Experimental Evidence for a Landau Level Coupling Induced Rearrangement of the Hofstadter Butterfly

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In a 2DES subjected to a perpendicular magnetic field as well as a 1D potential modulation, Landau levels broaden into bands. Their bandwidth vanishes for certain commensurate values of the cyclotron orbit size and modulation period. If a modulation along the second dimension is added, fine structure develops within each of these Landau bands and the celebrated Hofstadter butterfly energy spectrum with its fractal characteristics ensues, as shown in Fig. 1. This butterfly like spectrum repeats at integer multiples of Φ_0/Φ, where Φ_0 is the elementary flux quantum and Φ is the flux penetrating a unit cell. When the Fermi energy lies in a gap within this spectrum, the Hall conductance is predicted to take on quantized values in accordance with the solution of a Diophantine equation [1] and no longer necessarily behaves monotonously as the Fermi energy is swept through a Landau band (See Fig. 1). Recently, some of the authors experimentally demonstrated definite precursors of this behavior for the primary gaps in the Hofstadter spectrum for a 100nm period lateral superlattice in a regime where coupling between adjacent Landau bands can be ignored [2].

Significant advances in both the heterostructure design as well as careful optimization of the fabrication procedure for the periodically displaced metallic gate (which generates a square symmetric potential) have in comparison with previous best samples more than doubled the electron mobility after processing. The Hall conductance for the largest gaps in the spectrum now reaches its quantized value as shown in Fig. 2 and additional, more subtle, gaps are resolved. These improvements have opened up the possibility to investigate the so far inaccessible intermediate regime in which neither the potential modulation nor the applied magnetic field can be viewed as a small perturbation in the problem. Under these conditions, coupling between adjacent Landau bands can no longer be ignored. It may significantly distort and even rearrange the energy spectrum as well as lift the usual flat band condition as illustrated for one specific theoretical example in Fig. 3 [3]. We provide experimental evidence for both at fields below 0.29T. At a field, where flat band behavior is anticipated in the weak coupling regime, we notice that the butterfly is not compressed to a single level in experiment. For instance in Fig. 4, Shoulders in the longitudinal resistance as well as non-monotonous behavior in the Hall conductance are resolved near "flat band". Furthermore, the Hall conductance when traversing path **c** differs erratically from the predicted quantized values in Fig. 1, whereas for path **b** at fields above 0.29T the Hall conductance sequence agrees. To compare theory with experiment some level broadening has to be taken into account. These features are ascribed to a Landau band coupling induced rearrangement of subbands in the Hofstadter energy spectrum. It takes place only at low enough magnetic fields for which the cyclotron energy is comparable to the modulation amplitude.

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[2] C. Albrecht, et.al., Phys. Rev. Lett. **86**, 147 (2001).
[3] D. Springsguth, R. Ketzmerick, and T. Geisel, Phys. Rev. B **56**, 2036 (1997).

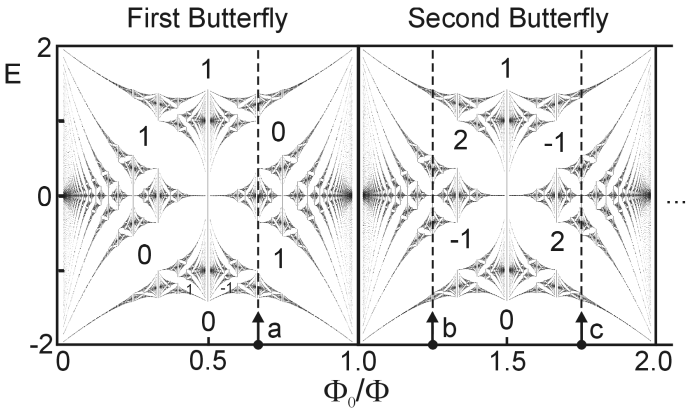

Figure 1: The repeated Hofstadter Butterfly. The contribution to the total Hall conductance in units of $2 \cdot e^2/h$ by the partially filled Landau Band is indicated for the Fermi energy in the main gaps. (Spin splitting is not resolved.) The three paths studied are indicated by letters a,b,c. The magnetic flux through a unit cell with area A of the superimposed modulation potential is $\Phi = B \cdot A$. The flux quantum is $\Phi_0 = h/e$.

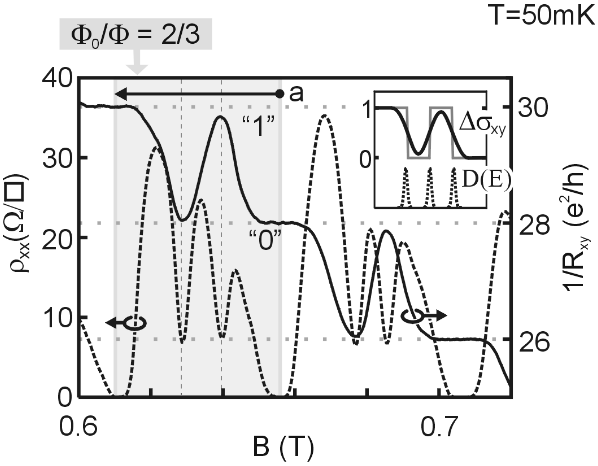

Figure 2: Measurement for a hallbar with 100nm modulation period. Longitudinal resistivity is dashed, Hall conductivity solid. The Hall conductivity reaches the expected quantized values even for the minigaps of the Hofstadter spectrum. The inset shows the density of states and Hall conductance for the lowest Landau level including a gaussian broadened version.

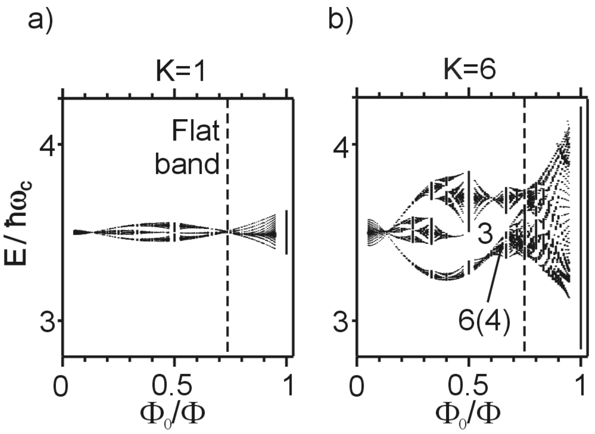

Figure 3: The Hofstadter Butterfly spectrum inside the 4th Landau Band for a) negligible coupling strength and b) stronger coupling. For stronger coupling the Hofstadter Butterfly spectrum is resolved even at flat band positions and anomalous Hall conductances arise. Reproduced from [3].

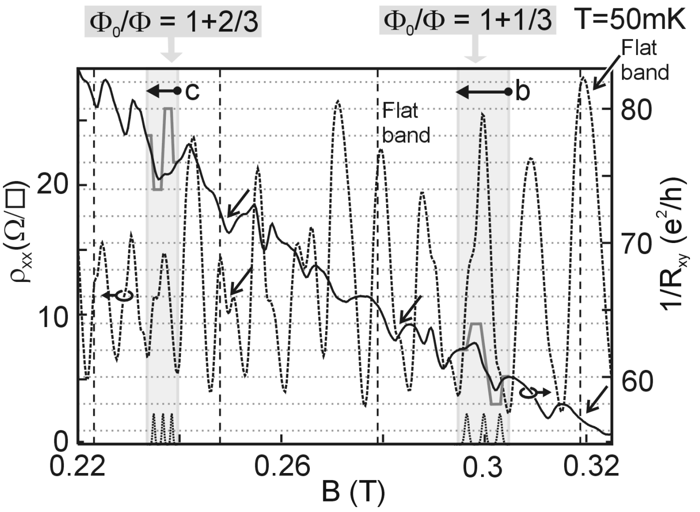

Figure 4: The solid drawn Hall conductivity shows nonmonotonic behavior at flat band positions for magnetic fields below 0.3T. At the same positions the longitudinal resistivity shows shoulders. Unexpected Hall conductances are observed e.g. for $\Phi_0/\Phi = 1 + 2/3$.