New Resistance Maxima in the Fractional Quantum Hall Effect Regime

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The magnetoresistance of a narrow single quantum well is spectacularly different from the usual behavior. At filling factors $\frac{2}{3}$ and $\frac{3}{5}$ we observe large and sharp maxima in the longitudinal resistance instead of the expected minima. The peak value of the resistance exceeds those of the surrounding magnetic field regions by a factor of up to 3. The formation of the maxima takes place on very large time scales which suggests a close relation with nuclear spins. We discuss the properties of the observed maxima due to a formation of domains of different electronic states. [S0031-9007(98)07239-1]

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The integer and fractional quantum Hall effects (IQHE [1] and FQHE [2]) have been the subject of intense investigation for more than a decade. The basic properties of these effects are both quantization of the transverse resistance and the nearly complete vanishing of the longitudinal resistance. These two properties are observed in more or less all two dimensional electron gases (2DEG) subjected to an intense magnetic field. The physical reason for the IQHE is the splitting of the electronic energy spectrum of a 2DEG into Landau levels in a magnetic field. If the Fermi energy lies in the regime of the localized states between two Landau levels, one obtains an insulating phase which leads to the IQHE. In the case of the FQHE, one of the Landau levels is filled by a rational fraction with charge carriers, and a gap in the excitation spectrum is also observed. In an elegant approach the descriptions of the IQHE and the FQHE have been unified in the composite fermion picture [3,4].

The energy gaps which are responsible for the FQHE are the result of electron-electron interaction [5,6]. Therefore, the properties of these fractional states depend not only on the Landau level filling factor but also on the interaction strength between the electrons. Chakraborty and Pietiläinen [7] calculated the ground and excited states in the FQHE and postulated that many fractions show a nontrivial behavior. For example, their model calculations showed that the ground state of filling factor $\frac{2}{3}$ is partly polarized if $B < 7$ T but if $B > 15$ T it is fully polarized, and in the intermediate regime the gap vanishes. This behavior has experimentally been observed with magnetoresistance measurements in tilted magnetic fields [8–10]. A question that naturally arises is, If one would succeed in modifying the electron-electron interaction, can other nontrivial effects be found in the FQHE regime?

The interaction strength depends very much on the sample properties such as mobility and finite layer thickness [11]. Experimental studies of the well-thickness dependence were difficult in the past due to lack of samples having both high mobility and narrow well thickness. We have succeeded in realizing such 2DEG structures and have indeed found unexpected and dramatic resistance structures at several fractional filling factors between $\nu = 1$ and $\nu = \frac{1}{2}$. At these filling factors the longitudinal magnetoresistance shows narrow and large maxima instead of the expected and well-established minima.

In this experiment we use a modulation doped AlGaAs/GaAs structure with a GaAs quantum well of 15 nm thickness; the spacer thickness is 120 nm. A typical carrier density is about 1.3×10^{11} cm^{-2} after illumination with a light-emitting diode. At this density the mobility of the sample is 1.8×10^6 cm^2/V s. The samples are processed in the shape of a standard Hall bar and contacted by alloying In. Measurements are done on two different Hall bars having different widths (80 and 800 μm). Four voltage probes along the Hall bar are used to verify the spatial homogeneity of the longitudinal resistance. The resistance measurements are performed either in a ^{3}He bath cryostat at 0.4 K or in a dilution refrigerator at 40 mK using a standard ac lock-in technique with a modulation frequency of 23 Hz. We also make dc measurements and find identical magnetoresistance traces. In this Letter we show only ac results.

The longitudinal resistance (R_{xx}) of the 80 μm Hall bar, measured at 0.4 K with a sweep rate of 0.7 T/min and a current of 100 nA, is shown by the thin line in Fig. 1. The resistance shows no unusual behavior at this sweep rate. The minima of the IQHE are well developed and in the fractional regime the minimum at $\nu = \frac{2}{3}$ approaches zero. If, however, the sweep rate of the magnetic field is reduced to 0.002 T/min, a huge longitudinal resistance maximum (HLR) develops very close to the original minimum at $\nu = \frac{2}{3}$. This resistance peak stands out dramatically from the resistance values at the surrounding magnetic field regions. Particularly striking is the sharpness (width $\Delta B \approx 0.2$ T) of the HLR. This anomalous HLR is observed in all studied samples

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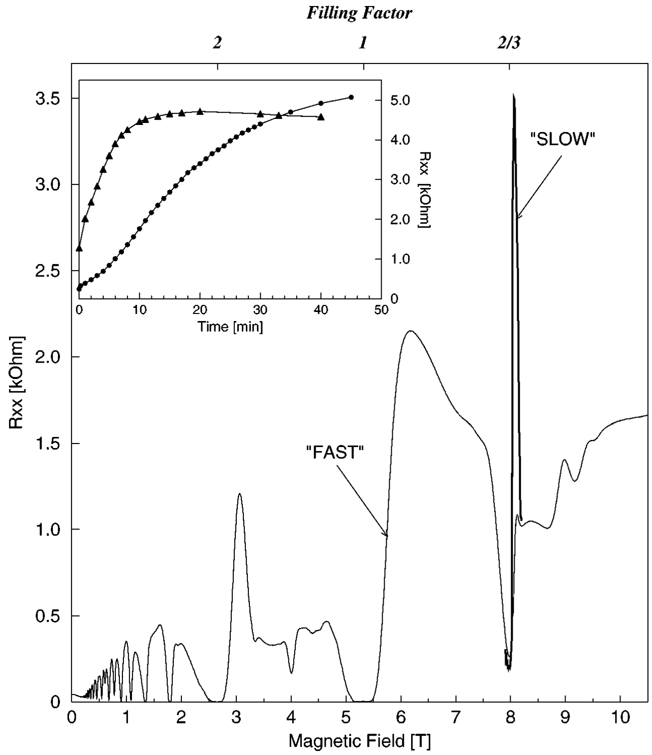

FIG. 1. The longitudinal resistance of a Hall bar at 0.4 K. If the magnetic field is swept upwards very slowly (0.002 T/min, trace "slow"), one observes a very prominent and sharp huge resistance maximum at filling factor $\frac{2}{3}$. The inset shows the temporal evolution of the HLR for two different sample widths [800 μm (dots) and 80 μm (triangles)].

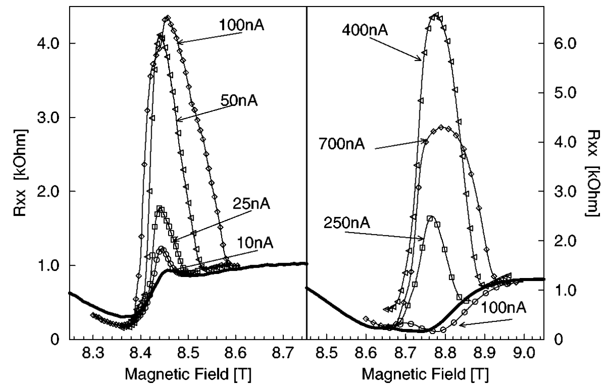

FIG. 2. Result for Hall bars of two different widths, 80 and 800 μm, left and right panel, respectively. All sweep rates are 0.002 T/min. The currents are given in the figure. The maximum is most prominent at finite currents which correspond to nearly identical current densities in the two samples. The bold lines correspond to fast sweeps.

from this wafer. The position of the maximum remains at filling factor $\nu = \frac{2}{3}$ even if the carrier density is varied over the range of 1.2×10^{11} cm^{-2} to 1.4×10^{11} cm^{-2}.

Typical times to form the HLR are determined by setting the appropriate magnetic field and recording R_{xx} as a function of time. Examples are shown in the inset of Fig. 1. It takes 20 min for the HLR to saturate in the case of the 80 μm Hall bar, and several hours for the 800 μm wide one. These times are longer than the internal electronic relaxation times expected in this system.

Figure 2 shows the current dependence of the HLR for two different samples. The left panel shows the results obtained with the 80 μm wide Hall bar and the right one shows those obtained with the 800 μm wide one. Surprisingly, the height of the HLR depends on the current. For the data of the left panel the maximum of the HLR is achieved for current values exceeding approximately 50 nA. For the wider samples (right panel) approximately 400 nA are necessary, corresponding to nearly identical current densities of about 0.6 mA/m. In some cases, the resistance maximum decreases substantially at higher current densities. The right panel shows an example.

The fact that the peak resistance of the maxima is usually more than 2 times larger than the resistance at the surrounding magnetic field regions rules out any trivial heating effects. Heating could be responsible for the decrease of the HLR at larger currents since the HLR vanishes at bath temperatures exceeding 0.6 K at all currents. With the same arguments we can also rule out current-induced breakdown of the QHE. Contact problems can be ruled out because the contact resistances are less than 400 Ω and they are not dependent on the magnetic field, as checked in the IQHE regime.

Unexpected large resistance values in 2DEGs have been reported before in systems which undergo a metal-insulator phase transition [12]. We believe, however, that this does not occur in our experiment. First, no resistance maxima nearly as sharp as we observe have been reported. Second, the current dependence of our maximum does not point to the formation of an insulating phase because the resistance should rather increase for smaller currents in case of a metal-insulator transition. Nevertheless, we performed measurements in a dilution refrigerator at 40 mK to test the possibility of an insulating phase. Indeed, the measurements at 40 mK do not support the occurrence of an insulating phase, we rather find a much more complicated behavior of the huge longitudinal resistance.

In Fig. 3 we show results obtained at 40 mK. The dashed trace shows the longitudinal resistance as a function of the magnetic field from 6.5 T (i.e., $\nu = 1$) up to 12 T at a sweep rate of 0.3 T/min. A very regular behavior is observed at this "fast" sweep rate. The minima at $\nu = \frac{2}{3}$ and $\nu = \frac{3}{5}$ are well developed. The dotted trace shows the results of the same measurement with the magnetic field being swept down at the same rate. The curves are markedly different in the magnetic field range from 8.5 to 11.5 T (filling factors $\nu = \frac{2}{3}$ to $\nu = \frac{1}{2}$). The difference is even more pronounced if the down-sweep is performed at a slower rate such as 0.006 T/min. We observe an anomalous behavior, a huge longitudinal resistance in

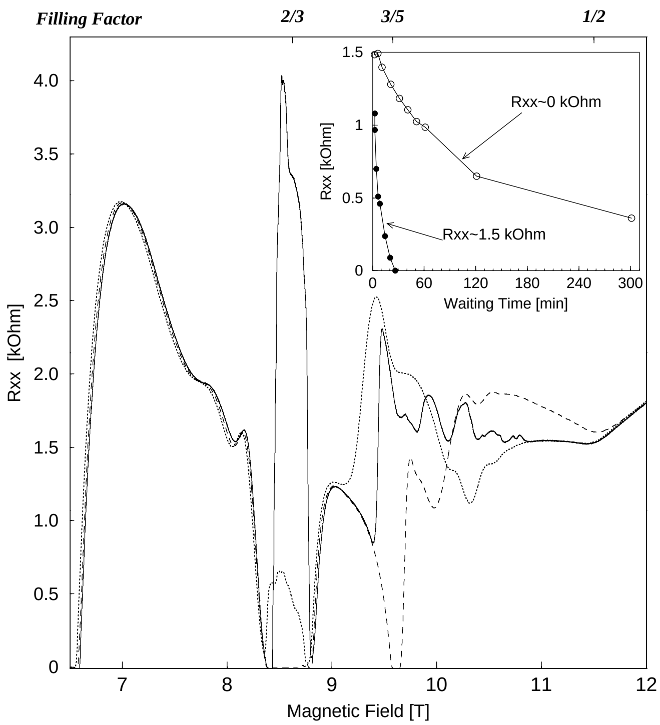

FIG. 3. Longitudinal resistance measurements at 40 mK (80 μm width, 100 nA). The HLR is not observed when sweeping the field upwards (0.3 T/min, dashed trace). If the field is swept up with 0.006 T/min, the anomalies exist but are usually relatively small. It is already seen in relatively fast down-sweeps (0.3 T/min, dotted trace), but is fully developed at slow down-sweeps (0.006 T/min). The HLR can now be seen also at fractions such as $\frac{3}{5}$. The inset shows the relaxation of the HLR via conduction electrons if the sample is temporarily kept at different magnetic fields.

the down-sweeps at all filling fractions that are well developed between filling factor $\nu = \frac{1}{2}$ and $\nu = 1$ in the fast up-sweep. We take this again as a signature that the HLR is indeed closely related to the formation of the FQHE. However, it is noteworthy that the FQHE is also well developed at magnetic fields corresponding to filling factors below $\nu = \frac{1}{2}$ and to filling factors between $\nu = 1$ and $\nu = 2$, but we cannot find any anomalous behavior in those regions so far. The data of Fig. 3 show that the qualitative behavior of the HLR is the same at 40 mK and at 0.4 K. Particularly, the anomalous resistance value at $\nu = \frac{2}{3}$ does not exceed the one at higher temperature, which makes a metal-insulator transition unlikely. Furthermore, the dependence of the HLR on current was approximately the same as at higher temperatures. In addition, the time scale on which the HLR reaches its maximum value is very similar to the one observed at 0.4 K.

The main difference between the two temperatures is, first, that the HLR is observed at more fractions and, second, that the hysteretic behavior is much more pronounced at the lower temperature. For example, when sweeping the magnetic field upwards we usually do not observe the HLR peaks. Exceptions to this are related to the history of the sample, for example, if a down-sweep was made shortly before. A slight hysteresis remains at temperatures above about 250 mK: The width of the HLR peak is smaller when sweeping the magnetic field upwards as compared to sweeping downwards.

Measurements of the Hall resistance (R_{xy}) reveal that the quantized Hall resistance disappears whenever the HLR is observed. There are, however, deviations from the classical (linear) behavior. In the HLR regime the R_{xy} is approximately 2% less than the classical value when sweeping upwards and approximately 2% more when sweeping downwards, i.e., the hysteretic behavior is also shown by the Hall resistance.

It is rather unusual to find such pronounced resistance peaks in magnetic field regimes where one observes minima and a nearly complete disappearance of the longitudinal resistance. The new effect is not just a consequence of the very slow sweep rates because we already observe the HLR with standard sweep rates at 40 mK. One difference between our sample and those which are traditionally used is the reduced thickness of the quantum well in combination with the high mobility of the 2DEG. The importance of the experimental parameters is underlined by our observation that the HLR disappears completely if the sample is tilted by 40° against the magnetic field direction (Fig. 4). Furthermore, when a carrier density of 0.9×10^{11} cm^{-2} was achieved on a different cool-down, the effect likewise disappears.

For the HLR to occur, it seems not to be enough to have a state with a vanishing excitation gap because, if this were the case, we would not expect the resistance maxima to be larger than the resistance in the surrounding magnetic field regions. Actually, according to [11], the reduction of the well thickness should lead to an increase of the excitation gap, i.e., an increased stability of the FQHE, which is contrary to what we observe. Therefore the explanation of this new effect must be found elsewhere.

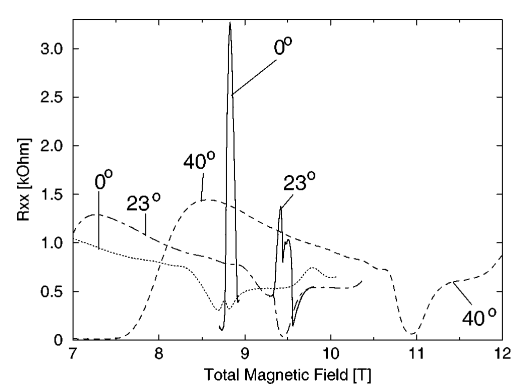

FIG. 4. R_{xx} for different tilt angles; broken lines: fast sweep; solid lines: slow sweep. At 40° the effect is not visible for all sweep rates down to 0.002 T/min.

We think it is possible that the electronic system separates spontaneously into different domains. The high resistance would then be a consequence of the domain walls. The formation of domains would rather naturally explain the different time constants which we observe in Hall bars of different widths. Possible candidates for such phases are the two different ground states for filling factor $\nu = \frac{2}{3}$ which were predicted in [7]. These two phases differ in total spin of the ground state and in the size of the excitation gap. Let us assume that in our experimental situation the energies of these two ground states are nearly identical. Then the formation of a domain structure is conceivable. Similar competing ground states are predicted theoretically and are found experimentally at $\nu = \frac{3}{5}$ [10], where we also see the HLR. At $\nu = \frac{2}{5}$, on the other hand, the spin unpolarized state has only been found under high pressure [13] and therefore the nonoccurrence of the HLR seems logical. Our experimental data do indeed strongly support a close connection with the electron spin. First, we do not observe the HLR at $\nu = \frac{1}{3}$, where theory does not predict the formation of competing ground states. Second, tilting of the sample leads to a rapid disappearance of the HLR. This is a strong hint that the HLR is connected with the electron spins because the additional parallel magnetic field component affects mainly the Zeeman energy of the electrons. At the lower densities the relative balance of Coulomb and Zeeman energies is different which may prevent the domain formation.

With such a domain structure, it is necessary that the spins of some of the electrons flip. Since electron spin flips are very often connected to nuclear spin flips, it is possible that an electronic domain structure is related to a domain structure in the spin configuration of the nuclear system. Actually our results are very supportive of a close relation between the nuclear spins with the resistance maxima. Long time constants, of the order of several minutes to several hours, are very typical of nuclear spins of this type of host lattice [14]. We assume that the domain structure must be stabilized by a nuclear spin polarization and therefore takes a long time to form. On the other hand, an existing nuclear spin polarization should facilitate the formation of the electronic domains. This was verified by the following experiment: The magnetic field and the current are set to have the maximal HLR. After the HLR is fully developed, we sweep the magnetic field fast to a "waiting" position, where the magnetic field is kept constant for times varying from a few seconds to five hours. Then the magnetic field is set back to the original value and R_{xx} is read immediately. In this way, one can determine the relaxation time of the HLR as a function of the density of extended electronic states at the Fermi edge. Results are shown as inset of Fig. 3. The two sets of data correspond to magnetic fields representing two different longitudinal resistances of the sample, about 8.1 T (solid dots) and 8.55 T (hollow dots), respectively. In the first case R_{xx} is about 1.5 kΩ, i.e., the Fermi energy is in the region of extended electronic states. One sees that the HLR decays rapidly. In contrast, the relaxation time is of the order of hours if the waiting field is 8.55 T. At this field, the resistance is nearly zero and the Fermi energy is in the region of localized states. This difference in time constants is exactly what is expected for the relaxation of nuclear spins via conduction electrons (Korringa effect [15]).

In conclusion, we have found sharp resistance maxima at fractional filling factors between $\nu = 1$ and $\nu = \frac{1}{2}$, where the resistance tends to vanish in standard samples. We suspect that these resistance maxima are caused by a domain structure of different electronic spin states connected with a nuclear spin polarization. This new effect seems to be a consequence of slightly different experimental parameters, especially the quantum well width, compared to other similar experiments.

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