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Correlated electron states at level crossings of bilayer two-dimensional electron systems in tilted magnetic fields

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Abstract

We have measured the energy-level structure of high mobility, strongly coupled bilayer two-dimensional electron systems in tilted magnetic fields by means of magnetotransport experiments. At tilt angles where single-particle levels with opposite spin and symmetry cross, we observe a surprising sudden broadening of the quantum Hall plateaus and a deepening of the Shubnikov–de Haas minima. This observation is explained by an interaction-induced rearrangement of the energy level structure which strongly increases the energetic splitting of two (anti-)crossing levels.

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1. Introduction

In a bilayer two-dimensional electron system (2DES) an additional degree of freedom is added to the intensively studied single-layer 2DESs realized in semiconductor heterostructures. In particular, the conceptually simple Landau level fan of a 2DES subjected to a perpendicular magnetic field evolves into a much more complex energy level structure in a bilayer, which can be effectively accessed by means of tilted field experiments [1].

More generally, Landau level crossings induced by an in-plane field can give rise to numerous new phenomena, such as the manifestation of quantum Hall ferromagnetism in wide quantum wells [2] and the two-valley system of X-electrons in AlAs [3], the appearance of new correlated electron states in Si/SiGe heterostructures [4] and the observation of a highly anisotropic transport in a two-subband quantum well [5].

In this work we will report on the experimental investigation of level crossings in bilayer 2DESs by means of tilted-field magnetotransport experiments. We will show how an in-plane magnetic field together with the interaction between energetically coinciding symmetric and antisymmetric levels with opposite spin can lead to the closing and reopening of the related gaps.

2. Experimental

We have investigated two different bilayer structures consisting of two 10 nm wide GaAs quantum wells separated by a 2.5 nm wide $Al_{0.35}Ga_{0.65}As$ barrier. Electrons are provided by symmetric modulation doping of the outer $Al_{0.35}Ga_{0.65}As$ barriers surrounding the double quantum well. In sample A a total electron concentration $n = 3.9 \times 10^{15}\,m^{-2}$ is present in the bilayer with a mobility $\mu = 12\,m^2/V\,s$. The splitting between the symmetric and antisymmetric state of the bilayer amounts to $\Delta_{SAS} = 2.5\,meV$. By illumination with an infrared diode the electron concentration can be increased to

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$n = 7.1 \times 10^{15}\,\mathrm{m}^{-2}$, with $\mu = 19\,\mathrm{m}^2/\mathrm{V\,s}$ and $\Delta_{\mathrm{SAS}} = 3.5\,\mathrm{meV}$. Sample B has an electron concentration $n = 2.5 \times 10^{15}\,\mathrm{m}^{-2}$, a mobility $\mu = 50\,\mathrm{m}^2/\mathrm{V\,s}$ and $\Delta_{\mathrm{SAS}} = 4.3\,\mathrm{meV}$ (in the dark).

In a perpendicular magnetic field the samples display Shubnikov–de Haas (SdH) oscillations and the quantum Hall effect (QHE), for more details see Ref. [6]. For high enough magnetic fields, where the Landau-level (LL) splitting $\hbar\omega_c$ exceeds Δ_{SAS}, the SdH-minima and QH plateaus appearing around filling factors $\nu = 4(N+1)$ ($N = 0, 1, 2\ldots$ is an integer) are related to a transition of the Fermi energy from the symmetric state of LL $N+1$ to the antisymmetric state of LL N with opposite spin. Filling factors $\nu = 4(N+1) - 2$ correspond to a transition from a spin-up antisymmetric state to a spin-down symmetric state within the same LL N. Finally, at low enough odd-integer filling factors $\nu \leqslant 9$, we are also able to observe the Zeeman splitting ΔE_z.

3. Magneto-transport in tilted magnetic fields

Experiments in a tilted magnetic field can be conceptually viewed as adding an additional in-plane field to the bilayer at a fixed perpendicular field, i.e. at a fixed filling factor. The in-plane field increases the spin-splitting $\Delta E_Z = g^* \mu_{\mathrm{B}} B_{\mathrm{tot}}$, governed by the *total* magnetic field B_{tot}. Additionally, the presence of an in-plane field reduces the coupling between the layers, leading to a reduction of Δ_{SAS} [7]. For a large enough in-plane field, Δ_{SAS} becomes smaller than ΔE_z and finally collapses totally. This leads to the disappearance of all SdH minima and QH plateaus at odd-integer filling factors for high enough tilt angles [6].

In between the small tilt angles where $\Delta_{\mathrm{SAS}} > \Delta E_Z$ and the large angles with $\Delta_{\mathrm{SAS}} \to 0$ a crossing point where $\Delta_{\mathrm{SAS}} = \Delta E_Z$ must exist. For a given filling factor (e.g. $\nu = 2, 6, 10, \ldots$ for LL $N = 0, 1, 2, \ldots$) the single-particle energies of the symmetric spin-down and the asymmetric spin-up state of the corresponding LL coincide at this crossing point.

The experimental magnetotransport data around such a crossing point for sample A is shown in Fig. 1. When approaching the crossing point from the low-angle side (51–55°) the Hall plateau at $\nu = 6$ indeed becomes narrower and the SdH minimum starts to be lifted. With a further increasing tilt angle, however, the plateaus start to broaden abruptly reaching a maximum width around 59°. Additionally, we also find a narrowing of the gaps at $\nu = 5$ and $\nu = 7$ around tilt angles where two levels cross above or below the Fermi energy, respectively.

These observations can be illustrated more quantitatively by plotting the width of the Hall plateaus as a function of the tilt angle. For this, we define a relative Hall resistance

$$\Delta\rho_{xy} = \left|\frac{\rho_{xy} - \rho_k}{h/e^2}\right|, \tag{1}$$

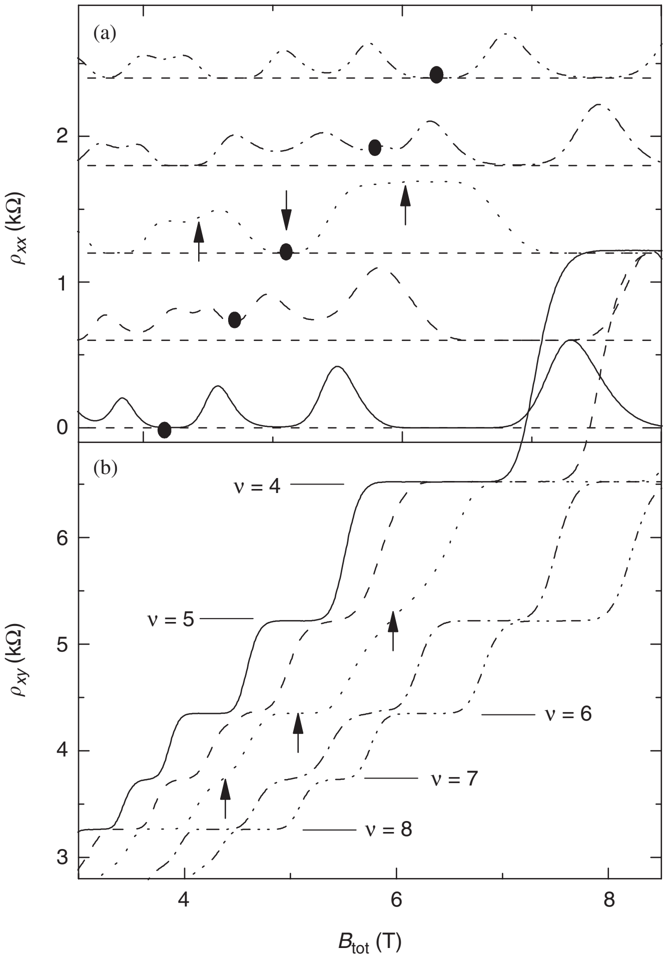

Fig. 1. (a) Resistivity ρ_{xx} and (b) Hall resistivity ρ_{xy} of the sample A at 0.35 K at 51°, 55°, 59°, 62°, and 65° as a function of the *total* magnetic field. The curves in (a) are shifted by 0.6 kΩ and sorted from bottom (51°) to top (65°). The (unshifted) traces in (b) cover the same angle range from 51° for the leftmost curve to 65° for the rightmost curve. The dots in (a) mark the position of the $\nu = 6$ minimum, the horizontal lines in (b) indicate the quantum Hall plateaus. <!–The broadening of the $\nu = 6$ energy gap and the gap narrowing at $\nu = 5$ and $\nu = 7$ are indicated by the arrows.

where $\rho_k = h/e^2 k$ is the closest QH plateau with integer filling factor k to a given value of ρ_{xy}. By definition, $\Delta\rho_{xy}$ varies between 0 on a QH plateau and 0.5 between two plateaus. The width of a plateau can then be defined as $w_{\mathrm{QH}} = 2(B_1 - B_2)/(B_1 + B_2)$ using the perpendicular fields B_1 on its left and B_2 on its right where $\Delta\rho_{xy}$ becomes larger than a threshold value $\delta = 0.05$ [8]. This definition of w_{QH} provides a sensitive access to level spacings in the QH regime. Roughly speaking, the QHE shows a quantized plateau as long as the distance between two levels exceeds their width Γ and starts to disappear as soon as the level spacing falls below Γ.

In Fig. 2 we have plotted the plateaus widths w_{QH} for the QH plateaus at $\nu = 5, 6$, and 7. For sample A (filled symbols) we observe a closing and re-opening of the gap at $\nu = 6$ accompanied by a closing of the gaps at $\nu = 5$ and $\nu = 7$. We observed a similar re-opening of the gap at