n_s^{1/2}w$ = 3.9 and $\hbar\omega_0 \simeq E_F/7.5$, eight levels are populated at $B = 0$. (b) Corresponding quantized Hall resistance cannot reach zero because of the finite number of transverse states. The model is expected to break down near $B = 0$, as indicated by the shaded region.

dimensional wire. This is depicted in Fig. 4(b). R_H appears to head in to a finite intercept at zero field. Being an odd function of magnetic field, however, it clearly must vanish at $B=0$. Precisely how it descends to zero from the region of the last plateau is not addressed by the arguments we present here. Perturbative approaches to the problem appear to be precluded by the singular nature of R_H at $B=0$. Indeed, the experiments offer evidence *prima facie* that R_H in quasi-lD wires is not a well-defined quantity for small B.

We note parenthetically that the curvature and finite intercepts of the 1D fan diagram will also cause the Shubnikov–de Haas effect to deviate from the $1/B$ periodicity holding in 2D. This has also been pointed out previously by others.[9,1,3]

Our experimental data support the channel-counting picture presented here. In all of the submicron wires, especially the smaller ones, R_H exhibits a tendency to form a last plateau as the field is decreased. In other recent studies of narrow quantum-well wires[3,5] this tendency is also evident at low fields, but essentially left unexplained. (We note that in their wider wires, the last plateau will occur at reduced R_H, consistent with the idea that smaller subband splittings make more channels available.)

As we point out earlier, our narrowest wires show a precipitous drop from the last plateau to essentially $R_H=0$ at repeatable and nonnegligible magnetic fields. Our simple channel-counting arguments are silent on this issue, offering no insight into either the collapsing *or* the quenching of the Hall resistance at finite field. We believe that the systematic experiments we report here provide strong evidence for the existence of a critical field to establish an appreciable Hall resistance. Naively, this seems as expected; by definition, one dimensional means *no* transverse degrees of freedom, and hence no transverse voltage. True 1D transport would, strictly speaking, involve only the lowest subband and require a large energy splitting to the excited state. To break into two dimensions, the higher subbands must be accessed —at the cost of the energy splitting. The data graphically demonstrate this for us. Our experimental results do not agree with an earlier calculation of the Hall effect in a 2D system oriented to develop a Hall voltage in the direction normal to the plane,[10] but this model may not pertain to the 1D regime we investigate.

With the channel-counting model in hand, we can use the value of the Hall resistance at the last plateau, R_{lp}, to determine the number of channels carrying the current at $B=0$. The relation is simply given by $N=h/2e^2R_{lp}$. Using this, we estimate from our 75-nm wire data that nine orbital channels, ignoring spin, are active at 4.2 K. This is approximately 3 times as many as one estimates from the known 2D Fermi energy and computed particle-in-a-box eigenvalues for this wire width. A number of factors may account for this; perhaps most interesting is the possibility that the true boundary conditions of the "cross" region (where R_H is actually measured) may introduce additional states into the problem. Or a simpler, and certainly less exalted, explanation may be that our wires are wider than we think. If we assume that the subband splittings can be determined by the *field* scale of the R_H anomalies, B_{crit}, the latter seems unlikely.

In summary, we observe large and unexpected anomalies in the Hall resistance at low temperatures and low magnetic fields when both k_BT and $\hbar\omega_c$ are less than the energy splitting of the states created by transverse confinement. We develop arguments to explain a last plateau in the Hall resistance based on the fact that, unlike the situation in 2D, conduction in 1D wires at low magnetic fields involves only a finite number of states. These arguments, however, lead to the paradoxical and unphysical result that the Hall resistance should jump discontinuously at zero field. Experimentally we find that the resistance drops precipitously at small, but finite, magnetic field to near zero in our smallest wires. At present we have no insight as to why the Hall effect is quenched or what mechanism controls the point at which the last plateau is driven to zero.

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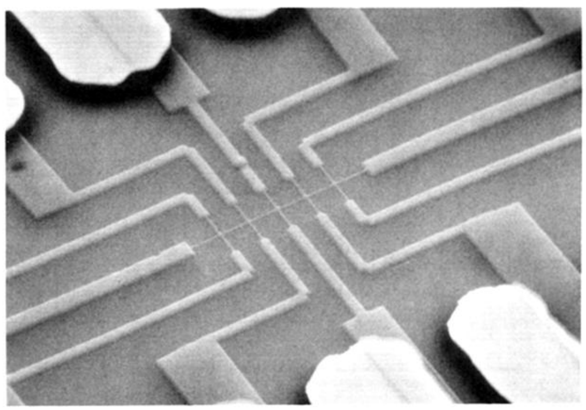

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