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DESTRUCTION OF CORRELATED BILAYER STATES SUBJECTED TO TILTED MAGNETIC FIELDS

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We use tilted magnetic fields to effectively decouple a strongly coupled bilayer two-dimensional electron system into two separate layers. For our specific sample (tunnelling gap $\Delta_{SAS} = 2.5$ meV) the inter-layer coupling is quenched by an in-plane field $B \approx 14$ T, leading to the successive disappearance of all odd-integer states visible in the quantum Hall effect. Such a transition from a bilayer into two single layers is also observed in a solely parallel magnetic field. Surprisingly, the $\nu = 1$ the quantum Hall state remains present even for in-plane fields exceeding 20 T. Only when decreasing the total Landau level filling slightly below $\nu = 1$ the system undergoes an abrupt transition from a $\nu = 1$ quantum Hall state into two (insulating) systems with a half filled Landau level.

Keywords: Quantum Hall effect; bilayers.

1. Introduction

The two-dimensional electron system (2DES) realized in semiconductor heterostructures is an ideal model for the investigation of strongly correlated electrons. The physics of such a 2DES can be additionally enriched by adding an extra degree of freedom, e.g by utilizing two coupled systems in a bilayer.[1] Due to the inter-layer coupling new correlated quantum Hall states emerge at total filling $\nu = 1$,[1–5] $\nu = 2$[6] and $\nu = 2/3$.[6,7]

In this paper we will show how an in-plane magnetic field can be used to effectively decouple two layers of an initially strongly coupled bilayer 2DES. This decoupling will be illustrated by the abrupt disappearance of odd-integer filling factors $\nu = 3, 5, 7, \ldots$ in the quantum Hall effect when tilting the sample in a field. We will explain this observation by a quenching of the symmetric-antisymmetric

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splitting Δ_{SAS} of the bilayer by an in-plane field. This in-plane field necessary for the destruction of the correlated bilayer will be compared to the value found for experiments in parallel fields.

Additionally, we will demonstrate how the correlated bilayer state at $\nu = 1$ behaves distinctively different from the higher odd-integer states. The bilayer state remains present for in-plane magnetic fields considerably exceeding the value needed to quench the inter-layer coupling, before undergoing a rather abrupt transition into an insulating system of two uncoupled 2DESs with a half-filled Landau level.

2. Experimental Results and Discussion

Our sample consists of two 10 nm wide GaAs quantum wells separated by a 2.5 nm thick $Ga_{0.65}Al_{0.35}As$ barrier. Electrons are provided by modulation doping both the outer $Ga_{0.65}Al_{0.35}As$ barriers yielding a total electron concentration $n = 4 \times 10^{15}$ m^{-2} and an electron mobility $\mu = 14$ m^2/Vs. The bilayer is strongly coupled with an energy splitting between its symmetric and its antisymmetric state $\Delta_{SAS} = 2.5$ meV.

Experiments were performed in tilted magnetic fields up to 33 T and at temper-

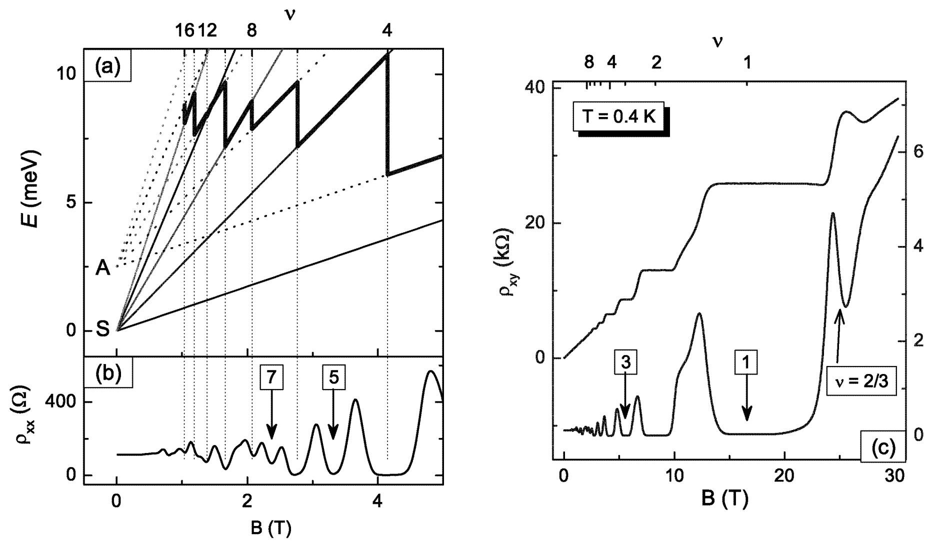

Fig. 1. (a) Lowest five Landau levels of the symmetric state (solid lines) and the antisymmetric state (dotted lines) as a function of the magnetic field for a bilayer with $\Delta_{SAS} = 2.5$ meV. The thick line sketches the position of the Fermi-energy for a bilayer with $n = 4 \times 10^{15}$ m^{-2}. The top axis shows the corresponding total Landau level filling .
(b) Resistivity ρ_{xx} of the bilayer 2DES for the field range shown in (a) at $T = 0.4$ K.
(c) Hall resistivity ρ_{xy} (left axis) and resistivity ρ_{xx} (right axis) over a larger field range up to 30 T. The arrows in (b) and (c) mark addition minima appearing due to spin splitting (not visible in Fig 1a).

atures down to 0.3 K. We measured the magneto-resistance and the Hall resistance on different positions of two standard Hall bars; all these measurements yielded results very comparable to those reported in this paper.

When subjected to a perpendicular magnetic field the energy spectrum of a 2DES splits up into quantized, spin-split, Landau levels. In a bilayer, an additional splitting of each Landau level into a symmetric and an antisymmetric state appears. They are separated energetically by the symmetric-antisymmetric splitting Δ_{SAS}. The resulting Landau level fan of such a bilayer with $\Delta_{SAS} = 2.5$ meV is depicted in Fig. 1a. Please note that each level consists of two spin-split sub-levels, a splitting which is too small to be visible in the figure.

A consequence of the Landau quantization is the occurrence of minima in the resistivity ρ_{xx} as visualized for our sample in Fig. 1b and Fig. 1c. The gaps between two different Landau levels are visible at total filling factors $\nu = 4, 8$, and 12, the symmetric-antisymmetric splitting of the same Landau level at $\nu = 2, 6$, and 10, and spin splitting appears at $\nu = 1, 3, 5$ and 7.

Tilting the sample in a magnetic field adds an additional in-plane field to the system. This leads to a decrease of the interlayer coupling, and, therefore, to a reduction of Δ_{SAS}.[2,1,9] Additionally, the spin-splitting, proportional to the *total* field, increases. As a consequence, the $\nu = 6$ and $\nu = 10$ quantum Hall states

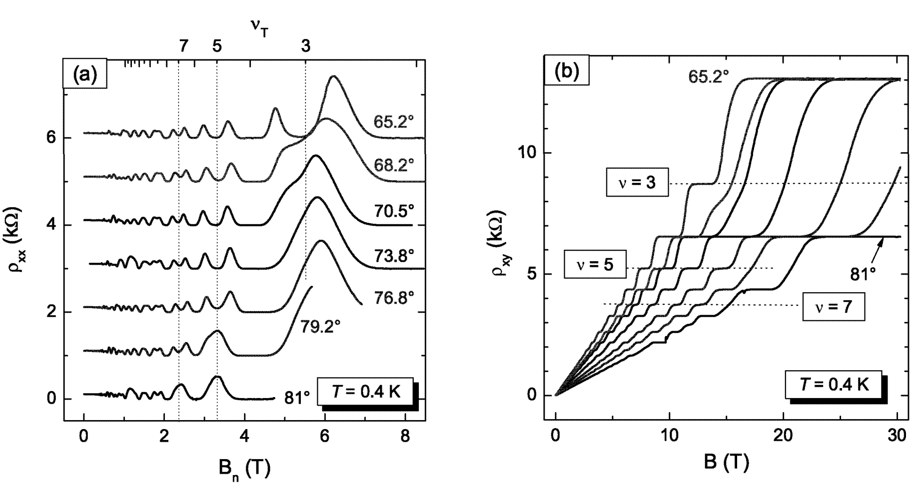

Fig. 2. (a) Resistivity ρ_{xx} as a function of the normal field component B_n in a tilt angle range where odd-integer filling factors $\nu = 3, 5$, and 7 successively disappear. The curves are shifted for clarity by 1 kΩ. On the top axis the total filling factor is shown.
(b) Hall resistivity ρ_{xy} as a function of the total magnetic field for the same tilt angles range as shown in (a).
The dashed lines in both graphs denote the odd-integer filling factors successively quenched with increasing tilt angle.

weaken with increasing tilt angle, because they are associated to the gap between the energetically higher lying spin level of a symmetric state and the energetically lower lying spin level of an antisymmetric state. At high enough tilt angles the spin-splitting starts to exceed Δ_{SAS} for a given filling factor. Therefore, the gaps at filling factors $\nu = 4$ and $\nu = 10$ become dominated by the Zeeman splitting and the corresponding quantum Hall states start to strengthen again. Odd-integer filling factors, in turn, must now be related to the symmetric-antisymmetric splitting Δ_{SAS}. Eventually, when further increasing the tilt angle, this gap is totally quenched by the in-plane field and the odd-integer filling factors disappear.[2]

This description is demonstrated experimentally in Fig. 2. With increasing tilt angle the pronounced quantum Hall plateaus at odd-integer filling factors $\nu = 3, 5,$ and 7 disappear successively and the corresponding Shubnikov-de Haas minima are lifted. Such a quenching of the odd-integer quantum Hall states can be regarded as a transition from a strongly coupled bilayer state to two-independent, equally filled single layers.

The value of an in-plane field necessary to effectively decouple the bilayer can also be estimated from experiments where the bilayer is subjected solely to a parallel field. The corresponding parallel magneto-resistivity $\rho_{\|}$(B), normalized to its value at zero field, is plotted in the left panel of Fig. 3. The sharp S-type shape can be tracked down to the shifting of the two parabolic dispersion curves in the bilayer along the k_y-direction perpendicular to the applied magnetic field by $\Delta k_y = eBd/\hbar$. Here $d = 12.5$ nm is the distance between the center of the two quantum wells. The features observed in $\rho_{\|}$ occur when the two parabola cross at the Fermi energy and a gap opens in the dispersion.[8]

A sketch of the parabolic dispersion at zero field and for a high parallel field (22 T) is shown in the right panel of Fig. 3. At zero field both parabolic dispersions of the symmetric and antisymmetric states are centered at $k_y = 0$. As a consequence, identical k_y can be filled for both states and the system can be regarded as a

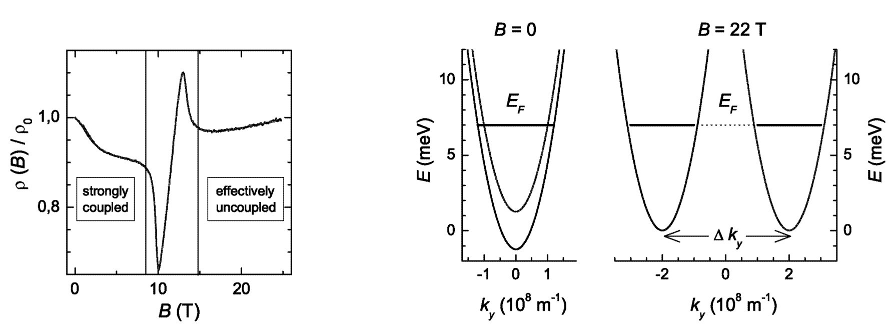

Fig. 3. Normalized magneto-resistivity in a parallel magnetic field (left panel). The right panel sketches the parabolic dispersion along the k_y-direction for zero magnetic field and for a field of 22 T. The thick lines show the Fermi energy.

strongly coupled bilayer. At high enough fields, however, the parabola are shifted with respect to each other by Δk_y, and only the bottom parts with different k_y for the two states are filled. The bilayer now behaves as a system consisting of two effectively uncoupled 2DESs.

The parallel magnetic field B_x in the Landau gauge couples the k_y-direction to the z-direction in real space, and, therefore, a layer separation in k_y-space can be equivalently interpreted as a separation into two single 2DESs along the z-direction perpendicular to the 2DES.

As can be deduced from Fig. 3, the transition to a totally decoupled bilayer is accomplished at an in-plane magnetic field $B_0 \approx 14$ T. This value corresponds nicely to the in-plane field required for the quenching of the $\nu = 3, 5$ and 7 quantum Hall states show in Fig. 2.

A much higher in-plane field, however, is necessary to destroy the $\nu = 1$, quantum Hall state totally. This statement is illustrated in Fig. 4 where we have plotted the resistivity ρ_{xx} in the tilt angle range where the $\nu = 1$ minimum starts to be lifted. The $\nu = 1$ quantum Hall states remains clearly developed up to a tilt angle of 51^o. At this angle, the in-plane field component already exceeds 20 T. When increasing the field further the resistivity drastically increases towards an insulating state.

These observations suggest that the coupling between two slightly more than half filled Landau levels is strong enough to stabilize the $\nu = 1$ quantum Hall state even with an additional in-plane field exceeding the value necessary to decouple the

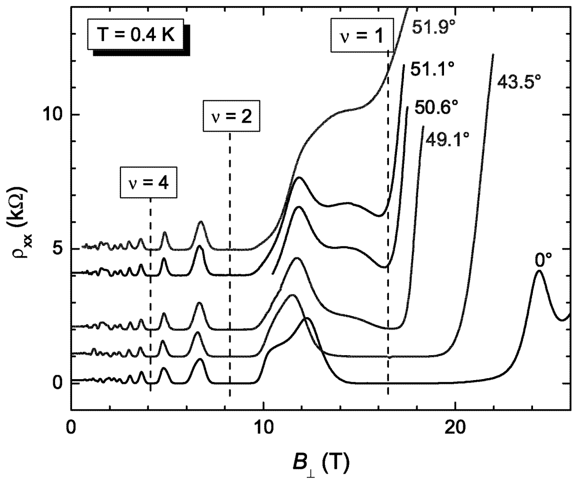

Fig. 4. Development of the resistivity $\nu = 1$ quantum Hall state with increasing resistivity. The curves are shifted for clarity.

bilayer. As soon as the filling of the individual states falls below half filling, the coupling abruptly disappears and a transition from the $\nu = 1$ quantum Hall state to two independent $\nu = 1/2$ insulating systems occurs.

3. Conclusions

In conclusion we have used an in-plane magnetic field to effectively decouple a bilayer two-dimensional electron system into two single layers. The decoupling shows up as a disappearance of odd-integer quantum Hall states when the in-plane field exceeded a critical value of 14 T. The low field side of the $\nu = 1$ quantum Hall state, however, remains present in a considerably higher in-plane field.

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