RAPID COMMUNICATIONS

PHYSICAL REVIEW B VOLUME 43, NUMBER 9 15 MARCH 1991-II

Resonant suppression of the quantized Hall effect in ballistic junctions

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(Received 26 December 1990)

We have fabricated a quantum dot with four leads attached via variable-width constrictions. At high magnetic fields and low temperatures, the $h/2e^2$ and $h/4e^2$ quantized Hall plateaus observed for wide constrictions are replaced by a series of minima that go to zero or below as the constrictions are squeezed. These resonances are explained well by a recent model proposed by Kirczenow (following paper) to describe this structure, in which each lead transmits only one edge state. The minima can be explained by interference between edge states near the constrictions.

At low temperatures, the Hall resistance R_H in narrow Hall bars made from high-mobility heterostructures deviates astonishingly from the linear, classical Hall effect.[1-5] At low magnetic fields B, the electrons from the current source emerge collimated[6,7] and follow classical trajectories until finding their way into a voltage probe or the current sink.[3,4,8] The specularly bouncing trajectories cause a geometry-dependent anomaly which gradually crosses over to a constant Hall voltage called the "last plateau", as discrete edge states (Landau levels) form.[1] For a crossing between current and voltage probes with approximately constant width [see the inset to Fig. 1(b)], this leads to a quenched Hall effect.[1,2] For other cross geometries, the Hall effect is different, and can be enhanced or negative depending on the shape.[3-5,8] For instance, for the cross displayed in the inset of Fig. 1(a), the Hall voltage is negative at low fields, because most of the electrons are reflected from the diagonal "mirrors" into the *wrong* voltage probe.[3,4] At higher fields and moderate temperatures ($T \approx 4$ K), these crosses exhibit the standard quantized Hall effect (QHE).[1,2] At low temperatures, however, quantum-mechanical phase coherence becomes important, and the QHE can break down when the interference between edge states is propitious.[9,10] In fact, simple models have predicted resonances that can reduce R_H to zero.[11-14] In this paper we report the observation of such resonant breakdown of the QHE in ballistic Hall bars comprising a quantum dot connected via point contacts to four probes. Our observations are well described by calculations for a model system where interference between different edge states in the dot occurs near the constrictions feeding the probes.[14]

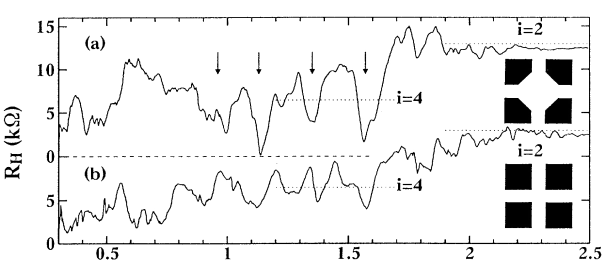

FIG. 1. R_H for (a) a widened cross without constrictions and (b) a normal cross, for a particular gate voltage V_g at which the dips in the widened cross went closest to zero. The arrows indicate the resonances. $T < 100$ mK.

In the widened cross [see inset to Fig. 1(a)], we found that at very low temperatures and high B a series of dips going close to zero appeared in R_H as the channels were made narrower by changing a gate voltage V_g [see Fig. 1(a)].[4] They occurred in the region associated with the $i=4$ quantized Hall plateau, and were not apparent in a "normal" cross having nominally square corners [Fig. 1(b)]. It was difficult to interpret these dips in terms of the passage of edge states around the junction and into the leads, because the leads were uniformly narrow for distances of a few microns around the junction, so that when the channels became very narrow, fluctuations in the channel width or potential would cause some parts of the channels to pinch off before others, leading to edge states being backscattered at unpredictable positions along the leads. We have therefore fabricated a sample identical to the previous widened cross, but with constrictions around the junction. Each constriction can be pinched enough to allow through only some of the edge states, largely avoiding the problem of width fluctuations in the leads.

There have been various theoretical predictions of resonances on or around quantized Hall plateaus.[9,11-13] Al-

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though some of these models can find more than one resonance per Hall plateau, the resonances are strongly attenuated with increasing temperature, due to smearing of the Fermi surface.[14] Most recently, Kirczenow has fitted the results we present here using a different model, which will be described in the following paper.[14]

The samples were fabricated on a GaAs-$Al_xGa_{1-x}As$ heterostructure with a 300-Å GaAs cap layer, by etching away the cap except over the conducting channels. The whole area was then covered with an Au gate, so that the channel width w and carrier concentration n_s could be varied by changing V_g.[15] The mobility was probably between 10 and 30 m^2/Vs for n_s in the range $(1-4)\times10^{15}$ m^{-2}. Magnetic depopulation of the one-dimensional subbands indicates that the corresponding widths were between 0.09 and 0.19 μm for uniform wires of lithographic width 0.3 μm. The constrictions in the third sample probably became much narrower than this, because care was taken to ensure that they were the narrowest parts of the device. Their short lengths ($\sim$0.07 μm) made irregularities and fluctuations less of a problem. High-quality electron-beam lithography enabled all four constrictions to be of very similar width, so that they would all pinch off at close to the same gate voltage. In fact, the pinch-off voltage was fairly well defined, and measurements could be made to within a few mV of threshold, at which point it was sometimes a current lead or sometimes a voltage lead which would pinch off first, indicating that at least two of the constrictions had very similar widths. At fields above a few tesla, some of the leads depopulated, and hence pinched off, completely.

The cross with constrictions was measured in a dilution refrigerator at temperatures from below 100 mK up to 8 K using a constant ac of 0.1 nA rms at 11 Hz and a phase-sensitive detector. Figures 2(a)–2(c) show the results at various gate voltages, for $T<100$ mK. In 2(a), the constrictions are fairly wide still, and quantized Hall plateaus are present, the lowest one being a long last plateau corresponding to three spin-degenerate edge states passing through the junction. Figures 2(b) and 2(c) show the case much closer to pinch off. At low magnetic fields, the Hall resistance R_H is negative, as found previously for a similar geometry.[3] A great deal of fairly random structure is visible on the curves, but the most remarkable feature of the data is that a series of dips develops in the $i=2$ (or maybe $i=4$) plateau as the channels are squeezed. When almost at pinch off [see Fig. 2(c)], R_H goes sharply to zero in four places (marked with arrows) between $B=0.4$ and 1.5 T, instead of remaining close to the last quantized Hall plateau as is usually found for small normal crosses at higher temperatures, and at higher V_g for this sample [Fig. 2(a)].[1–3] At these fields, edge states are reasonably well defined in the junction region since it is fairly wide, but at the probes the edge states try to leave the junction. Since the constrictions are very narrow, only one or two can leave, and electrons are more likely to scatter between the various edge states there. At particular fields, the phase changes and paths can be such that the probability of an electron leaving through the first probe it comes to is much reduced, and that of it leaving through another probe increased, giving rise to resonances in R_H where it goes to zero or to some other value.

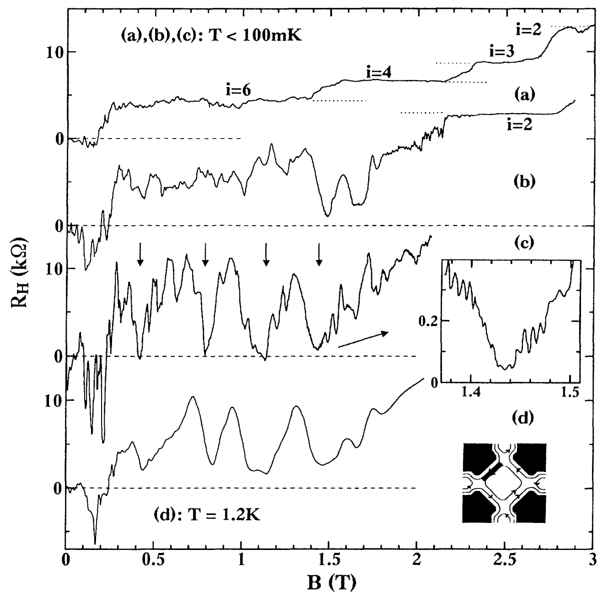

FIG. 2. (a)–(c) R_H for various values of V_g, for $T<100$ mK. The plateaus are labeled with the height h/ie^2. (a) is for $V_g\sim50$ mV above threshold (run III), (b) $V_g=0.085$ V, and (c) $V_g=0.026$ V (run I). The arrows indicate the resonances. The inset shows oscillations around $B=1.4$ T for a very similar V_g. (d) R_H for identical conditions to (c) but for $T=1.2$ K.

Our results have very recently been modeled by Kirczenow.[14] In this model, only one edge state is transmitted through each constriction, and incoming electrons can be scattered into the second edge state, which is confined inside the dot. The two states travel in parallel, their wave functions overlapping but not coincident, around to the next probe, where electrons in the second state may be scattered back into the first state and hence may pass through the constriction. The phase difference between these two paths depends on B, giving rise to oscillations in R_H, with period of order 0.3 T, for realistic values of the materials and scattering parameters. [Loosely, this is an Aharonov-Bohm effect between the two edge states due the flux enclosed between them, in the lightly shaded region in the inset to Fig. 2(d).] The minima may be zero or negative. We believe that these are the series of dips that we have observed. In the model, higher-frequency structure similar to that in Fig. 2(c) is also found, corresponding to interference between paths which encircle the whole junction in a particular state. The resonances observed here, *which completely break up the plateau*, are different from effects seen previously only in the risers of the QHE staircase from samples with special geometries,[16(a)] and from very-small-scale generic Hall bars.[16(b)]

Classical skipping orbits might instead account for the dips in R_H if both voltage probes were to meet an *anti*-focusing criterion at the same time. In the usual focusing experiment,[17] the injected electrons are focused on to the voltage probe whenever the classical cyclotron diameter

$d_c = 2\hbar k_F/eB$ is an even multiple of the length of the wall between the injector and detector. If (allowing for depletion around the edge) we take the distance from current to voltage probe to be 0.42 μm and estimate n_s to be 1.5×10^{15} m^{-2}, we expect that 3.6 cyclotron diameters will fit along one side at $B=1.1$ T, and 4.6 at 1.4 T, the positions of two adjacent minima. This is probably few enough bounces to allow simple focusing at this mobility if the walls are smooth, and the periodicity is appropriate. In order for R_H to go to zero at a series of four fields, however, both the focused beams from the current channels must *miss* the voltage probes at the same fields. This requires nearly perfect symmetry, which is probably not achieved in real samples. The interference model, on the other hand, is quite robust against asymmetry in the cross.

Figure 2(d) shows R_H at $T=1.2$ K, at the same V_g as in Fig. 2(c). The fine structure has almost disappeared, whereas the dips remain very pronounced, although they no longer reach zero. The junction is so small (0.4 μm across) that the phase-coherence length is probably still long enough at 1 K for electrons to travel coherently a quarter of the way around the junction. Note also the very sharp negative spike at low B, where the fine structure of the negative quench has become one very sharp and deep minimum, probably due to a classical focusing path between the constrictions around the junction,[8] which survives to higher temperatures than the fine structure because it does not require coherence and is only a short trajectory.

After the sample was cycled to room temperature and back, only one dip was apparent, going down to 10 kΩ *below* zero. Upon cycling it again (run III), we found at least three dips, in similar places to those shown in Fig. 2. On each occasion, the threshold voltage was different, due to the changing occupancy of surface states or the movement of impurities. A more extensive temperature dependence was measured, up to 8 K, as shown in Fig. 3. The minima gradually move up as T increases, but the strong negative dip at 175 mK has become a zero at 870 mK.

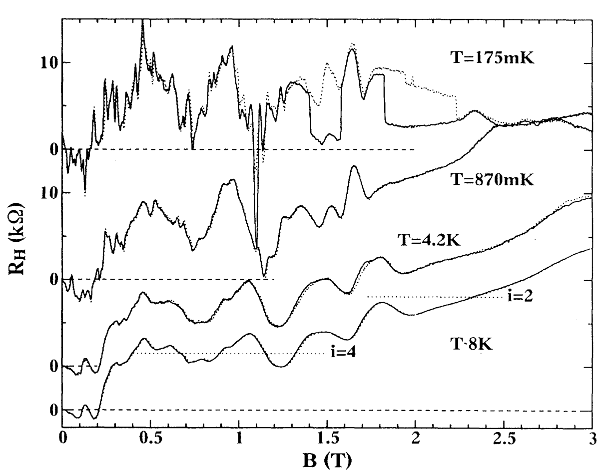

FIG. 3. The temperature dependence of R_H between $T=175$ mK and $T=8$ K (run III). The solid and dotted lines are up and down sweeps under the same conditions to show the degree of reproducibility. $V_g=0.042$ V.

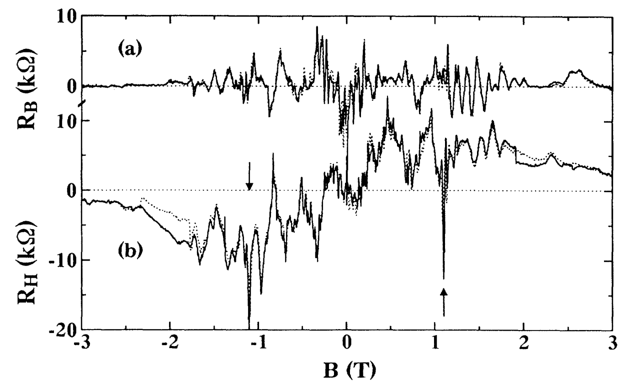

FIG. 4. R_H and R_B (the bend resistance), run III, $T<100$ mK, $V_g=0.044$ V. The arrows indicate a dip at $+B$ and a matching spike at $-B$.

The dips become a series of oscillations above and below $h/4e^2$ rather than just dips below the $h/2e^2$ plateau. This might be the case also at the lowest temperatures, or else the elevated temperature could be sufficient to give some electrons in the second edge state enough energy to surmount the barriers in the constrictions. The model[14] predicts that the high-temperature limit should indeed be a plateau at $h/4e^2$ provided that there is strong mode mixing at the constrictions and inelastic scattering within each state, but little mixing among the edge states in between.

Figure 4 contains R_H and R_B (the bend resistance[18]). The dips in R_H at $+B$ do not line up with those at $-B$, as expected for an asymmetric (i.e., any real) cross.[17] Sometimes dips at $+B$ complement spikes at $-B$ and sometimes large fluctuations in R_B (usually exactly zero in the absence of the resonant structure[18]) align with resonances in R_H. Frequently, however, there is no obvious correspondence between structure in R_H and R_B. All of these observations are consistent with the model calculations.[14] In the sample the asymmetry appears to be caused by impurities (probably not in the channel but close enough to change the width of a constriction) which rearrange from time to time (causing the random telegraph switching in Figs. 3 and 4) or between runs. The model allows for these impurity effects by invoking an *ad hoc* asymmetry in the junction. Slight lithographic asymmetries may also become significant in the constrictions where fractional width variations are largest.[19]

In conclusion, we have fabricated a quantum dot consisting of a widened junction between two pairs of high-mobility wires, with a constriction at the entrance to each lead. In the quantized Hall regime, it appears that only one edge state enters the junction from each lead and interacts with an edge state trapped there, producing an interference pattern as the magnetic field is varied, in agreement with a model proposed to explain our results. We see that a series of deep minima going to zero or below develops at low gate voltage due to this interference effect. We have also studied the bend resistance and temperature dependence of the effect, and find them to be in reasonable agreement with the model.

We would like to thank M. Büttiker for his advice and suggestions, and G. Kirczenow for sharing his results with us and for many fruitful discussions. We also thank K. R. Milkove for technical assistance.

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