Quenching of the Hall Resistance in a Novel Geometry

A. M. Chang, T. Y. Chang, and H. U. Baranger
AT&T Bell Laboratories, Room 4C-428, Holmdel, New Jersey 07733
(Received 21 February 1989)

We have observed quenching of the Hall resistance in a GaAs-$Al_xGa_{1-x}As$ heterostructure Hall junction containing four narrow constrictions leading into a quantum dot. Backgated junctions show quenching within a broad but finite electron density range. In contrast, junctions containing fewer constrictions show little or no quenching behavior. These results show conclusively that the nature of the junction region is crucial in producing quenching and can be explained in terms of junction scattering using the Büttiker-Landauer formulas.

PACS numbers: 72.20.My, 73.50.Jt, 73.60.Br

Quenching of the Hall resistance[1] at low magnetic fields in GaAs-Al_xGa_xAs quasi-one-dimensional wires represents an interesting and surprising discovery in low-temperature quantum transport. It is found that in a four-terminal measurement, the Hall voltage, or, more accurately, the slope of the Hall voltage, vanishes over a finite magnetic field range between positive and negative fields of a few hundred gauss.[1,2] The conditions needed for observing the quenching appear to be (1) ballistic transport through the Hall junction region, (2) width of the quasi-1D wires of order 1000–3000 Å, and (3) thermal energy less than the level spacing of the transverse modes of electronic states. Theoretical attempts to explain this phenomenon have centered on the nature of the electronic wave functions in a ballistic wire, and on scattering of the electron waves at the Hall junction.[3-5] Junction scattering can severely modify the transmission and reflection of electron waves in and out of the current and voltage leads and, consequently, affect the chemical potentials measured, in accordance with the formulas of Büttiker and Landauer.[6,7] These theories, however, have not yet succeeded in reproducing the experimental results. An unresolved question remains as to whether the quenching is fundamentally a junction scattering effect.

In this Letter, we describe our study of the quenching of the Hall resistance in junctions of novel geometries, specially designed to address this question. We report the discovery of quenching in a Hall junction consisting of four narrow constrictions leading into a quantum dot. This geometry is markedly different from the usual one[1,2] of nominally narrow wires throughout. In our device, at high carrier densities, the Hall effect is not quenched. By lowering the density, a quenching is produced. Further reduction below a critical density, however, again removes the quenching. Junctions containing three, two, and one constriction show no substantial quenching over comparable density ranges. Our results indicate that the four-constriction geometry satisfies a minimal requirement for quenching to occur, and lend support to the theoretical idea put forth by Baranger and Stone[8] that an adiabatic transition from a narrow to a wide region at the Hall junction is essential. In the four-constriction geometry, the transition region allows the injection of collimated electron waves[9] at the input of the junction and the proper collection of the carriers by the receiving leads. In this light, our results strongly suggest that junction scattering is responsible for the quenching of the Hall effect. In addition to the quenching region, we study the so-called "last plateau" at magnetic fields just above this region, and find a close connection between this feature and the presence of quenching.

In Fig. 1. we show our device containing the Hall junctions. The solid lines depict the structure as defined by lithography; the dotted lines approximately indicate the conducting region. The lithographic dimensions are as follows: the wide regions are 1 μm in width, the narrow regions 0.5 μm in width, and the spacing between junctions is 3 μm center to center. The device is made from a modulation-doped GaAs-$Al_xGa_{1-x}As$ heterostructure material using standard electron beam and photolithography techniques to define the pattern, and a wet chemical etch to confine the electrons underneath the patterned region. Surface depletion reduces the conducting width below the lithographic width and smooths out the corner features.

The starting material has an electron density of 3.3×10^{11} cm^{-2} and a mobility of 320000 cm^2/Vs at T =4.2 K. The device shows a reduced density of 2.75×10^{11} cm^{-2} in the wide region with a mobility of 180000 cm^2/Vs. The corresponding elastic scattering

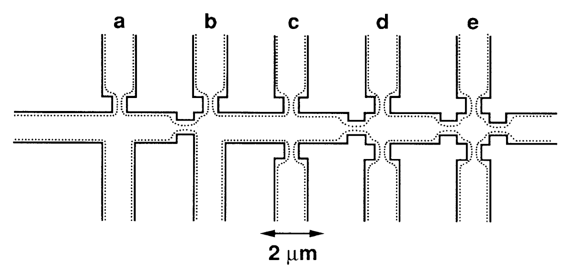

FIG. 1. Schematic of the GaAs-$Al_xGa_{1-x}As$ device containing the various Hall junctions of novel geometries. Solid lines indicate device as defined by lithography. Dotted lines depict approximately the conducting structure.

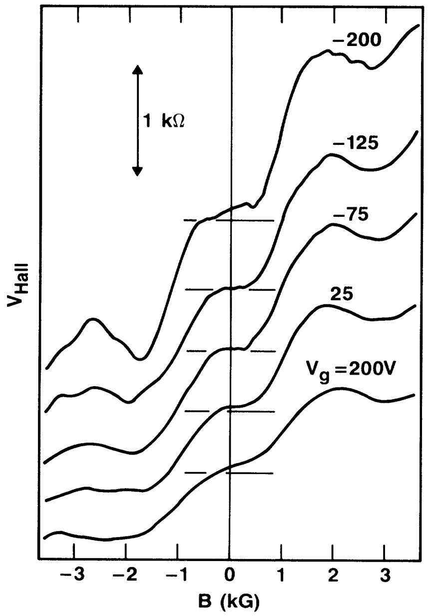

FIG. 2. The Hall resistance, $R_{Hall} \equiv V_{Hall}/I$, of the four-constriction Hall junction, vs magnetic field, between ± 3 kG, at $T = 4.2$ K. The traces correspond to different backgate voltages.

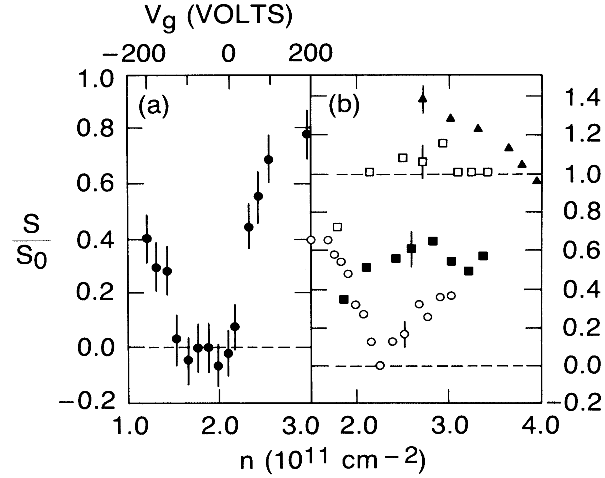

FIG. 3. (a) Ratio of the Hall slope at $B = 0$, s, and the classical slope, s_0, vs electron density and backgate voltage, for the four-constriction junction. (b) s/s_0 vs electron density for the Hall junctions containing (1) three constrictions, circles; (2) two opposite constrictions, solid squares; (3) two constrictions at right angle, open squares; and (4) one constriction, triangles.

length is 1.6 μm. In segments containing a narrow constriction, the longitudinal resistance is dominated by the contact resistance of the constriction,[10,11] yielding a transverse-mode occupation number of 10–20 levels for the various junctions. Although all constrictions are lithographically identical, the presence of a different number of constrictions at each junction brings about a difference in surface depletion characteristics where a greater number of constrictions implies a lower density. In addition, a reduction of the density by gating reduces the width correspondingly.

We perform our measurements at $T = 4.2$ K with a lock-in amplifier at 23 Hz and 5 nA excitation current. The current is passed through the main horizontal channel. In Fig. 2 we present raw data for the Hall resistance, $R_{Hall} \equiv V_{Hall}/I$, for the four-constriction junction between ± 3 kG magnetic field. The traces correspond to different applied backgate voltages, V_g, where a more positive gate voltage corresponds to a higher electron density. At $V_g = -200$ V, the Hall resistance is not quenched in the vicinity of $B = 0$. At -125 V, the Hall resistance nearly quenches. At -75 V a full quenching is observed with a region of approximately zero average slope between -200 and $+300$ G. At $+25$ V the Hall slope starts to increase again, and at $+200$ V, the quenching is completely removed. In Fig. 3(a) we plot the ratio of the slope at $B = 0$, s, to the classical slope of the 3–6-G region, s_0, versus the electron density at the bottom scale, and V_g at the top. The disappearance of the quenching with increasing density and width is similar to the results of Ford *et al.*[2] observed in a junction defined by electrostatic confinement via side gating. The quenching behavior is observed over a density range of $(1.6\text{-}2.2) \times 10^{11}$ cm^{-2}. A rough estimate of the number of transverse modes in the constriction is five at the low limit and nine at the high limit. The quenching result has been duplicated in a separate device of this four-constriction geometry.

In Fig. 3(b), we plot s/s_0 for the other junctions containing three, two, and one constriction, over comparable density ranges. With the exception of the three-constriction case, all other junctions show no quenching at all. The three-constriction junction exhibits a zero slope in a very small density region about 2.25×10^{11} cm^{-2} and a small $|B|$ region (< 30 G) as well. Interestingly, in the two-constriction case, the Hall slope, s, is nearly to the classical value, s_0, for the geometry of opposite constrictions, and it is considerably reduced for the case of two constrictions at a right angle. Moreover, the single-constriction case shows substantial enhancement of s over s_0.

We study the "last-plateau" region at magnetic fields just beyond the quenching region. In Fig. 2, we see in R_{Hall} a relatively flat portion above 1.5 kG, which is vaguely suggestive of a quantized plateau. In wires of nominally uniform width, Roukes *et al.*[1] and Chang *et al.*[12] independently attempted to relate this feature to the number of transverse modes occupied. Our data indicate that this feature can also be observed in a four-constriction, quantum-dot geometry. However, the transverse-mode number estimated from this feature is substantially higher than that estimated from the constriction contact resistance at $B = 0$. Surprisingly, a last plateau is observed even in the three- and two-constriction geometries, as shown in Fig. 4. In the two-constriction case, the right-angle geometry strikingly shows a last plateau in one magnetic field direction only, while the opposite-constrictions geometry shows no sign of a plateau region. These results suggest that the occurrence of or approach to a quenching about $B=0$ and the last plateau at higher B go hand in hand.

What causes quenching? Since transport is ballistic through the Hall junction, and the measurement is a four-lead measurement, it is natural to analyze this problem in terms of the multilead coherent transport formulas of Büttiker.[6] Scattering of the electron waves by the junction is the only relevant physical process. Theoretical analysis carried out for a junction of four incoming narrow wires of uniform and identical widths, with[4] or without[5,8] the assumption of weak coupling to the voltage leads, failed to produce either any quenching[4] or quenching over an appreciable density range,[5,8] in contrast to experiment.[2] Recently, Baranger and Stone[8] analyzed an experimentally more realistic model: four narrow leads attached to a junction of twice the width, with a *smooth transition* in between. Realistic quenching of the Hall resistance is produced in these numerical calculations, within a finite density range, after appropriate thermal averaging.

The physical picture for the quenching[8] is as follows: Based on the work of Büttiker,[6] the Hall voltage is produced by the difference in the ability of electron waves to turn a corner to the right versus to the left, caused by the Lorentz force exerted by the perpendicular magnetic field. Two mechanisms combine to give rise to quenching: (1) a collimation-collection effect which greatly reduces the probability for turning a corner in either direction, hence reducing the difference, and (2) an equalization effect which further reduces the asymmetry in the probability. The first is produced by the geometrical structure of a narrow constriction and the hornlike smooth transition region into the wide Hall junction. This structure acts as a beam collimator on an injection lead,[9] and as an efficient collector on a receiving lead. Quantum mechanically, as electron waves are injected into a constriction at the Fermi energy, the higher-lying transverse modes are filtered out.[10,11] In the *smooth* horn, each wave is able to *preserve its transverse-mode number in an adiabatic manner, resulting in a preferential occupation of the lower transverse modes in the wide Hall junction.*[8] A low transverse mode has most of its velocity directed forward, and is less likely to turn a corner. In addition, the smooth horn of the receiving lead adiabatically preserves the mode number for the electrons entering the narrow constriction, and greatly reduces back reflection,[13] resulting in an efficient collection process. The second mechanism arises from the complex scattering in the interior of the junction from the side walls, Fig. 1(e), which tend to reflect some electrons deflected by the Lorentz force toward the top (bottom) voltage lead into the bottom (top) lead, hence equalizing the two turning probabilities. This mechanism has been emphasized independently by Beenakker and van Houten.[9]

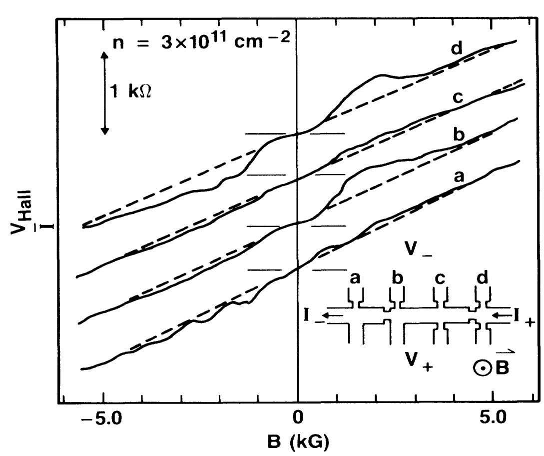

FIG. 4. The Hall resistance, $V_{\rm Hall}/I$, as a function of magnetic field for the junctions containing three, two, and one constriction. Note that the junctions containing three constrictions and two constrictions at right angle show a last-plateau feature between 1 and 3 kG in $|B|$, the latter in positive B direction only. In contrast, the junctions containing two opposite constrictions and one constriction show no last-plateau feature. Inset: The junctions, the polarity of current flow and voltage measurement, and the magnetic field direction pointing out of the page for positive B.

Our geometry of four constrictions leading into a quantum dot satisfies, in a minimal way, these requirements. The constrictions and horns act as the collimators and collectors, and the transition into the quantum-dot region is smooth due to the electrostatics of surface depletion. In our experiment, we can intuitively understand the disappearance of the quenching as follows. At low densities, when very few transverse modes are occupied and the constrictions become very narrow, the transition into the wide region may no longer be smooth; *diffraction at the constriction removes the collimation effect.* At high densities, the width of the constrictions approaches that of the wide regions and the collimation effect is lost. Our results demonstrate experimentally that junction scattering contains the essential physics of quenching.

We can also understand the results for the other geometries of three, two, and one constriction, in terms of junction scattering. The three-constriction geometry comes closest to exhibiting a quenching. However, one current lead is wide and does not contain the constriction-horn structure; the collimation effect is lost for electrons injected in this lead. Therefore, a less complete quenching is expected. The geometry of two constrictions at right angle shows a more pronounced approach to a quenching than the geometry of two opposite constrictions. This may seem surprising. However, note that the former has an approximately 45° wall between the constrictions which can reduce the left-right transmission asymmetry by reflection of electrons into the lead opposite to the direction of the Lorentz force, whereas the latter has no horn structure at all, and can neither collimate properly nor reduce the asymmetry by reflection. We emphasize that our results show that when a junction with no constriction does not show quenching, a similar junction with two opposite constrictions continues to show no quenching. Similarly, the one-constriction geometry is not expected to show much quenching behavior. In fact, one may expect the single constriction to inhibit transmission into that lead, thereby enhancing the asymmetry and thus the Hall voltage.

In order to confirm the experimental results, we have carried out calculations of the Hall resistance for junctions in four of the geometries in Fig. 1. We use a previously developed method[8] based on the recursive Green's-function technique. The cross section of the wires is taken to be a harmonic potential, and the constrictions are made by slowly narrowing and then widening the wire. The slope of the Hall resistance near $B=0$ normalized to the expected 2D value and averaged over energies is a good measure of whether a given structure shows quenching. (We average over energies for which 1–6 modes are open in the constriction.) Denoting this quantity $\langle S/S_{2D}\rangle_i$ for a structure with i constrictions, we find that $\langle S/S_{2D}\rangle_4 = -0.15 \pm 0.16$, $\langle S/S_{2D}\rangle_3 = 0.48 \pm 0.01$, and $\langle S/S_{2D}\rangle_{2,\mathrm{opposite}} = 1.8 \pm 0.1$. For the case of two adjacent constrictions, the traces are asymmetric; we find $\langle S/S_{2D}\rangle_{2,\mathrm{adjacent},+} = 0.48 \pm 0.10$ while $\langle S/S_{2D}\rangle_{2,\mathrm{adjacent},-} = 1.12 \pm 0.09$. The good agreement between these calculated results and the experimental results strongly supports an explanation of quenching based on junction geometry and, in particular, collimation.

How does the last plateau arise? The ability of the hornlike structure to efficiently collect the injected collimated electron wave is responsible for the quenching in the four-constriction geometry. In the same way, at higher magnetic fields, when the Lorentz force is able to bend the electrons injected from the negative current lead just right to properly reach a top voltage lead (inset to Fig. 4), this voltage lead becomes efficient in collecting the electrons over a finite B region, giving rise to the plateaulike structure. Other than the four-constriction geometry, both geometries of three constrictions and two constrictions at right angle contain this structure of constrictions and horns at negative current and top leads. In the latter geometry, this feature is lost under field reversal, since the relevant collecting lead is now the bottom one. This explains why there is a plateau in one field direction only. This lack of B field symmetry is in complete agreement with the predictions of the Büttiker formulas.[14]

Note added.— After submission of our paper, we became aware of similar work by Ford *et al.*[15]

[1] M. L. Roukes, A. Scherer, S. J. Allen, Jr., H. G. Craighead, R. M. Ruthen, E. D. Beebe, and J. P. Harbison, Phys. Rev. Lett. **59**, 3011 (1988).

[2] C. J. B. Ford, T. J. Thornton, R. Newbury, M. Pepper, H. Ahmed, D. C. Peacock, D. A. Ritchie, J. E. F. Frost, and G. A. C. Jones, Phys. Rev. B **38**, 8518 (1988).

[3] C. W. J. Beenakker and H. van Houten, Phys. Rev. Lett. **60**, 2406 (1988).

[4] F. M. Peeters, Phys. Rev. Lett. **61**, 589 (1988).

[5] D. G. Ravenhall, H. W. Wyld, and R. L. Schult, Phys. Rev. Lett. **62**, 1780 (1989); G. Kirczenow, Phys. Rev. Lett. **62**, 2993 (1989).

[6] M. Büttiker, Phys. Rev. Lett. **57**, 1761 (1986).

[7] R. Landauer, Philos. Mag. **21**, 863 (1970).

[8] H. U. Baranger and A. D. Stone, Phys. Rev. Lett. **63**, 414 (1989).

[9] C. W. J. Beenakker and H. van Houten, Phys. Rev. B **39**, 10445 (1989); (to be published).

[10] B. J. van Wees, H. van Houten, C. W. J. Beenakker, J. G. Williamson, L. P. Kouwenhoven, D. van der Marel, and C. T. Foxon, Phys. Rev. Lett. **60**, 848 (1988).

[11] D. A. Wharam, T. J. Thornton, R. Newbury, M. Pepper, H. Ahmen, J. E. F. Frost, D. G. Hasko, D. C. Peacock, D. A. Ritchie, and G. A. C. Jones, J. Phys. C **21**, L209 (1988).

[12] A. M. Chang, G. Timp, R. E. Howard, R. E. Behringer, P. M. Mankiewich, J. E. Cunningham, T. Y. Chang, and B. Chelluri, Superlattices Microstruc. **4**, 515 (1988).

[13] L. I. Glazman, G. B. Lesovick, D. E. Khmelnitskii, and R. I. Shekhter, Pis'ma Zh. Eksp. Teor. Fiz. **48**, 218 (1988) [JETP Lett. **48**, 238 (1988)].

[14] M. Büttiker, Phys. Rev. B **38**, 9375 (1988).

[15] C. J. B. Ford *et al.*, Phys. Rev. Lett. **62**, 2724 (1989).