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Hysteresis and spikes in the quantum Hall effect

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We observe sharp peaks and strong hysteresis in the electronic transport of a two-dimensional electron gas (2DEG) in the region of the integral quantum Hall effect. The peaks decay on time scales ranging from *several minutes* to more than an *hour*. Momentary grounding of some of the contacts can vastly modify the strength of the peaks. These features disappear under application of a negative bias voltage to the backside of the specimen. We conclude that a conduction channel parallel to the high mobility 2DEG is the origin for the peaks and their hysteretic behavior.

The hallmarks of the integral and fractional quantum Hall effects are wide regions of vanishing magnetoresistance and wide plateaus in Hall resistance.[1–3] These features are centered around magnetic fields that correspond to integral or fractional fillings of Landau levels of a two-dimensional electron gas (2DEG). Their origin is quantization of the electron orbits into Landau levels and the formation of localized states in real, slightly disordered 2DEG in the presence of a high magnetic field B. Electrons in the localized states provide a reservoir in equilibrium with the current-carrying, delocalized states and keep their occupation constant over wide stretches of B. While in the integral quantum Hall effect (IQHE) (Ref. 1) the ingredients of this picture are of single-particle origin; they are of many-particle origin in the fractional quantum Hall effect (FQHE).[2,3]

Two recent experiments have observed hysteretic behavior and/or peak formation in electronic transport of 2DEG in the regime of the FQHE.[4,5] Minor discrepancies in data taken on opposite field sweeps are common and are usually attributed to the large inductance of the magnet and the resulting time delays or to slight temperature differences between both sweeps. However, the recently observed effects are very large. Kronmueller *et al.*[4] observed the appearance of a huge spike at the position of the $\nu=2/3$ minimum when the magnetic field is ramped very slowly. The time scale for development of this feature can be as long as hours, which suggested to the authors the involvement of nuclear spins in its creation.[6] Cho *et al.*[5] have observed hysteretic behavior in resistance traces taken on several fractions around filling factor $\nu=1/2$ and attribute it to nonequilibrium phases of composite fermions in this regime. The origin of these observations remains puzzling and the nature of the underlying nonequilibria remains unclear.

We have observed strong hysteresis and the formation of sharp peaks in magnetotransport experiments on 2DEGs in quantum wells in the regime of the IQHE at temperatures of $\sim$0.1 K. To our recollection, we have never observed such features in a traditional single heterojunction interface sample. Their lifetime can be strongly altered by momentary grounding of the contacts. Hysteresis and spikes disappear on application of a voltage bias to an electrode on the back side of the specimen. We conclude that the origin of hysteretic behavior and spike formation in our samples is the result of a nonequilibrium charge distribution, which arises due to the coexistence and dynamic exchange of electrons between the high-mobility 2DEG and a low-mobility parallel conduction channel in the vicinity of the doping layer.

Our samples are modulation-doped GaAs/$Al_xGa_{1-x}As$ *quantum-well* structures grown by molecular-beam epitaxy (MBE). A high density 2DEG resides in a 300 Å-wide quantum well 2000 Å below the surface. The well is δ doped on both sides with silicon impurities at a distance of 950 Å in sample A and 750 Å in sample B. Samples are cleaved into 4 mm$\times$4 mm squares and eight indium contacts are diffused at the corners and the middle of the edges. Transport measurements are performed using standard lock-in techniques in a dilution refrigerator with a base temperature of 70 mK. A 100 nA current is used in most of the measurements. Both samples have mobility higher than 13×10^6 cm^2/V sec. The density is 2.3×10^{11} cm^{-2} in sample A and 3.2×10^{11} cm^{-2} in sample B.

As an example of the hysteresis and resistance spikes that arise at many IQHE positions, we show in Fig. 1 the magnetoresistance R_{xx}, of sample A in the vicinity of filling factor $\nu=3$, measured at a slow sweep rate of 0.05 T/min. Solid and dash-dotted lines represent traces taken on upward and downward field sweeps, respectively. Both traces largely reproduce, although there is a slight discrepancy in the position of the high-field flank. Most remarkably, however, a sharp spike appears in the central part of the $\nu=3$ minimum. This peak is only $\sim$0.01 T wide, comparable in height to the surrounding R_{xx}, and it is completely missing on the upsweep.

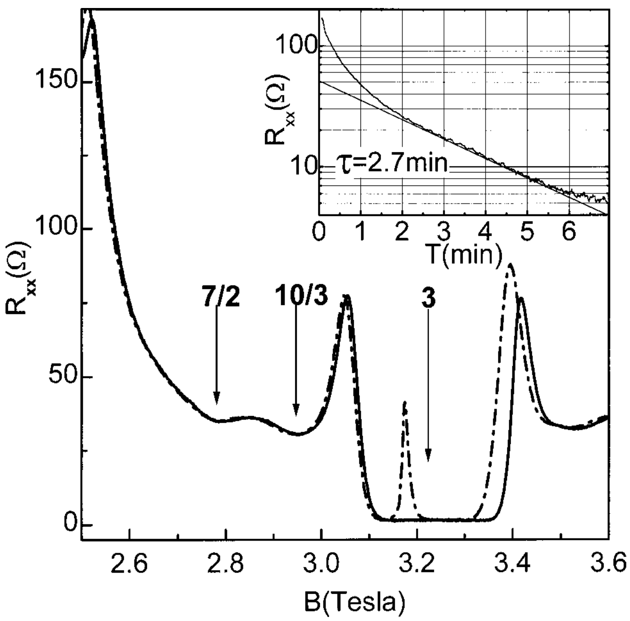

FIG. 1. Magnetoresistance of sample *A* in a magnetic field from 2.5 to 3.6 T. Solid and dash-dotted traces represent upward and downward field sweep, respectively. Arrows indicate filling factor ν. A sharp hysteretic resistance peak occurs at $\nu=3$. Inset: A typical decay process of the peak at $\nu=5$.

Hysteretic resistance peaks similar to the one observed around $\nu=3$ occur in our sample at the positions of most resolved integral filling factors. Figure 2 shows an extended R_{xx} trace of sample *A*. A superposition of two oscillations is evident. A set of sharper Shubnikov–de Haas (SdH) oscillations is superimposed on a slowly oscillating background. In spite of this complication, we can clearly identify the positions of the IQHE minima in the SdH oscillations, of which we have labeled $\nu=3$–9 (see also inset on an expanded scale). Similar to the occurrence of the sharp peak in the $\nu=3$ minimum, such spikes are also present at these higher filling factors (see circles), most notably at $\nu=5$, where the spike dominates over any other feature of this trace. The details of the hysteresis vary. The peaks appear on the up-sweep ($\nu=9,7,6,5$) or on the down-sweep ($\nu=3$) and in some cases in both directions, but with very different amplitudes ($\nu=8$). Instead of being absent in one direction, the previous peak position is sometimes marked by a small dip. At fields higher than $\nu=3$ and up to the highest field of 14 T (not shown), traces from both field sweeps largely reproduce and there are no further spikes observed. In this high-field regime all the regular features of the IQHE and FQHE are well developed.

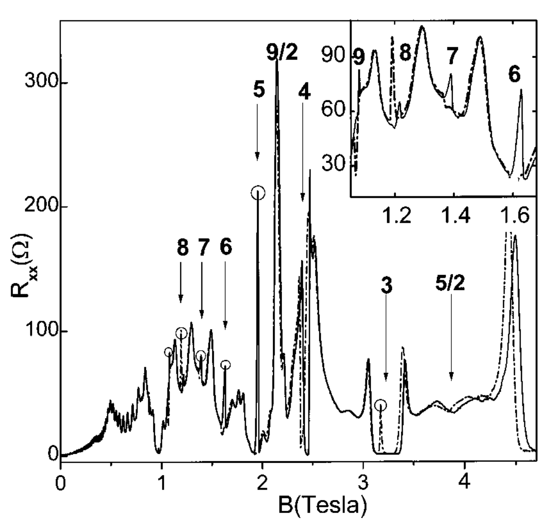

FIG. 2. Magnetoresistance of sample *A* up to 4.7 T. The notation is the same as in Fig. 1. Sharp resistance peaks are circled. Inset: Expanded scale of regions between 1 and 1.7 T, corresponding to $\nu=6$ to 9.

Sample *B* behaves similarly to sample *A*, despite the difference in electron density. The shapes of the low-field envelopes in both samples resemble one another. Their maxima and minima occur roughly at the same field values. The backgrounds in both samples reach their highest values near 2.5 T and gradually disappear above it. In sample *A*, the region of most pronounced hysteresis occurs for $9 \geqslant \nu \geqslant 3$, while in sample *B* this occurs for $12 \geqslant \nu \geqslant 4$.

To examine the time dependence of the peaks, we swept the field slowly to their maxima and stopped at the summit. The inset of Fig. 1 shows the subsequent time evolution of the peak at $\nu=5$. After a rapid drop the decay becomes exponential with a time constant of $\tau \sim 2.7$ min. The time constant is sample dependent, ν dependent, and depends on the contact configuration. The typical value for sample *A* is a few minutes and for sample *B* a few hours, with a maximum of ~ 10 h. These are enormously long time scales for the decay of an electrical resistance in a 2DEG.

We made a critical observation during such decay experiments in sample *B*. A quick grounding and subsequent ungrounding of some of the contacts led to a dramatic decrease of the amplitude of the peaks. Although this observation was not reproducible during all cool-downs, it points clearly to the existence of some nonuniform, nonequilibrium configuration, that can be equilibrated by the redistribution of charge within the specimen.

To characterize peak creation and decay we performed several additional experiments. The amplitudes of the peaks increase with increasing sweep rate, but much less than proportional. They increase by less than a factor of 2 when the sweep rate is raised 20 times from 0.02 to 0.4 T/min. The decay of the peaks with time probably accounts for the small difference in amplitude. Raising the temperature weakens the observed hysteresis and increases the background, while the amplitudes of the peaks and dips shrink. The hysteresis at $\nu=5$ in sample *A* disappears at about 400 mK. Sample *B* shows similar behavior. Both ac and dc excitations were used to conduct the experiments and data from both largely resemble each other. The data remain essentially independent of ac amplitude from 10 nA to 1 μA.

The oscillatory background in the low-field data strongly suggests the existence of a conduction path parallel to the 2DEG channel. The occupation of a second subband in the quantum well can safely be ruled out on the basis of a simple calculation. Other sources for a parallel current path are the silicon modulation-doping layers on both sides of the quantum well. A fraction of the electrons can remain at the site of this layer and provide a conducting path parallel to the 2DEG. At high enough mobility, such an impurity channel can exhibit its own magnetotransport superimposed on R_{xx} from the 2DEG.

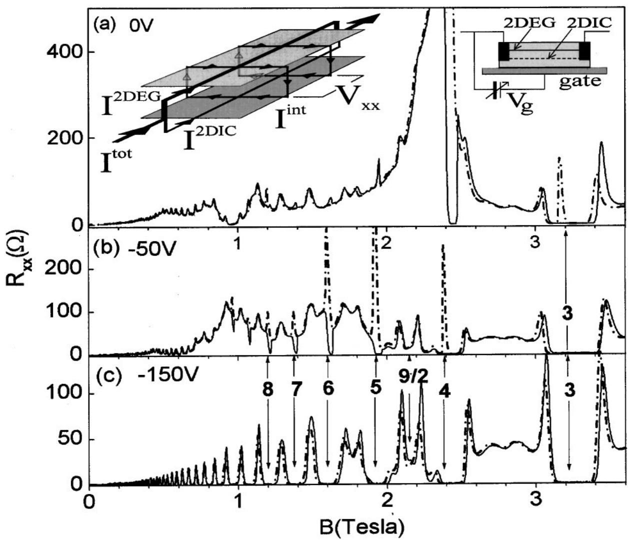

FIG. 3. Magnetoresistance of sample A at different backgate voltages. Left inset schematically shows the current configuration in the two-channel system. Right inset shows the diagram of the sample and the backside gate.

To investigate the origin of the parallel channel we applied a voltage V_g to a backside electrode (gate) placed under the substrate (see the right inset in Fig. 3). Figure 3 shows the magnetoresistance of sample A at different backgate biases. Here we have chosen a current direction perpendicular to the one used in Figs. 1 and 2. Although the hysteresis is less pronounced in this current configuration, several hysteretic peaks are clearly visible in panel (a) at zero bias. A bias of -50 V on the backgate across the 0.5-mm-thick substrate has a dramatic effect on the trace in panel (b). While the R_{xx} background weakens, the previously small hysteresis peaks grow enormously in amplitude and the sharp spikes at ν=4,5, and 6 dominate the graph. Uniformly, peaks occur on the down-sweep, while the up-sweeps either show the customary IQHE minima (ν=4,5) or sharp downward cusps that approach vanishing R_{xx} (ν=6,7,8). The last and cleanest hysteretic peak has moved from its previous position at ν=3 in panel (a) to ν=4 in panel (b). In general, with increasing back bias, we see such a progression from higher to lower magnetic field. Eventually, all hysteresis effects disappear in panel (c) at a backgate bias of -150 V. The specimen shows a clean R_{xx} behavior as is customary for very high mobility samples. Not only is the fragile state at ν=7/2 visible, but the data also show the recently discovered anisotropic states at ν=9/2 and 11/2,[7,8] manifested by deep minima in Fig. 3(c) and well-documented clear maxima in Fig. 2.

Backgate bias does not change the electron density in the 2DEG as is evident from the stationary B positions of its IQHE and FQHE features. The oscillations of the background, on the other hand, are steadily moving to lower field. Sample B behaves similarly to sample A and its data resemble those of panel (c) at a higher bias of -170 V. The backgate bias experiments on both samples provide strong evidence for the existence of a parallel conducting path in the form of a two-dimensional impurity channel (2DIC) on the substrate side of the quantum well and for its role in the appearance of the background as well as the hysteretic spikes. The symmetric doping channel on the top side of the sample does not provide such a parallel channel, probably due to depletion by the nearby surface of the sample.

From the shift of the minimum in the background at ~0.95 T in Fig. 3(a) with increasing V_g and a gate capacitance of $C_g \sim 22 pF/\mathrm{cm}^2$, we derive an initial density of $n_{2\mathrm{DIC}} \sim 5.7\times 10^{10}$ cm^{-2} in the impurity channel. This identifies the 0.95 T minimum in Fig. 2 as the ν=2 IQHE of the 2DIC. The other minima in the background follow quite well the usual $1/B$ sequence, with the strong minimum at B ~1.9 T representing ν=1. This indicates at least a moderate mobility for this 2DIC, since spin splitting is just resolved. At -150 V the density of the 2DIC has been depleted to 3.0×10^{10} cm^{-2} and has probably fallen below the conduction threshold of such a disordered channel. Therefore, parallel conduction has vanished and a clean R_{xx} trace is observed.

In the remainder of the paper, we develop a model that can account for many of our observations. We regard our system as consisting of two parallel sheets of conductors, a high-mobility 2DEG and a low-mobility 2DIC. Both are connected via eight contacts at the perimeter of the specimen and are coupled by a mutual capacitance of $C = 120 nF/\mathrm{cm}^2$. At any given magnetic field a complex current distribution emerges. The situation with the 2DEG in a quantum Hall state is shown as the left inset to Fig. 3. We do not differentiate between resistance R and resistivity ρ, since both differ only by a factor of order of unity in our square sample. Following the value of the Hall resistances, the total current I^{tot} divides between both layers according to their density ratio $n^{2\mathrm{DIC}}/n^{2\mathrm{DEG}}$. Therefore, about 1/5 of the total current is flowing through the 2DIC. In addition, due to the different resistivities between the 2DEG and the 2DIC, an *interlayer* current I^{int} is induced, which contributes to the voltage V_{xx}. Whenever the 2DEG is in the IQHE, a simple calculation[9] shows, that the measured $R_{xx} = V_{xx}/I^{\mathrm{tot}}$ simply reflects $\rho_{xx}^{2\mathrm{DIC}}$, attenuated by the square of the ratio of electron densities in both layers. From a value of ~100 Ω for the smoothly varying background in Fig. 2, we deduce $\rho_{xx}^{2\mathrm{DIC}} \sim 2.5$ kΩ. This establishes the parallel channel as a moderately good conductor.

As the magnetic field is swept, the Fermi levels of both layers oscillate due to Landau quantization, creating an oscillating imbalance in the chemical potential between the layers. The resulting potential difference is particularly drastic in the regime of the IQHE of the 2DEG, where its Fermi energy changes abruptly by $\hbar\omega_c$. To keep the Fermi levels in equilibrium, a charge $Q \sim C\hbar\omega_c/e$ needs to be transferred between the layers. At $B \sim 3$ T, $Q \sim 4\times 10^9$ e/cm^2 or ~10% of the charge of the 2DIC. The relevant series conductance to charge or discharge the 2DEG sheet from its edge, where the contacts reside, is its diagonal conductivity σ_{xx}. In the regime of the IQHE this parameter tends toward zero. The resulting RC time constant for equilibration can assume values as long as hours if $\sigma_{xx} \sim 10^{-11}$ Ω^{-1} which is not uncommon in a high mobility 2DEG sample.[10,11]

The combination of a finite field sweep rate and a long-time constant for equilibration gives rise to a density inhomogeneity in the 2DEG. While the edges of the 2DEG and the 2DIC are quickly equilibrated, the center of the 2DEG lags far behind and maintains a higher or lower electron density concentration depending on the field sweep direction.

The resulting radial density gradient in the 2DEG is imprinted with opposite sign onto the 2DIC due to the electrostatic interaction between both layers. Since the diagonal resistivity ρ_{xx}^{2DIC} in the low density, disordered 2DIC depends strongly on electron density, the sudden change of the Fermi level in the 2DEG and the resulting density gradient in the 2DIC can abruptly alter the local ρ_{xx}^{2DIC} and hence the current pattern. This leads to a nonequilibrium V_{xx} which is observed in the experiment as a time-dependent spike. In particular, if the electron system in the 2DIC is near one of the metal-insulator transitions, as they arise close to the edge of a Landau level, the change in $\rho_{xx}^{2DIC}$and hence in V_{xx} can be dramatic. This explains why exceedingly sharp spikes always occur on a very low or completely absent background such as $\nu=3,5$ in Fig. 2. It also accounts for the enormous growth of the spikes with decreasing carrier density in the 2DIC in Fig. 3(b). To predict the direction a particular spike is pointing (up or down) requires knowledge of the transient nonequilibrium current distribution. This pattern can be very complex since it depends on the local ρ_{xx}^{2DIC},which is sensitive to the position of the Fermi level with respect to the density of states in the disordered 2DIC. The resulting current pattern is difficult to assess in detail.

The characteristic time of the phenomenon is the RC time of the electric discharge between 2DEG and 2DIC. However, it is *not* the actual discharge current that is observed in V_{xx}. There is simply insufficient charge in the capacitor to account for the observed, minute-long interlayer current. What is rather observed is the influence of the induced nonequilibrium charge distribution in the 2DEG on the resistivity pattern in the 2DIC and the resulting transient redistribution of currents in the specimen. The narrowness of the spikes is a result of the narrowness of the regions within the IQHE over which σ_{xx} takes on sufficiently low values to create sufficiently long RC times to be observable on the time scale of our experiment. Outside of these narrow regions of exceedingly small σ_{xx} charge transfer between 2DEG and 2DIC happens rapidly, both layers maintain equilibrium and V_{xx} is time independent. Raising temperature increases σ_{xx}, therefore, peaks disappear at high temperature. The long decay times of the peaks is a direct result of the long RC times. Our model also explains the hysteresis of the spikes. Obviously, opposite field sweeps generate radial density gradients of opposite signs which lead to different current patterns and hence hysteretic behavior.

In conclusion, the strong spikes and large hysteresis in the magnetoresistance of our 2DEG in the regime of the IQHE are the result of a nonequilibrium charge distribution caused by the long RC times to modify the electron density in the 2DEG in the IQHE regime. The origin of these spikes is a parallel impurity channel. We can explain our observations as resulting from the capacitive coupling between 2DEG and this neighboring impurity channel and the time-dependent current distribution it creates.

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[9] The total injected current I^{tot} divides between both layers according to their two-point resistances, which, apart from small contact resistance, are ρ_{xy}^{2DEG} for the 2DEG and $\sim\rho_{xy}^{2DIC}+\rho_{xx}^{2DIC}$ for the 2DIC. Assuming $(\rho_{xy}^{2DIC})^2\gg(\rho_{xx}^{2DIC})^2$, we obtain $I^{2DIC}/I^{2DEG}\sim n^{2DIC}/n^{2DEG}$. While the longitudinal voltage drop V_{xx}^{2DEG} in the 2DEG is zero by virtue of its IQHE state, $V_{xx}^{2DIC}\sim\rho_{xx}^{2DIC}\times I^{2DIC}$. This potential difference induces an interlayer current I^{int} through the voltage contacts which increases V_{xx}^{2DEG} by $\rho_{xy}^{2DEG}\times I^{int}$ and reduces V_{xx}^{2DIC} by $\sim\rho_{xy}^{2DIC}\times I^{int}$(Ref. 12). In equilibrium $I^{int}\sim I^{2DIC}\times\rho_{xx}^{2DIC}/\rho_{xy}^{2DIC}$ since $\rho_{xy}^{2DIC}\gg\rho_{xy}^{2DEG}$. This yields $R_{xx}=V_{xx}/I^{tot}\sim\rho_{xx}^{2DIC}\times(\rho_{xy}^{2DEG}/\rho_{xy}^{2DIC})^2\sim\rho_{xx}^{2DIC}\times(n^{2DIC}/n^{2DEG})^2\sim\rho_{xx}^{2DIC}\times(1/5)^2$.

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