Strong, Ultranarrow Peaks of Longitudinal and Hall Resistances in the Regime of Breakdown
of the Quantum Hall Effect

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With unusually slow and high-resolution sweeps of magnetic field, strong ultranarrow (width down to
100 μT) resistance peaks are observed when high currents are applied through quantum Hall samples.

The peaks are dependent on the directions and even the history of magnetic field sweeps, indicating
the involvement of a very slow physical process. Such a process and the sharp peaks are, however, not
predicted by existing theories. We also find that the sharp resistance peaks are influenced by the nuclear
spin flips.

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The integer quantum Hall effect (QHE) is a most remarkable phenomenon of two dimensional electron system
(2DES), in which the Hall resistance is quantized to $h/e^2$ while the longitudinal resistance nearly vanishes ($h$

is Planck’s constant, $e$ the electron charge, and $i$ an integer) [1]. To employ the QHE for the resistance standard, it is
desirable to apply a high current through a Hall bar. However, it was early discovered that the QHE breaks down if
the current reaches a critical value, $I_c$ [2,3]. Extensive investigations were thereafter performed to study the origin
of the breakdown [4–15]. So far, most studies have focused on factors that influence the critical current around,
in particular, even filling factors. A number of models have been proposed, such as inter-Landau-level scattering
[4,7] and the superheating process [2,5]. However, the exact mechanism responsible for the breakdown is still under
debate.

Here, we report on the measurement of the differential longitudinal and Hall resistances $R_{xx}$ and $R_{xy}$ (the derivative
of voltage with respect to the total applied current) at high injected currents close to $I_c$. With unusually slow,
high-resolution sweeps of magnetic field $B$, ultranarrow $R_{xx}$ peaks (width down to 100 μT) are observed. The peak
values exceed the resistances of the surrounding magnetic fields by a factor of 36. While no substantial change in
$R_{xy}$ is noticed around the odd filling factor $ν = 3$, strong, sharp peaks are also shown on the $R_{xy}$ curves for $ν = 2$
and 4. We find the peaks to be sensitively dependent on the directions and even the history of the $B$ sweeps. This
indicates that a physical process with a very large time constant is involved, which is orders of magnitude longer
than that which may be predicted by the existing models for the QHE breakdown. We will also show that the sharp
resistance peaks are influenced by the nuclear spin flips. Furthermore, we present a model which qualitatively explains
the different aspects of our observations.

We use two GaAs/AlGaAs modulation-doped heterostructures (wafer I and wafer II) with carrier densities of $n_s = 3.7$ and $3.5 \times 10^{15}$ m$^{-2}$ and mobilities of $μ = 59$ and 130 m$^2$/V·s at 0.3 K, respectively. A modulation-doped In$_{0.75}$Ga$_{0.25}$As/InP structure ($n_s = 2.8 \times 10^{15}$ m$^{-2}$, $μ = 22$ m$^2$/V·s) is also studied. For all these wafers, $I_c$ is found to scale linearly with the device width. The experiments are performed in a $^3$He refrigerator at 0.3 K. Hall devices with different widths (from 43 to 200 μm) and different geometries are investigated using a standard lock-in technique with a frequency of 17 Hz. Together with a 5 nA ac current, large dc currents, $I_{dc}$, are sent through the sample to drive the 2DES close to the regime of the QHE breakdown. Qualitatively similar behavior is observed in all samples fabricated from different material systems. We report here on measurements performed on a Hall bar made from wafer I.

The inset of Fig. 1(a) shows the curves of differential resistances $R_{xx}$ and $R_{xy}$ as a function of $B$ around $ν = 3$

and at a dc current close to, but below, the critical current $I_c = 11$ μA. The Hall bar has a width of 43 μm and five pairs of voltage probes, as is schematically shown in the inset of Fig. 1(b). The $B$ sweep is at a “normal” speed of 0.14 T/min and the curves are “as expected,” i.e., $R_{xx}$ nearly vanishes and $R_{xy} = h/3e^2$ within a $B$ range (i.e., the dissipationless regime) that is narrower than that at $I_{dc} = 0$. However, by reducing the sweep speed and increasing the magnetic field resolution, the two $R_{xx}$ peaks at the left and right edges of the dissipationless regime become successively higher and narrower. Furthermore, the curves of the upward and downward sweeps become increasingly different. Figure 1(a) shows the differential resistances around the left edge of the dissipationless regime at a sweep speed of 0.13 mT/min and a sweep step of 0.000015 T, which is the resolution of our magnet system. The arrows on the curves indicate the sweep directions. While there are only very small changes in $R_{xy}$, strong peaks are observed on the $R_{xx}$ curve. The narrower $R_{xx}$ peak has a full width at half maximum (FWHM) of only 100 μT. The resistance value at the peak is almost 4 times as high as the value at the Hall plateau and about 36 times higher than the $R_{xy}$ value on the lower $B$ side. For lower magnetic fields, $R_{xx}$ is found to remain virtually constant [16]. When sweeping upwards from 5.03 T, however, $R_{xx}$
narrow resistance peaks from different parts of the Hall bar. For instance, it can be seen in Fig. 1(b) that the peak on the higher field side has a fine structure, which can be seen on all the three traces. This rules out the possibility that our observations are due to local breakdown induced by inhomogeneities of the sample. Further studies of the fine structure, however, require a magnet system with a better resolution. The behavior of $R_{xx}$ and $R_{xy}$ at the higher $B$ edge of the dissipationless regime is very similar to that shown in Fig. 1. There, an upward sweep results in sharp $R_{xx}$ peaks while a downward sweep shows only a sudden drop to zero.

If $I_{dc}$ is decreased, the height of the $R_{xx}$ peaks is reduced, while the width increases. Furthermore, there is less difference in the $R_{xx}$ curves between upward and downward sweeps. Figure 2 shows the $R_{xx}$ traces obtained from different segments of the Hall bar at a lower current, $I_{dc} = 9.5 \, \mu$A. Five successive sweeps [Fig. 2, curves (a)–(e)] are made back and forth between 5.160

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FIG. 1. (a) $R_{xx}$ and $R_{xy}$ as a function of $B$ around $\nu = 3$ at $I_{dc} = 10.5 \, \mu$A. The sweep speeds are 0.13 mT/min (main curves) and 0.14 T/min (inset). (b) $R_{xx}$ curves of a downward sweep from different segments of the Hall bar, which is shown in the upper inset. The lower inset shows an NMR spectrum of $^{75}$As. The applied dc current is 8.5 \, \mu$A, with which a sharp $R_{xx}$ peak is detected at 5.0 T. By fixing $B$ at 5.0 T, however, we find that $R_{xx}$ slowly decreases with time and after about 15 min becomes stabilized at about 825 $\Omega$. By applying rf signal to a small coil around the sample, a clear threefold splitting is observed.

remains at this constant value (no peak structures) until it suddenly drops to zero at about 5.048 T. The behavior is thus totally different from the hysteresis effect of the breakdown of the QHE [2,3] where only a shift in the magnetic field position is observed.

We have simultaneously measured $R_{xx}$ using different segments of the Hall bar. Figure 1(b) shows the results of a downward sweep within 2 mT, using probes 1 and 2, 2 and 3, and 4 and 5. We obtain almost identically strong,
and 5.175 T with a speed of 0.3 mT/min. The curves are plotted only in the range between 5.1625 and 5.1690 T for clarity. The change in the peak position of about 3 mT with sweep direction is most likely due to hysteresis of the magnet system. Although each sweep takes about 1 h, the peak structure changes gradually, indicating the involvement of a very slow physical process. We have noticed the following points. First, curves obtained in the same sweep direction, such as (a), (c), and (e) or (b) and (d), are similar. Second, the greater the number of sweeps made, the less the difference in the $R_{xx}$ curves between upward and downward sweeps. This can already be seen from the increased similarity between (d) and (e), and is more clear in later sweeps (not shown here). Third, an increasing number of peaks and fine structures are obtained when more sweeps are made. This rules out any trivial heating effects, as heating is expected to smear out fine structures.

Although strong peaks are observed on the $R_{xx}$ curves, the Hall resistance around $\nu = 3$ shows only small changes, as can be seen in Fig. 1(a). The behavior of $R_{xy}$ around the even filling factors $\nu = 2$ and 4 is, however, totally different. This suggests that the phenomenon is connected with the spin of the 2DES. Figure 3 shows three $R_{xx}$ traces taken from different segments of the Hall bar and one $R_{xy}$ curve around $\nu = 2$. The dc current is 24 $\mu$A, which is about $I_c/2$ at this filling factor [17]. In contrast to the results for odd filling factors [see Fig. 1(a)], an equally strong, narrow peak (FWHM below 3 mT) forms on the $R_{xy}$ trace as on the $R_{xx}$ traces. The peak value is more than 5 times higher than the Hall plateau $h/2e^2$.

It can be observed that $R_{xx}$ becomes negative on the higher $B$ side of the peaks in Fig. 3. A dc measurement of the longitudinal resistance is shown in the inset. Obviously, dc resistances can be quite different from differential resistances in the nonlinear regime. This is the reason why no anomalous behavior is observed in the dc measurement at 8.1354 T where sharp peaks form on the differential resistance curves. In fact, we do not see any unusual behavior of the dc resistance at other $B$ values.

The general features reported here are observed at all filling factors at sufficiently high magnetic fields and in all the Hall bars and wafers studied. Thus, the above phenomena seem to be general in 2DES. The fine structures are, however, very difficult to fully reproduce in different samples. This is, at least in part, due to the fact that the fine structures are extremely sensitive to the exact $I_{dc}$ used, sweep speed, starting point of sweeps, history, etc.

While many disordered electronic systems are characterized by very slow relaxations [18], to our knowledge, the above unusually slow physical process has never been observed in the integer QHE regime. It is orders of magnitude slower than the time scale of the instabilities in the regime of the QHE breakdown [3,8,9]. The existing models for the breakdown of the QHE, such as inter-Landau-level scattering [4,7] and electron superheating [2,5], do not predict any physical process with a time constant longer than microseconds. Interestingly, we have noticed that certain aspects of our observations, such as the long time constant, strong $R_{xx}$ peaks, and current dependence, are similar to the recently discovered anomalous resistance peaks in the fractional QHE regime at $\nu = \frac{2}{3}$ and $\frac{3}{3}$ [19]. However, some other aspects are different, such as the existence of fine structures, strong $R_{xy}$ peaks, the much sharper peaks (more than 3 orders of magnitude narrower), etc. Very recently, the peaks observed in Ref. [19] were found to be influenced by the nuclear spin polarization [20]. We have also performed nuclear magnetic resonance (NMR) experiments on $^{75}$As, $^{69}$Ga, and $^{71}$Ga. A typical result for $^{75}$As is shown by the lower inset in Fig. 1(b). The splitting of the line is, however, threefold—that is, different from the fourfold splitting observed in Ref. [20]. Furthermore, we observe resonance peaks rather than dips as in Ref. [20]. While the above NMR response is strong in the GaAs/AlGaAs samples, so far, no clear observation has been obtained in our InGaAs/InP samples. One reason might be the comparatively low mobility of those samples.

In the following, we present a model, which qualitatively explains the different aspects of our observations. In the $B$ range of a dissipationless regime, the bulk of the Hall bar is actually insulating. In the single-particle picture, if $B$ is sufficiently high, each Landau level is split into two well-separated, spin-polarized levels with a degeneracy proportional to $B$. Therefore, a change in $B$ will induce a redistribution of the electrons in the bulk of the Hall bar (denoted “bulk electrons”) among the Landau levels, i.e., some electrons need to have their energies changed and their spins flipped in order to achieve equilibrium. However, as the bulk electrons have no effective interaction with the electrons at the edge nor with electron reservoirs (the Ohmic contacts) in the

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dissipationless regime, the scatterings required to flip the spins and change the energies are virtually absent. The redistribution among the single-particle Landau levels is thus not possible. This means that the bulk electrons can be far from the “normal equilibrium” (the equilibrated distribution among the single-particle Landau levels) inside the dissipationless regime if \( B \) is changed. To the best of our knowledge, no study has been carried out on how these electrons redistribute in the energy and spin space in such a “nonequilibrium” situation. As it is not possible for the bulk electrons to redistribute among the single-particle Landau levels, effects such as electron-electron interactions must take place. We speculate that the real distribution maintains some order, which means that the electrons might rearrange to form “minigaps” and “minibands” in the energy and spin distribution.

When the 2DES starts to enter the dissipation regime where the bulk-edge interactions are still considerably weak, we expect the electrons in the minibands to be affected. Each time a miniband starts to participate in the scattering process, a differential resistance peak is observed. In this picture, the multiple resistance peaks and fine structure reflect the miniband structure of the nonequilibrium distribution of the bulk electrons. One may speculate that similar nonequilibrium distribution also forms in the fractional QHE regime \([21]\), which might as well give rise to resistance peaks. If a strong current is applied to the Hall bar, the large Hall electric field will substantially enhance the interaction between the electrons at the edge and those in the bulk, and therefore give rise to much stronger and sharper resistance peaks, in agreement with our experimental observations. Note that the ranges of \( B \) in which the resistance peaks and fine structures are observed are only slightly away from the dissipationless regime. Therefore, the scattering between electrons in the bulk and electrons at the edge is expected to be rather weak. In addition, since the bulk area of a Hall bar is fairly large, the time constant of the equilibration can be very long, which explains the slow physical process indicated especially in Fig. 2. The details of the distribution of nonequilibrium electrons, and thereby the minibands, depend on the initial \( B \) position, the sweep direction, and the sweep speed. This thus explains the observed strong dependence of the resistance peaks and fine structures on the experimental history.

The observed NMR resistance peaks shown in the inset of Fig. 1(b) also support our model. The dynamic nuclear polarization has been observed as Overhauser shifts in electrically detected spin resonance experiments \([22]\) and in, e.g., the time dependency of current-voltage characteristics in transport experiments in which spin polarized electrons were injected \([23–25]\). Via the hyperfine interaction an electron spin can flip with a simultaneous flop of a nuclear spin, which can be induced by, for example, applying NMR rf signals \([26]\). Because in our model the lack of electron spin-flip scatterings is the reason for the nonequilibrium distribution of bulk electrons, the additional electron spin-flip scattering induced by the NMR signals will reduce the degree of nonequilibrium distribution. This leads to an increased scattering probability from edge to bulk, which is detected as an increase of the resistance, as shown in the lower inset of Fig. 1(b). The threefold splitting is most likely caused by the electric quadrupole interaction, which is possible in our sample where large electric field gradients are expected.

To conclude, unexpected strong, ultranarrow resistance peaks have been observed when high currents are applied through QHE samples. The possible role of nonequilibrium of bulk electrons has been demonstrated.

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[16] \( R_{xx} \) actually has a very weak linear dependence on \( B \).
[17] If \( I_{dc} \) is increased close to \( I_{c} \), at \( v = 2 \), the \( R_{xx} \) and \( R_{xy} \) curves (not shown here) exhibit complicated structures with serious instability behavior.