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Manifestation of the Bulk Phase Transition in the Edge Energy Spectrum in a Two-Dimensional Bilayer Electron System¶

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We use a quasi-Corbino sample geometry with independent contacts to different edge states in the quantum Hall effect regime to investigate the edge energy spectrum of a bilayer electron system at a total filling factor of $\nu = 2$. By analyzing nonlinear *I–V* curves in normal and tilted magnetic fields, we conclude that the edge energy spectrum is in a close connection with the bulk one. At the bulk phase transition spin-singlet–canted antiferromagnetic phase, the *I–V* curve becomes linear, indicating the disappearance or strong narrowing of the $\nu = 1$ incompressible strip at the edge of the sample.

In a quantizing magnetic field, energy levels in a two-dimensional (2D) electron gas (2DEG) bend up near the edges of the sample, forming edge states (ESs) at the intersections with the Fermi level. Electron transport through ESs is responsible for many transport phenomena in 2D, as it was firstly proposed by Büttiker [1] and further developed by Chklovskii *et al.* [2] for interacting electrons. This ES picture is in good agreement with experimental results [3] on the transport both along ESs and between them.

Two principally different sample geometries were applied for transport investigations *between* different ESs: (i) a cross-gated Hall-bar [3] and (ii) a split-gated quasi-Corbino geometry [4, 5]. While measurements in a Hall-bar geometry provide information on the equilibration length between ESs [3, 6], investigations in a quasi-Corbino geometry are used to study the energy spectrum at the edge of a 2D system [5]. So far all experiments on the interedge channel equilibration have been performed on single-layer 2D systems, despite the fact that bilayer electron systems also seem to be very interesting.

In the bulk of a bilayer system, each Landau level is split into four sublevels corresponding to the spin and symmetric–antisymmetric splitting, which is caused by interlayer tunneling. In the simplest case of a weak Coulomb interlayer interaction, the interplay between the symmetric–antisymmetric splitting Δ_{SAS} and the Zeeman splitting is responsible for the bulk properties of bilayer systems at a filling factor of $\nu = 2$. Δ_{SAS} depends only on the electron concentration, so at fixed total filling factor, it diminishes with increasing magnetic field. In contrast, the Zeeman splitting is proportional to the absolute value of the magnetic field. For this reason, at a total filling factor of $\nu = 2$, in low quantizing magnetic fields, two occupied energy levels are separated by a bare Zeeman energy. These two occupied levels belong to different spin orientations, so that the system is in a spin-singlet state. The excitation energy at a filling factor of $\nu = 2$ is determined by the next energy scale, i.e., the symmetric–antisymmetric splitting, and is equal to $\Delta_{SAS} - g\mu B$. Increasing the magnetic field at fixed total filling factor, the excitation energy goes to zero. At zero excitation energy, $\Delta_{SAS} = g\mu B$ and a spectrum reconstruction occurs: at higher fields, Δ_{SAS} is the minimal energy scale, so both the filled levels are at the same spin orientation (in the field direction). The bilayer system is said to be in a ferromagnetic state. This spin-singlet–ferromagnetic phase transition can be driven also by an in-plane field component at fixed normal magnetic field. Indeed, this is only the Zeeman term which depends on the absolute value of the field, while the other energy scales are determined by the normal field component.

Regarding the single-particle approximation (without significant inter-layer interactions), while increas-

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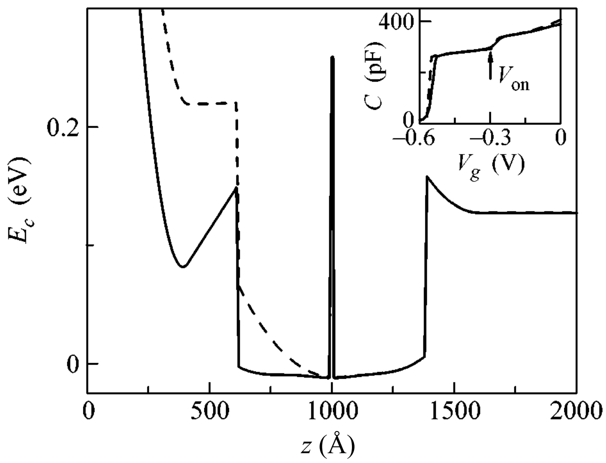

Fig. 1. Quantum well subband diagram at zero gate voltage (solid line) and at twice smaller electron conservation (dashed line) as calculated from the growth sequence of the structure (calculated using Poisson–Schrodinger solver by G. Snider). Inset shows the capacitance of the sample in dependence on the gate voltage calculated from the subband diagram (dashed) and measured in the experiment (solid). The magnetic field is zero.

ing the Zeernan splitting, the bilayer system at a filling factor of $\nu = 2$ undergoes a direct phase transition from a spin-singlet to a ferromagnetic state [7] at a critical magnetic field of $B_c = \Delta_{SAS}/g\mu$. However, in experiments with high interlayer Coulomb interaction [8, 9] (the distance between the layers is comparable to the magnetic length), the transition point is significantly shifted to lower fields. This was understood as a manifestation of many-body effects [10–12]. It was shown theoretically that the interlayer Coulomb interaction shifts the transition point to a value of $\mu g B_c \approx \Delta_{SAS}^2/E_c$, where E_c is the Coulomb energy. At the field B_c, a transition from the spin-singlet to a novel canted antiferromagnetic state now occurs. In this new phase, electron spins in both layers are canted from the field direction due to the Coulomb interaction. This bulk phase was experimentally investigated [8, 9] and the obtained results are in good agreement with theoretical predictions [10–12].

The situation at the sample edge is expected to be more complicated. The ES structure is determined by both the edge potential and the bulk spectrum of a bilayer system. The latter can be very complicated even for the simplest situation of a total filling factor of $\nu = 2$ in the bulk [7–9, 13]. Moreover, the excitation spectrum is strongly dependent on the local filling factor, which varies widely at the sample edge. For these reasons, even a systematic of the excitations at the edge is unknown *ab initio*.

Here, we use a quasi-Corbino sample geometry to investigate the edge spectrum of excitations at a total filling factor of $\nu = 2$ in a bilayer electron system in normal and tilted magnetic fields while approaching the bulk phase transition from a spin-singlet to a canted antiferromagnetic state. At the bulk transition point, the *I–V* curve becomes linear, indicating a strong narrowing of the incompressible strip between two ESs.

Our bilayer structures are grown by molecular beam epitaxy on a semi-insulating GaAs substrate. The active layers form a 760 Å wide parabolic quantum well. In the center of the well, a three-monolayer-thick AlAs sheet is grown which serves as a tunnel barrier between both parts on either side. The symmetrically doped well is capped by 600-Å $Al_xGa_{1-x}As$ ($x = 0.3$) and 40-Å GaAs layers. The symmetric–antisymmetric splitting in the bilayer electron system as determined from far infrared measurements and model calculations [14] is equal to $\Delta_{SAS} = 1.3$ meV.

At zero gate voltage, the quantum well is practically symmetric, see Fig. 1 (solid line). It contains 4.2×10^{11} cm^{-2} electrons, which are distributed in both parts of the well. Applying a negative voltage to the gate makes the potential relief asymmetric (see Fig. 1, dashed line), indicating the depletion of the upper electron layer at low enough voltages.

This is illustrated in the inset to Fig. 1, where both measured (solid) and calculated (dashed) capacitances are shown as a function of the gate voltage in zero magnetic field. At the point of the abrupt changing of the capacitance (bilayer onset, $V_{on} = -0.3$ V), electrons are leaving the top part of the well and the distance between the gate and the 2D system is enlarged.

Samples are patterned in a quasi-Corbino geometry [5] (see Fig. 2). The square-shaped mesa has a rectangular etched region inside. Ohmic contacts are made to the inner and outer edges of the mesa (each of the contacts is connected to both electron systems in the two parts of the well). The top gate does not completely encircle the inner etched region but leaves uncovered a narrow (3 μm) strip (gate-gap) of 2DEG at the outer edge of the sample.

At integer total filling factor $\nu = 2$, edge channels are running along the etched edges of the sample (see Fig. 2). Depleting the electron system under the gate to a smaller integer filling factor $g = 1$ (as shown in the figure), one channel is reflected at the gate edge and redirected to the outer edge of the sample. In the gate-gap region, ESs originating from different contacts run in parallel along the outer (etched) edge of the sample, at a distance determined by the gate-gap width. Thus, the applied geometry allows us to separately contact ESs with different spin and layer indices and bring them into an interaction at a controllable length.

In our experimental setup, one of the inner contacts is always grounded. We apply a dc current to one outer ohmic contact and measure the dc voltage drop between two remaining inner and outer contacts. To increase the Zeeman splitting with respect to other energy scales, in our bilayer structure, we apply an in-plane magnetic field at fixed normal field by tilting the sample. Experiments are performed at a temperature of 30 mK in magnetic field up to 14 T.

Measured *I–V* curves are presented in Fig. 3 for normal and tilted magnetic fields for a filling factor of ν = 2 in the gate gap and *g* = 1 under the gate.

In normal magnetic field, the obtained *I–V* curve is of a diode-like form. It is nonlinear and consists of two branches, which starts from corresponding onset voltages—positive V_{th}^{+} and negative V_{th}^{-} thresholds. In between these thresholds, the current is practically zero. The positive branch of *I–V* is close to linear and characterized by low resistance. In contrast, the negative branch is strongly nonlinear and of higher resistance, see Fig. 3.

In normal magnetic field, the positive threshold V_{th}^{+} is close to the bare Zeeman splitting (0.21 meV in a field of 8.7 T). The negative threshold is one order of magnitude higher (V_{th}^{-} is about 2 meV) and corresponds to Δ_{SAS} in our bilayer structure. In both cases, it is a problem to estimate the experimental accuracy—the exact value of the threshold depends on the determination method. For example, the positive threshold we can define either by an extrapolation from high currents or as the voltage at which a significant current appears. These values are slightly different, as can be seen from Fig. 3. For the negative threshold, the second method seems to be more appropriate because of the strong nonlinear form of the curve. Nevertheless all relevant energy scales in a bilayer system (Zeeman splitting, symmetric–antisymmetric splitting, and a cyclotron splitting, which is about 15 meV here) are very different, so it is easy to assign a threshold to the appropriate spectral gap.

Both threshold voltages are strongly dependent on the in-plane field, see Fig. 3. They are diminishing with increasing in-plane field and disappear at a tilt angle of θ = 45°. A calculated *I–V* trace for the case of full equilibration between two ESs is also shown in Fig. 3 (dash–dot line) for the comparison with θ = 45° data. It can be seen that, despite disappearance of the threshold voltages at θ = 45°, the experimental curve is still slightly nonlinear.

The curves in Fig. 3 are given for two sweep directions—from positive to negative currents and vice versa. A small hysteresis can be seen. It is a maximum in normal magnetic field, becomes smaller at a tilt angle of θ = 30°, and disappears at θ = 45°. This hysteresis is a key feature for transport between two spin-split ESs [15–17]—for some electrons, spin flip is accompanied by nuclear spin flop. The hysteresis is an effect of the high nuclear relaxation time (for a thorough discussion, see [17]).

The dramatic influence of the in-plane magnetic field on the experimental *I–V* traces can also be seen from Fig. 4a. It demonstrates *I–V* curves in a much wider current/voltage range. The experimental nonlinear *I–V* curves are clearly flattening when the in-plane field increases. At a tilt angle of θ = 45°, even the curve shape is very different from the normal field case.

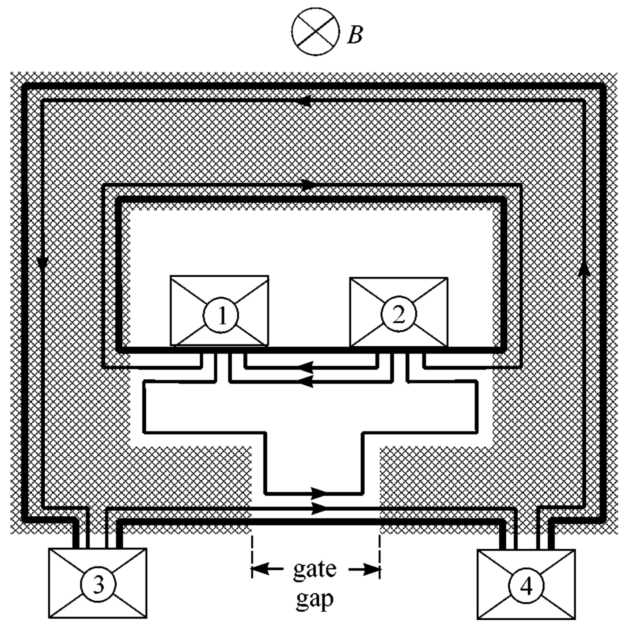

Fig. 2. Schematic diagram of the pseudo-Corbino geometry. Contacts are positioned along the etched edges of the ring-shaped mesa (thick outline). The shaded area represents the Schottky gate. Arrows indicate the direction of electron drift in the edge channels for filling factors of ν = 2 in the ungated regions and *g* = 1 under the gate.

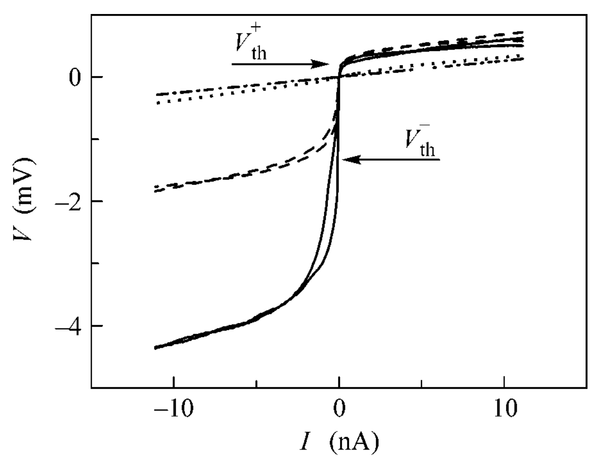

Fig. 3. *I–V* curves for a total filling factor of ν = 2 and *g* = 1 under the gate at different tilt angles. They are θ = 0 (solid line), θ = 30° (dashed line), θ = 45° (dotted line). Dash–dot line depicts fully equilibrium *I–V* curve, calculated from Landau–Buttiker formulas. The normal magnetic field is constant and equals 8.7 T.

The described behavior is totally different from that of a single-layer structure, where no influence of the in-

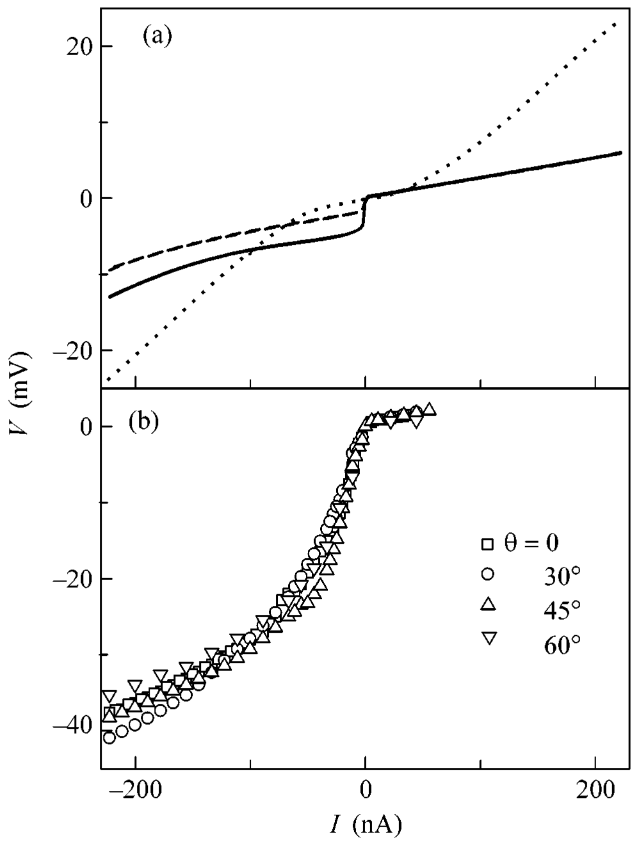

Fig. 4. I–V curves for a total filling factor of $\nu = 2$ and $g = 1$ under the gate at different tilt angles in a wide current/voltage range. (a) The present bilayer system. The tilt angles are $\theta = 0$ (solid line), $\theta = 30°$ (dashed line), $\theta = 45°$ (dotted line). (b) A single-layer heterostructure, discussed in [17]. The tilt angles are $\theta = 0$ (squares), $\theta = 30°$ (circles), $\theta = 45°$ (up triangles), $\theta = 60°$ (down triangles).

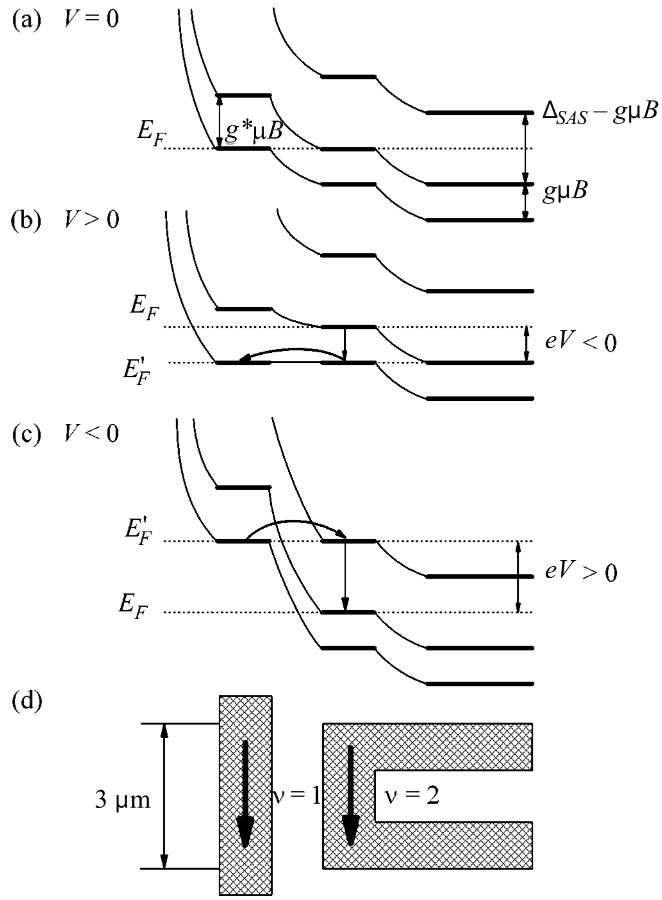

Fig. 5. Energy subband diagram of the sample edge in the gate gap for filling factors of $\nu = 2$ and $g = 1$. (a) No voltage V applied between the inner and outer ESs. (b) $V > 0$, in the situation shown, the outer ES is shifted down in energy by $eV = -|g|\mu_B B$; (c) $V < 0$, here the energy shift is $eV > 0$. (d) Sketch of the compressible strips in the gate-gap region. Arrows in Figs. 5b and 5c indicate new ways for electron relaxation opening up at high potential imbalance.

plane magnetic field on the nonlinear I–V curves can be observed [17]. To demonstrate it in comparison with the bilayer data, we present in Fig. 4b I–V curves for a single-layer structure [17] at different tilt angles. Because of high hysteresis in a single-layer case, these curves are obtained by waiting for 10 min at each point to have time-independent I–V curves. From both the values of the thresholds and tilted field behavior, we should conclude that bilayer properties are important in the present experiment.

Using the gated part of the sample for magnetocapacitance measurements, we reproduced the previously obtained results [9, 13] on the bulk bilayer spectrum at a total filling factor of $\nu = 2$ in normal and tilted magnetic fields: (i) In normal magnetic field, the bulk activation energy, obtained from the magnetocapacitance, is close to the single-particle Δ_{SAS}. (ii) While increasing the in-plane magnetic field component, the bulk bilayer system goes to the transition into the canted antiferromagnetic phase. This phase transition is characterized by the appearance of a deep minimum in the activation energy at a tilt angle of $\theta = 45°$.

Let us start the discussion from the case of normal magnetic field. The bulk bilayer system at a filling factor of $\nu = 2$ is in a spin-singlet state [13] and is far from the phase transition point. The energy structure in the bulk at a filling factor of $\nu = 2$ can therefore be depicted in a single-particle approximation as two filled quantum levels under the Fermi energy separated by the Zeeman gap. The energy level structure is depicted in Fig. 5a in the gate-gap region. Approaching the sample edge, two occupied energy levels bend up because of the rising edge potential.

In our experimental geometry, we independently contact inner (always grounded) and outer ESs. For this reason the measured voltage drop V is equal to the energy shift of the outer ES in respect to the inner one, see Figs. 5b and 5c. For a positive measured voltage,

$V > 0$, the outer ES is shifted down in energy by a value of $eV < 0$. It can be seen from Fig. 5b that, at the value of the voltage $V = V_{\text{th}}^{+} = -|g|\mu B/e$ (where g is the bare g factor, $e < 0$ is the electron charge), the lowest (the only occupied in both ESs) energy level is flattened between two ESs, so that electrons can easily move from one ES into the other. Thus, starting from the $eV_{\text{th}}^{+} = -|g|\mu B$, electrons can be transferred between ESs by vertical relaxation in the inner ES between two spin-split levels and move along the lowest energy level to the outer ES, see Fig. 5b. This positive voltage V_{th}^{+} is characterized by a sharp rise in the current; i.e., it is a threshold voltage for the positive branch of the I–V curve. It is a reason for the experimentally observed V_{th}^{+} to be close to the bare Zeeman gap. On the other hand, a negative voltage shifts the outer ES up in energy. Electrons always have to tunnel through the potential barrier from the outer ES into the inner one. This tunneling is only possible from the occupied states in the outer ES either into the empty states in the inner ES or into the excited energy states in it. The latter process (with further vertical relaxation in the inner ES to the Fermi level) is more likely for $eV > E_a$, where E_a is the energy of the first excited state. For this reason, experimental I–V traces change their slopes at $eV = E_a$, which we refer to as the negative threshold voltage V_{th}^{-}. As we know from bulk spectrum investigations, at a filling factor of $\nu = 2$, the first excited state is separated from the ground state by Δ_{SAS}. It is a reason for V_{th}^{-} to be close to Δ_{SAS} in normal magnetic field.

For an increase of the in-plane magnetic field component, the Coulomb interaction becomes more and more important, so that the simple single-particle picture described above is no longer adequate. In the bulk, the quantum levels are mixed into a new ground state of the system, which is separated from the excited state by a very low energy at the transition point [10]. Approaching the sample edge, the electron concentration is diminishing due to the edge potential. The local filling factor is still $\nu = 2$ before the inner ES and becomes $\nu = 1$ in between the inner and outer ESs (see Fig. 5d). The energy structure at the edge is determined by the local filling factor, so the system is still at $\nu = 2$ ground state before the inner ES and changes to the $\nu = 1$ ground state between two ESs. In the inner ES, the electron concentration changes from the value corresponding to $\nu = 1$ to the value $\nu = 2$.

The electron system in the vicinity of the $\nu = 1$ incompressible strip can be described as a $\nu = 1$ ground quantum Hall state with some amount of electron excitations (right side of $\nu = 1$ strip in Fig. 5d), or as a $\nu = 1$ ground quantum Hall state with some amount of holes, on the opposite side of the $\nu = 1$ strip. It is the edge potential in the $\nu = 1$ incompressible strip that separates electrons and holes on both sides of the strip. Consequently, the main result of our experiment should be interpreted as a practical disappearance of this potential barrier (or, possibly, of the incompressible $\nu = 1$ strip itself) under conditions of the canted antiferromagnetic phase in the bulk. In these conditions, electrons can freely move between ESs without spin-flips, so there is no reason both for the nonlinear behavior of experimental I–V traces and for the hysteresis on them.

We used a quasi-Corbino sample geometry with independent contacts to different edge states in the quantum Hall effect regime to investigate the edge spectrum of a bilayer electron system at a total filling factor of $\nu = 2$. By analyzing nonlinear I–V curves in normal and tilted magnetic fields, we found that the edge energy spectrum is in a close connection with the bulk one. At the bulk transition spin-singlet–canted antiferromagnetic phase, the I–V traces become linear, indicating the disappearance of the potential barrier between $\nu = 1$ ground state with some amount of electron excitations and the $\nu = 1$ ground state with some amount of holes at the edge of the sample.

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