The fractional quantum Hall effect in wide quantum wells

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Currently, there is a strong interest in the even-denominator fractional quantum Hall state at filling factor $\nu = 5/2$, observed in state-of-the-art GaAs based two-dimensional electron systems. This interest stems from the potential relevance of this ground state for topological quantum computation resulting from the non-Abelian statistics its quasi-particle excitations are predicted to obey. Pairing of composite fermions into a p-wave superconductor is presently considered the most likely scenario for the appearance of this incompressible state. The 5/2-state is usually studied in heterostructures with a single heterointerface or relatively narrow quantum wells where electrons occupy only the first subband. By widening the quantum well the physics is enriched, since it is possible to populate the second subband of the quantum well as well. This adds an additional degree of freedom. The second subband hosts another two-dimensional electron system that may interact with the one in the first subband and charge may be transferred from one to the other. Here, we have investigated the fractional quantum Hall states and in particular the 5/2-state under these conditions in a density tunable two-dimensional electron system. It is a widespread believe that the population of a second subband is detrimental for the quality and hence the observation of fragile Coulomb correlation physics as an additional channel for scattering, intersubband scattering, is opened up. We can not confirm this and instead demonstrate that the system continues to exhibit the 5/2 state in the lower subband even if the second subband becomes occupied but only when the quantum well is wide enough [1].

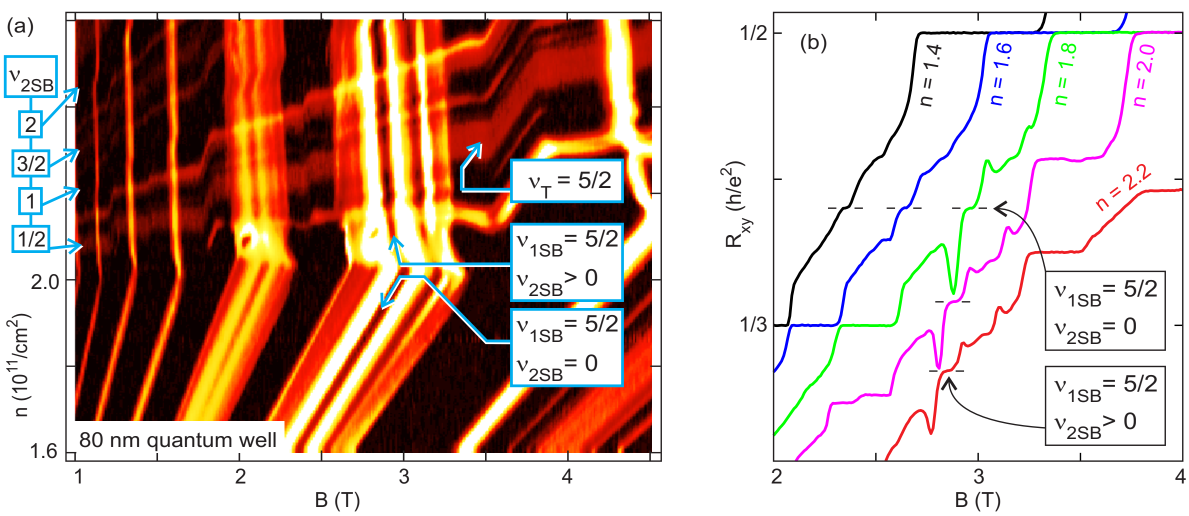

Figure 1: (a) Color plot of the longitudinal resistance of a two-dimensional electron system in an 80 nm quantum well. In the lower density range the second subband (2SB) of the host quantum well is not yet occupied. When it becomes populated at higher densities, we observe an interplay of quantum Hall states from both subbands, among them the $\nu = 5/2$ state of the first subband (1SB). (b) The Hall resistance for exemplary densities shows a vanishing of the plateau at total filling 5/2 upon population of the second subband. Yet, the plateau corresponding to 5/2-filling of the first subband alone is preserved.

Magnetotransport experiments were carried out on Hall bars with an 80, 60 or 50 nm wide quantum well and an in-situ grown backgate to tune the electron density. Figure 1(a) shows the longitudinal resistance in the density versus magnetic field plane measured on the 80 nm quantum well sample. Panel (b) shows the Hall resistance for selected densities. At lower densities electrons occupy only the first subband (1SB) and a 5/2 quantized Hall state is observed. At higher density when also the second subband (2SB) is populated the 5/2 state for the *total* electron density looses its quantization. The longitudinal resistance no longer vanishes and the Hall plateau disappears in accordance with previous observations [2]. The system becomes compressible, because total filling 5/2 corresponds to two compeletely filled LLs in the first subband, while only the lowest LL in the second subband is half filled. This situation closely resembles the composite fermion metallic state at filling factor 1/2 in a single subband system.

Upon occupation of the second subband at $n = 2 \times 10^{11}/\mathrm{cm}^2$ the QHE features of the lower subband remain at approximately constant B, indicating that the additional electrons go mainly into the second subband. Consequently, as the second subband density increases, various integer and fractional quantum Hall states are observed associated with this subband, some of which are indicated in Fig. 1. Even though at total filling factor

5/2 no quantization occurs, the 5/2 state of the first subband persists as an incompressible quantum Hall state over a wide range of fillings of the 2SB: the longitudinal resistance still vanishes and the Hall resistance still shows a plateau at filling factors ($\nu_{1SB} = 5/2$, $\nu_{2SB} > 0$). Yet, the plateau is found at progressively lower R_{xy} as is expected when the total density increases. Even though the 5/2 state is known to be very fragile, we find it surprisingly undisturbed by the presence of the partially populated 2SB. The present density tunability allows to vary the filling factor of the second subband between $0 < \nu_{2SB} \lesssim 1$. The activation energy, obtained from temperature dependent studies, along the line of constant filling factor $\nu_{1SB} = 5/2$ as a function of the total density do not show a change in the activation energy when the second subband gets populated. This energy seems independent of the 2SB filling.

A narrower quantum well of 50 nm width shows a very different behavior. The data for this well width are displayed in Fig. 2. Here, no independent quantum Hall states associated with the first and second subband are observed. Instead, the longitudinal resistance features follow the total density. However, the strength of the FQHE changes upon population of the second subband: When the highest occupied Laudau level belongs to the second subband, the 7/3 and 8/3 state strengthen while the 5/2 state looses its quantization as in the 80 nm quantum well for the same reason. We conclude that the quantum well width is a crucial parameter to observe the 5/2 state even when the second subband becomes populated.

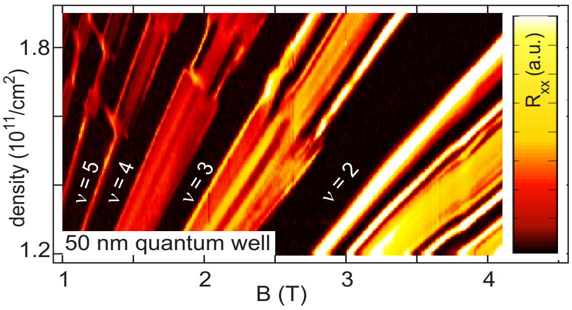

Figure 2: In a 50 nm quantum well sample the quantum Hall features follow the total electron density, even when the second subband is occupied. However, the strength of various FQHE states changes: the $\nu = 5/2$ state looses its quantization upon second subband population, whereas its neighbouring 7/3 and 8/3 states strengthen.

In order to understand the importance of the quantum well width we numerically calculated the wavefunction shapes of the first and second subband within the quantum wells as displayed in Fig. 3. It can be seen that the spatial separation of the wavefunctions is much larger in the wider quantum well. This has important implications. Our observation of a 5/2 state in the 1SB at a non integer filling of the 2SB implies that the topmost occupied LLs of both SBs are partially filled. They must be pinned at the same energy. If they are not, it would be energetically favorable to transfer electrons from one subband to the other. Charge transfer is however accompanied by a relative shift of the LLs of both subbands and hence both levels will get aligned. Then the levels remain pinned to each other when changing the density until one of the LL becomes full or completely depleted. The amount of charge transfer required to produce a given relative shift of the Landau levels is smaller the further the effective distance between the wavefunctions. We conclude that in general for narrower QWs more charges need to be transferred between the two SBs in order to align their topmost partially filled LLs. At the same time the total charge that can be transferred is limited by the degeneracy of the LLs and charge transfer will stop when either one of the SBs reaches the nearest integer filling factor. All in all, the parameter range in which LLs of both SBs are simultaneously only partially filled shrinks with decreasing QW width. Only in wide quantum wells, can both two-dimensional electron systems with partially filled upper levels co-exist over an extended range of density. A quantitative calculation of the electrostatic energy needed to transfer charges from one subband to the other (see [1]) reproduces our experimental results well and highlights the importance of the quantum well width.

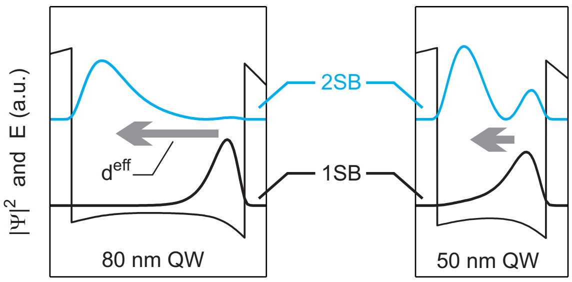

Figure 3: Wave functions of the first and second subbands within the quantum wells. The effective spatial displacement involved in intersubband charge transfer, d^{eff}, is indicated as arrows and depends strongly on the quantum well width. Furthermore, the spatial overlap of the subband wavefunctions is strongly reduced in the wider quantum well.

We further investigated the QHE in the presence of an in-plane magnetic field by tilting the sample with respect to the magnetic field axis. The observed changes in the magnetoresistance traces again strongly depends on the quantum well width: For the widest quantum well the in-plane field had only minor effects on the strength of the quantum Hall states. This was drastically different for a quantum well with an intermediate 60 nm width, which, in the absence of tilt, showed strong independence of both subband quantum Hall states very similar to Fig. 1 (data not shown). For this sample a tilt angle of only 10 degrees was sufficient to destroy the independence of the subband quantum Hall states, yielding a picture similar to Fig. 2 with all quantum Hall states determined by the total density alone, even when the second subband was occupied. This can be understood as a consequence of the spatial overlap of the subband wavefunctions in the quantum well: An in-plane field mixes different subbands and Landau levels, provided that they overlap in space. In the very wide quantum well this overlap is practically zero, and so is the effect of a tilted field. In the 60 nm quantum well the spatial overlap was significantly different from zero, which leads to substantial coupling in a tiled field, destroys the subband independence and makes the two subband system act as one single layer.

In conclusion, we have shown that in the transition region of single layer to bilayer quantum Hall effect systems the interplay of Landau level quantization and intersubband charge transfer leads to interesting new effects. In particular, we can observe various fractional quantum Hall states associated with the electrons residing in the first subband while continuously changing the electron density in the second subband. The existence of FQHE states in close proximity to an independent 2DES of variable density (formed by the 2SB electrons) may enable studies of their interaction.

References:

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