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Selective backscattering and the breakdown of the quantum Hall effect

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We study the breakdown of the quantum Hall effect in a narrow channel using quantum point contacts as edge channel mixers, and as voltage probes. We observe a dependence of the two-terminal and Hall resistances in the breakdown regime on the adjustment of the point contacts, in a manner which demonstrates selective backscattering in the highest occupied Landau level. An extension of Buttiker's theory of the quantum Hall effect with a Hall-voltage dependent backscattering rate accounts for some of our observations.

The breakdown of the quantum Hall effect at high current densities (the regime of non-linear response) still is not very well understood [1–3]. Several mechanisms have been proposed (see ref. [3] for a recent discussion), but the interpretation of the experiments is not unambiguous. Experimentally, the breakdown is conveniently studied [2] in a narrow (~ 1 μm) channel or constriction. In such structures large Hall fields can be generated at moderate current levels (~ 0.1–1 μA). Recently, we have reported [4] results of an experimental study of the breakdown of the quantum Hall effect in a novel geometry, i.e., a narrow channel fitted with adjustable point contact voltage probes. We use the voltage probes as edge channel mixers [5], to regulate the equilibration of the highest occupied Landau level with the lower levels [5,6]. This technique has enabled us to demonstrate that breakdown occurs predominantly through selective backscattering of electrons in the highest Landau level [4]. In our previous report, we discussed predominantly results on the four-terminal longitudinal resistance of the channel. Here, we present supplementary data on the two-terminal and Hall-resistance, and compare these experimental results with a model based on Büttiker's theory of the quantum Hall effect [7], extended to the non-linear regime.

The top of fig. 1 gives a layout of the structure used in this work. The sample is fabricated from a high mobility (Al, Ga)As heterojunction wafer containing a 2DEG with a sheet electron concentration $n_s = 3.5 \times 10^{11}$ cm^{-2} and a mobility $\mu = 1.4 \times 10^6$ cm^2/V·s. In the figure, crosses indicate ohmic contacts to the 2DEG; the hatched areas are split gates that are used to electrostatically define a channel of width $W = 4$ μm and length $L = 18$ μm. Two opposite pairs of quantum point contacts are defined on the top (t_1 and

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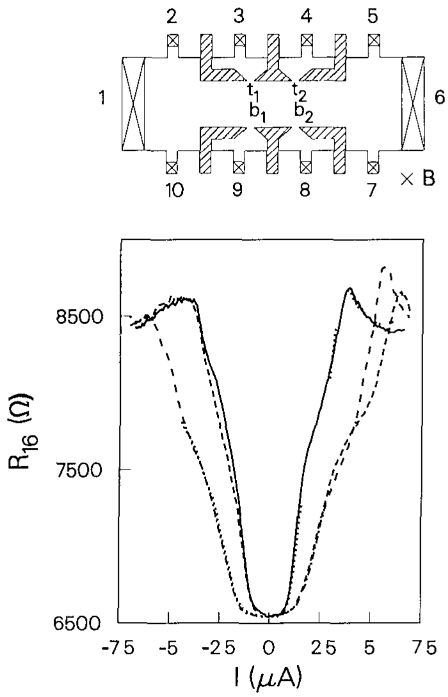

Fig 1 Top lay-out of the Hall-bar (not to scale), containing a narrow channel (of width 4 μm and length 18 μm) with point contact voltage probes (3 μm apart) Positive current flows from ohmic contact 1 to 6 Bottom two-terminal differential resistance R_{16} versus current for four different configurations of the point contact voltage probes $(N_t,N_b)=(2, 2)$ (solid curve), (1, 2) (dashed), (2, 1) (dotted), and (1, 1) (dash-dotted)

t_2) and bottom (b_1 and b_2) edge of the channel, with a separation of 3 μm between adjacent point contacts. The gate voltages are adjusted such that adjacent point contacts have equal resistance ($R_{t_1} = R_{t_2} \equiv R_t$ and $R_{b_1} = R_{b_2} \equiv R_b$). We present results obtained at a temperature of 1.65 K, and a magnetic field $B = 3.45$ T, corresponding to a filling factor $\nu = n_s h/2eB = 2.0$ in the narrow channel. (Because of electrostatic depletion, n_s in the channel is somewhat smaller than in the bulk 2DEG, where $\nu = 2.1$ at 3.45 T.) A current I is passed through the channel from ohmic contact 1 to 6. With the magnetic field direction as indicated in the figure, and for positive currents, the top edge of the channel has the highest electrochemical potential (i.e., it is charged negatively). The differential resistance between ohmic contacts i and j, $R_{ij} = \mathrm{d}V_{ij}/\mathrm{d}I$, with $V_{ij} \equiv V_i - V_j$, is measured using a low-frequency lock-in technique. Data have been obtained for four different sets of values of the point contact resistances R_t and R_b. These sets correspond to different numbers (N_t,N_b) of spin-degenerate edge channels that are fully transmitted through the point contacts on either side of the channel (note that $R_{t,b} = h/2e^2N_{t,b}$). The configurations used are $(N_t,N_b) = (2,2)$, (1,2), (2,1), and (1,1).

In the lower panel of fig. 1 we show the current dependence of the differential two-terminal resistance of the channel (R_{16}). Beyond a current of 1–2 μA, R_{16} suddenly increases, indicating the onset of breakdown. Clearly, the adjustment of the point contacts at the channel boundaries strongly influences the breakdown characteristics. When the point contacts transmit all edge channels ($(N_t,N_b) = (2,2)$, solid curve), the breakdown occurs at a relatively small current. However, when the highest occupied edge channel is reflected ($(N_t,N_b) = (1,1)$, dash-dotted), considerably larger currents are required to obtain breakdown. For positive currents, the breakdown curves for the mixed sets ($(N_t,N_b) =$ (1,2), dashed and (2,1), dotted) coincide with the curves for the symmetric sets (2,2) and (1,1), respectively. For negative currents, this correspondence is reversed. This implies that the breakdown characteristics are affected only by the adjustment of the voltage probes on the high-potential edge.

The effects of the adjustment of the point contacts on the breakdown can be understood qualitatively, assuming that backscattering occurs only in the upper Landau level, and that inter-Landau level scattering is negligible. Experimental support for both assumptions has been given in ref. [4]. The argument then is the following. Electrons entering the narrow channel along the top edge (assume positive current) in the highest Landau level are backscattered due to the proximity of the edge channel at the opposite edge. Further down the channel, a steady-state situation is reached, but when the highest Landau level is transmitted through the point contact at the high potential edge ($N_t = 2$), it is equilibrated with the other edge channels. This causes a repopulation of the partially depleted highest level,

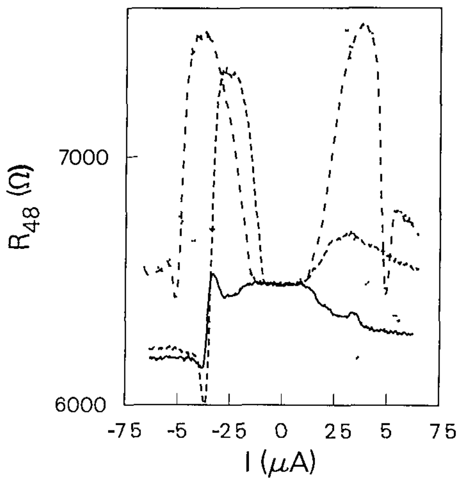

Fig 2 Differential Hall resistance R_{48} versus current for the same point contact configurations as in fig 1 (with the same coding of the curves)

and consequently a second opportunity for backscattering.

Fig. 2 shows the results of our experiments on the differential Hall resistance $R_{48} \equiv dV_{48}/dI$, measured using one of the quantum point contacts at the top (4) and one at the bottom (8) edge of the channel as voltage probes. In these data, we find a strongly enhanced breakdown when the point contact at the *low* potential edge is adjusted such that the highest occupied edge channel is not transmitted. We interpret this effect as a manifestation of the anomalous integer quantum Hall effect [6,8,9]. An anomalous Hall resistance is known to occur as a result of non-equilibrium population distribution of the edge channels, provided that at least one of the voltage probes used in the measurement is non-ideal (in the sense that not all edge channels are fully transmitted). In our experiment the current contacts are ideal, and the presence of a non-equilibrium population of the edge channels (essential for the observed anomalous behaviour) must be the result of selective backscattering in the channel. This observation supports our earlier conclusion [4] that breakdown occurs selectively in the highest Landau level, and is consistent with our interpretation of the two-terminal data, discussed above. For strongly positive currents, R_{48} as measured for the pairs (1, 1) and (2, 1) is suddenly reduced to values comparable to R_{48} for the pairs (1, 2) and (2, 2). (At strongly negative currents the same effect occurs for (1, 1) and (1, 2).) We attribute this to the onset of inter-Landau level scattering at the low-potential edge of the channel. A similar breakdown of adiabaticity has been observed in studies of the anomalous quantum Hall effect in wide conductors [8].

We have attempted to model our observations starting from Büttiker's description [7] of the quantum Hall effect in linear response. To account for the non-linearities, we have used an energy dependent backscattering probability $r(E)$ *which depends on the Hall voltage* V_{Hall} in a self-consistent manner. This is illustrated schematically in fig. 3, which depicts the variation of the energy of the highest Landau level along a cross section of the narrow channel at finite positive current [3], so that the electrochemical potential of the top edge (μ_t) is increased by eV_{Hall} with respect to that of the bottom edge (μ_b). Occupied states are denoted by a thick line for electrons with a negative group velocity, and by a dashed line for electrons with a positive group velocity. The bottom of the Landau level has energy E_0, which is independent of V_{Hall}. Fig. 3 illustrates that for electrons with energy E between μ_b and $E_0 + eV_{\mathrm{Hall}}$, the distance between the high- and low-potential edge can be continuously diminished by increasing V_{Hall}. We assume

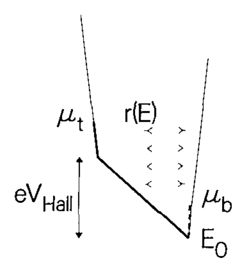

Fig 3 Schematic energy diagram of the highest occupied Landau level, tilted due to the Hall voltage V_{Hall} along a cross section of the narrow channel

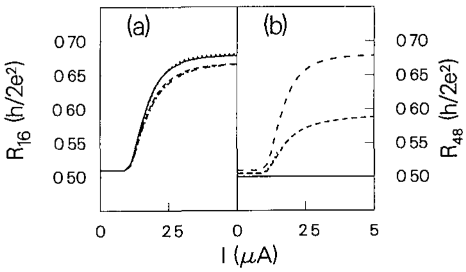

Fig 4. Results of our calculations for R_{16} (a) and R_{48} (b). The coding of the curves is the same as in figs. 1 and 2.

that backscattering in the highest level decreases exponentially with this distance, according to:

$$\begin{aligned} r(E) &= 0 \quad \text{for } E \leq E_0, \\ &= K \exp[-2(E - E_0 - eV_{\text{hall}})/eV_{\text{Hall}}] \\ &\qquad \text{for } E_0 < E \leq E_0 + eV_{\text{Hall}}, \\ &= K \quad \text{for } E > E_0 + eV_{\text{Hall}}. \end{aligned} \tag{1}$$

where K is a constant. We neglect backscattering in the lower Landau level. The above expression for $r(E)$ is incorporated in a set of Landauer–Büttiker equations describing a channel with two ideal current contacts, and two opposite point contact voltage probes, which are solved for the probe potentials. Since V_{Hall} and $r(E)$ are mutually interdependent, the calculation is iterated until a self-consistent result is obtained.

Results of our calculation for the differential resistances R_{48} and R_{16} are shown in fig. 4, for positive currents, and for filling factor $\nu = 2.0$. The value of $K = 0.067$ was chosen to yield approximately correct values for the differential resistance. The calculations for the two-terminal resistance R_{16} in fig. 4a exhibit for low currents a flat "quantized" region. In this region R_{16} is not exactly equal to $h/4e^2$, because of the finite backscattering probability $(r(E_F) \sim K)$ in the narrow channel for energies near the Fermi level ($E_F \approx \mu_b \approx \mu_t$ for low currents). The resistance starts rising steeply when $eV_{\text{Hall}} \approx \mu_b - E_0 \approx \hbar\omega_c/2$ (threshold of breakdown), and saturates for currents where the backscattering probability approaches $K \exp(2) \approx 0.5$ over a wide energy range, as follows from eq. (1) in the limit that $V_{\text{Hall}} \gg E, E_0$. Our calculations for R_{16} yield a similar pairing of the breakdown curves as the experimental data, reflecting the importance of the top edge voltage probes. The calculated Hall resistance R_{48} also agrees qualitatively with the experiment: the trace for $(N_t, N_b) = (1,1)$ shows the strongest anomalous resistance peak; the anomaly is somewhat smaller for (2, 1), and smaller still for (1, 2). For $(N_t, N_b) = (2, 2)$ no deviations from quantization occur, the reason being that the voltage probes used to measure the Hall resistance are ideal in this case.

Some notable discrepancies between calculation and experiment remain. Breakdown is found experimentally to occur at different current levels. In the calculation for the two-terminal resistance, however, the curves start to deviate from quantization at the same current level. For the Hall resistance, the experimental (2, 2) curve shows resistances reduced below the quantized value, whereas the calculation shows no breakdown at all. Also the reduction of R_{48} at large currents for the (1, 1), (1, 2) and (2, 1) configurations is not reproduced by the calculation.

In conclusion, our new experimental results support the idea proposed in ref. [4] that breakdown of the quantum Hall effect in a narrow channel proceeds predominantly via *selective* backscattering within the highest Landau level. Modelling the breakdown phenomena with a Hall-voltage dependent backscattering probability $r(E)$ yields a reasonable qualitative description of some characteristic features of the experiments, but other features call for a less simplified model (which presumably should also include inter-Landau level scattering).

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