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Shifting the quantum Hall plateau level in a double layer electron system

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We study the plateaux of the integer quantum Hall resistance in a bilayer electron system in tilted magnetic fields. In a narrow range of tilt angles and at certain magnetic fields, the plateau level deviates appreciably from the quantized value with no dissipative transport emerging. A qualitative account of the effect is given in terms of decoupling of the edge states corresponding to different electron layers/Landau levels.

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Much interest in double-layer electron systems is attracted by the presence of an additional degree of freedom which is associated with the third dimension. Strong interlayer correlations give rise to the appearance of novel states that are not observed in single-layer systems: (i) the even-denominator fractional quantum Hall effect [1 – 3], (ii) the many-body integer quantum Hall effect [4, 5], and (iii) broken-symmetry states [6]. All the states manifest themselves as quantum plateaux in the Hall resistance, ρ_{xy}, accompanied by zeroes in the longitudinal resistivity, ρ_{xx}. Driving the system out of the dissipationless regime leads to deviations of ρ_{xy} from the quantized value, i.e., the behaviour of ρ_{xy} is correlated with that of ρ_{xx}. A deviation of the quantum Hall plateau at filling factor $\nu = 3/2$ from the quantized value accompanied by non-zero ρ_{xx} was observed in a bilayer system with asymmetric hole density distributions [7]. Peaks at the low-field edge (so-called overshoots) of the quantum Hall plateaux along with corresponding peaks in ρ_{xx} were observed in wide parabolic GaAs quantum wells in the two-subband regime [8]. Similar overshoots were previously reported in GaAs/AlGaAs heterostructures with one occupied subband and explained in terms of decoupling/depopulation of the edge state associated with the topmost Landau level [9]. Normally, additional features on the quantum Hall plateau are comparable to corresponding ones in ρ_{xx}. On the other hand, whether or not the accuracy of the Hall resistance quantization is related to dissipative effects solely is not clear so far. In principle, decoupling of the edge states can lead to shifting the plateau level in the absence of dissipative transport as well. In the simplest case of a double layer electron system with two layers being in different quantum Hall states, the decoupling of the edge states belonging to different layers can be easily controlled, e.g., by the application of an in-plane magnetic field [8, 10].

Here, we perform precision measurements of the quantized Hall resistance at integer filling factor in a double layer electron system in tilted magnetic fields. In a narrow region of tilt angles and at certain magnetic fields, we observe pronounced deviations of the quantum Hall plateau from the quantized value which are not accompanied by any additional features in the dissipative resistivity. The obtained results are qualitatively explained by decoupling of the edge states corresponding to different electron layers/Landau levels, although the sensitivity of the effect to both tilt angle and magnetic field is unclear.

The samples are grown by molecular beam epitaxy on semi-insulating GaAs substrate. The active layers form a 760 Å wide parabolic well. In the center of the well a 3 monolayer thick $Al_xGa_{1-x}As$ ($x = 0.3$) sheet is grown which serves as a tunnel barrier between both parts on either side. The symmetrically doped well is capped by 600 Å AlGaAs and 40 Å GaAs layers. The samples are $450 \times 50\ \mu m^2$ Hall bars that have a metallic gate on the crystal surface and ohmic contacts connected to both electron systems in two parts of the well. Applying a dc voltage between the well and the gate enables us to tune the carrier density in the well. The sample is placed in the mixing chamber of a dilution refrigerator with a base temperature of about 30 mK so that the normal to its surface is tilted with respect to the magnetic field. The longitudinal and Hall resistivities of the bilayer electron system are measured as a function of either magnetic field, B, or gate voltage, V_g, using a standard four-terminal lock-in technique at a frequency of 10 Hz. The excitation current is kept low enough to ensure that measurements are taken in the linear regime of response. The data are well reproducible in different coolings of the sample.

For additional magnetocapacitance measurements, a small ac voltage 2.4 mV at frequencies in the range 3 – 600 Hz is applied between the well and the gate and both current components are measured. In the low frequency limit, the imaginary current component reflects the thermodynamic density of states in a double layer electron system whereas the active component of the current is inversely proportional to the dissipative conductivity (for details, see Ref. [11]).

The positions of the magnetocapacitance minima in the $(B_\perp, V_g)$ plane for filling factor $\nu = 2, 3$, and 4 are shown in Fig.1 by circles for different tilt angles, Θ,

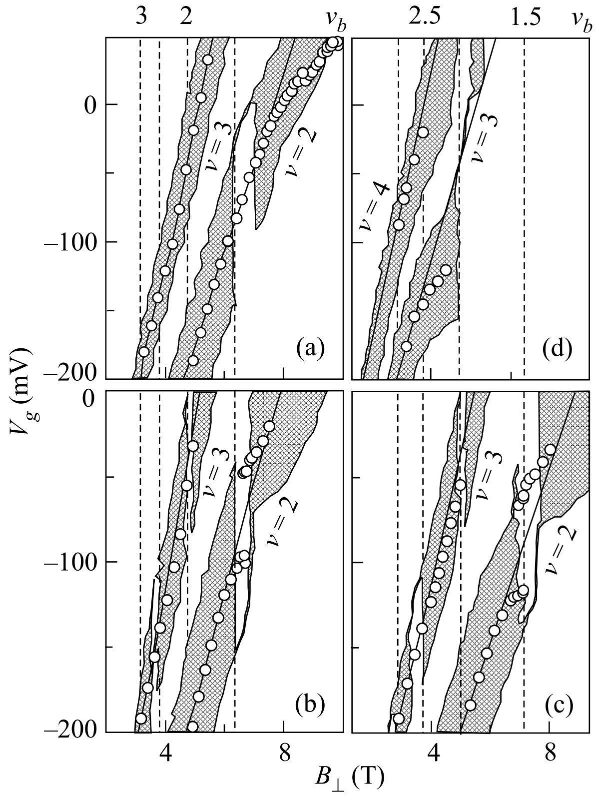

Fig.1. Positions of the magnetocapacitance minima (circles) in the $(B_\perp, V_g)$ plane for $\nu = 2, 3$, and 4 at tilt angles 45° (a), 50° (b), 53° (c), and 66.5° (d). The dashed lines correspond to the indicated values of filling factor ν_b in the back electron layer. In the shaded areas the deviation of ρ_{xy} from the quantized value does not exceed 0.05%

of the magnetic field. Another fan chart (not shown in the figure) is determined by magnetocapacitance minima corresponding to gaps in the spectrum of the front electron layer only; these two fan charts allow determination of the front layer depopulation voltage $V_g = -200$ mV (bilayer onset) and the voltage $V_g = 100$ mV at which the quantum well becomes symmetric (balance point) [11, 12]. As seen from Fig.1, discontinuities on the fan chart lines for $\nu = 2$ and $\nu = 3$ emerge with increasing tilt angle. This behavior is identical with reported earlier on similar samples with the same quantum well design and interpreted for $\nu = 2$ in terms of a formation of the canted antiferromagnetic phase [13].

In Fig.2(a), we show the Hall resistance ρ_{xy} as a function of magnetic field around filling factor $\nu = 3$

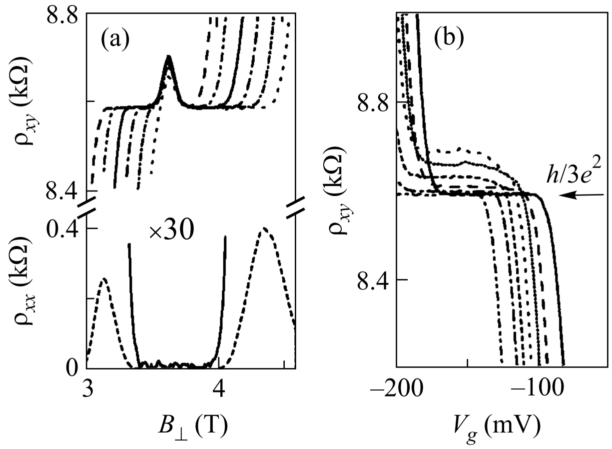

Fig.2. Traces of ρ_{xy} for $\nu = 3$ at $\Theta = 53°$ as a function of $B_\perp$ at gate voltages −170, −160, −150, −140, −130, and −120 mV (a) and as a function of V_g at perpendicular components of the magnetic field 3.45, 3.55, 3.60, 3.65, 3.70, 3.75, and 3.85 T (b). Also shown in case (a) is the dependence of ρ_{xx} on $B_\perp$ at $V_g = -150$ mV

for gate voltages between −170 and −120 mV at a tilt angle $\Theta = 53°$. There exists a pronounced peak on the quantum Hall plateau although the longitudinal resistivity ρ_{xx} zeroes nicely. (We have checked with the help of the magnetocapacitance measurements that the dissipative conductivity shows no additional features either.) This peak on the plateau is not sensitive to a variation of V_g so that at a fixed magnetic field within the peak, the dependence of ρ_{xy} on gate voltage has a plateau at a level above the quantized value, see Fig.2(b). Such a behavior of the $\nu = 3$ quantum Hall plateau is observed in a narrow range of tilt angles: it is present for $\Theta = 50°$ and $\Theta = 53°$ while at $\Theta = 45°$ and $\Theta = 66.5°$ the $\nu = 3$ quantum Hall plateau is found to be featureless.

Similar shifts of the quantum Hall plateau level accompanied by good zeroes in ρ_{xx} are also observed at filling factor $\nu = 2$ for $\Theta = 45°$, see Fig.3(a). Besides, near the splitting of the $\nu = 2$ fan chart line that arises with increasing Θ (Fig.1), an additional peak appears in both ρ_{xx} and ρ_{xy} on the shifted plateau, see Fig.3(b).

In this case the appearance of a dissipative transport is naturally reflected by ρ_{xy} behavior.

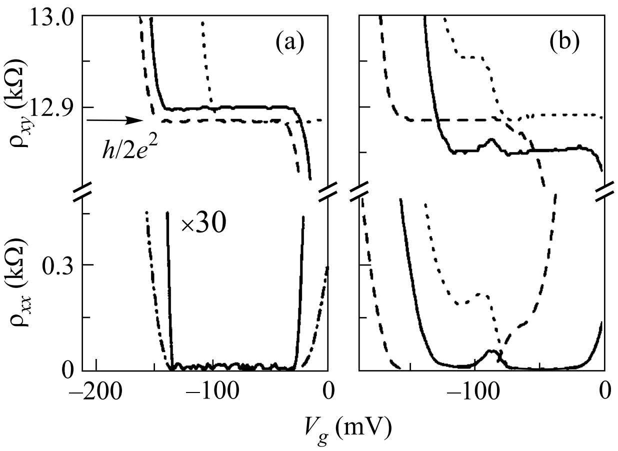

Fig.3. Dependence of ρ_{xy} and ρ_{xx} on gate voltage for $\nu = 2$ at $\Theta = 45^\circ$ for $B_\perp = 6.26, 6.38$, and 7.09 T and for $B_\perp = 6.50$ T, respectively (a) and at $\Theta = 53^\circ$ for $B_\perp = 6.04, 6.54$, and 6.74 T (b)

The overall data on deviation of the quantum Hall plateaux from the quantized values are depicted in Fig.1. The regions in which the plateau deviation does not exceed 0.05% are hatched. To our surprise, at some tilt angles these regions for the same ν are separated forming regular vertical strips whose position corresponds to integer and half-integer filling factor, ν_b, in the back electron layer. Note that the electron density in this layer is practically unchanged with changing V_g because of screening effect of the front electron layer.

In principle, one can expect possible shifts of the quantum Hall plateau level: at integer both ν_b and ν in an unbalanced bilayer electron system, two electron layers correspond to two lowest electron subbands with independent gaps in their spectrum at the Fermi level, i.e., the electron layers are independent. Therefore, the condition of inverse proportionality of their individual currents to ρ_{xy} can be broken, e.g., due to contact resistance, leading to distinct (decoupled) electrochemical potentials of the electron layers. Provided that the electrochemical potentials do not get equilibrated along the edge of the sample including contact regions, the measured Hall resistance plateau can be above or below the quantized value even in the absence of dissipative transport. Similar arguments apply for the observed dissipationless states at non-integer ν_b and integer ν. In these states the electron subbands are correlated as caused by wave function reconstruction in the unbalanced bilayer electron system [11, 12]. Subject to the absence of electrochemical potential equilibration between different Landau levels, the measured Hall resistance plateau can also be shifted.

However, from the above argumentation it is not clear why deviations of the quantum Hall plateaux are observed in narrow intervals of the magnetic field that correspond to integer and half-integer filling factor ν_b. The sensitivity of the effect to the tilt angle of magnetic field cannot be explained either. Thus, a more sophisticated interpretation of the experimental data is needed.

In summary, we have studied the behavior of the quantum Hall resistance plateaux at integer filling factor in a bilayer electron system in tilted magnetic fields. In a narrow range of tilt angles and at magnetic fields corresponding to integer and half-integer filling factor ν_b, pronounced deviations of the quantum Hall plateau from the quantized value are observed which are not caused by dissipative transport. We give a qualitative account of the effect in terms of decoupling of the edge channels belonging to different electron layers/Landau levels, although its sensitivity to both tilt angle and magnetic field is unclear.

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