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# Spin ordering: two different scenarios for the single and double layer structures in the fractional and integer quantum Hall effect regimes

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We investigate the ground state competition at the transition from the spin unpolarized to spin ordered phase at filling factor  $\nu = 2/3$  in single layer heterostructure and at  $\nu = 2$  in double layer quantum well. To trace the quantum Hall phase we use the minimum in the dissipative conductivity  $\sigma_{xx}$ . We observe two different transition scenarios in two investigated situations. For one of them we propose a qualitative explanation, based on the domain structure evolution in the vicinity of the transition point. The origin for the second scenario, corresponding to the experimental situation at  $\nu = 2$  in double layer quantum well, still remains unclear.

The change of the ground state at fixed filling factor was experimentally observed in a number of two dimensional electron systems (2DES) subjected to quantizing magnetic fields [1–4]. There are two very prominent examples of the ground state competition: (i) the phase transition from the spin unpolarized into the canted antiferromagnetic phase in double layer system [2] at filling factor  $\nu = 2$  and (ii) the transitions between spin unpolarized and fully spin polarized states in the fractional quantum Hall effect (FQHE) regime [3]. Electron correlations (inter-plane and intra-plane, correspondingly) play a significant role in both cases, allowing to combine them into a single class of physical phenomena [5]. It also seems natural to compare these transitions, because  $\nu = 2/3$  is mapped via composite fermion theory [6] to a single-layer  $\nu = 2$  state. Thus, the role of the isospin degree of freedom can be highlighted in this comparison. The competition between ground states still survives even at zero temperature, thus the above mentioned transitions are caused by quantum fluctuations and are supposed to be the quantum phase transitions [7].

Both the integer and the fractional quantum Hall effects are caused by the gap in the 2DES electron spectrum and disorder [8]. Quantum Hall phase exists within the strip in the  $(B, n_s)$ -plane, around the line of the corresponding integer or fractional filling factor. Within the strip, the electron density  $n_s$  and the magnetic field  $B$  can only affect on the Fermi level position and have no radical influence on the

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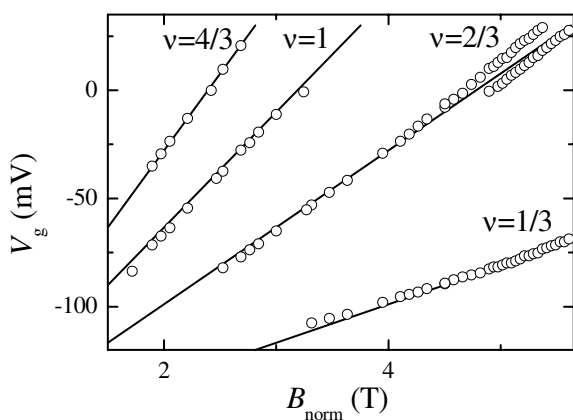
physical properties of the 2DES. In contrast to this situation, in the vicinity of the phase transition point the ground state itself is a function of these two parameters  $B, n_s$  and a complicated behavior of the 2DES properties can be expected.

Under the FQHE conditions, in a strong perpendicular magnetic field  $B_{\text{norm}}$ , corresponding to the particular fractional filling factor  $\nu = hc n_s / e B_{\text{norm}}$ , the Hall conductivity is of quantized value  $\nu e^2 / h$  while the longitudinal one vanishes in the high quality 2DES. Electron spins can be considered as parallel in the high- $B_{\text{norm}}$  limit, while at the simultaneous lowering of  $B_{\text{norm}}, n_s$  a transition into the partially spin polarized or even spin unpolarized state is predicted [9]. Qualitatively this transition can be understood as a result of the competition between the Zeeman and exchange energies in strongly correlated electron liquid. Disappearance of the minimum in the dissipative conductivity component at some electron density  $n_s^{\text{tr}}$  and reappearance of the minimum around  $n_s^{\text{tr}}$  at constant fractional filling factor was interpreted as the observation of the ground state competition [1, 3].

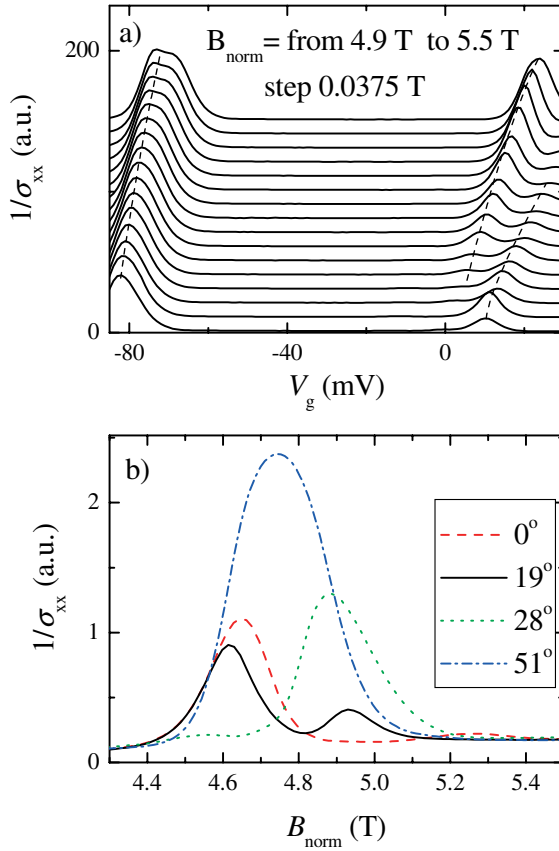
A very similar effect was experimentally observed [2, 10] and theoretically addressed [11] in a double-layer system with symmetric electron density distribution at integer total filling factor  $\nu = 2$ . In this case, the competition of different ground states is caused by the interplay between the inter-plane Coulomb energy, the spin splitting, and the symmetrical-antisymmetrical splitting. In the simplest single-particle picture (disregarding the Coulomb interaction), each Landau level has four sublevels, originating from the spin and symmetrical-antisymmetrical splittings. At total filling factor  $\nu = 2$ , increasing the spin splitting causes a transition from the spin-unpolarized ground state, with anti-parallel spin orientations of occupied sublevels, to the ferromagnetic one with parallel spins. Near the transition point, the intralayer exchange interaction mixes two lowest states of the electron system and gives rise to the intermediate canted antiferromagnetic phase, characterized by interlayer antiferromagnetic spin correlations. It is easy to see the analogy to the spin transition in the FQHE regime. Experimentally, both transitions can be forced, e.g., by the gate voltage [12], or by the parallel magnetic field component, which increases the Zeeman energy and suppresses tunnelling and interlayer correlations in a double layer system.

In the present paper we investigate a competition of the ground states within the narrow strip in the  $(B, n_s)$ -plane near the fixed filling factor  $\nu$  in two different electron systems. They are the single layer at fractional  $\nu = 2/3$  and the double quantum well at integer  $\nu = 2$ . We want to find common and different features of the 2DES behavior in the vicinity of the transition point.

Our samples are grown by molecular beam epitaxy on semi-insulating GaAs substrate. Single-layer GaAs/AlGaAs heterostructure contains a 2DEG located 150 nm below the surface. The mobility at 4 K is  $1.83 \times 10^6 \text{ cm}^2/\text{Vs}$  and the carrier density  $8.49 \times 10^{10} \text{ cm}^{-2}$ . Double-layer system is formed in a 760 Å wide symmetrically doped parabolic quantum well, containing a 3-monolayer thick AlAs sheet grown in the center, which serves as a tunnel barrier between both parts on either side. The symmetric-antisymmetric splitting in the bilayer electron system as determined from far infrared measurements and



**Fig. 1** Positions of the dissipative conductivity minima (open circles) as function of the gate voltage  $V_g$  (which controls the electron concentration) and the normal magnetic field component  $B_{\text{norm}}$ . Solid lines show the exact positions of integer and fractional filling factors  $\nu$ . Magnetic field is tilted in respect to the normal to the sample plane by the angle  $\alpha = 19^\circ$ . The phase transition at  $\nu = 2/3$  takes place at  $n_s^{\text{tr}} = 8.77 \times 10^{10} \text{ cm}^{-2}$ .



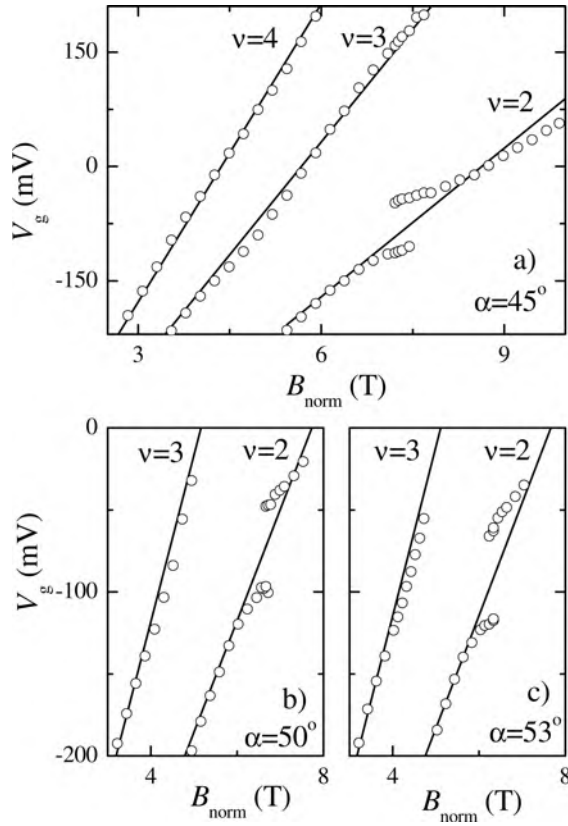
**Fig. 2** (online colour at: [www.pss-b.com](http://www.pss-b.com)) (a)  $1/\sigma_{xx}$  as function of the gate voltage  $V_g$  (electron concentration) at different magnetic fields  $B_{\text{norm}}$ . Magnetic field is tilted in respect to the normal to the sample plane by the angle  $\alpha = 19^\circ$ . Curves are shifted for clarity. Dash highlights the minima positions (b)  $1/\sigma_{xx}$  as function of the perpendicular to the sample plane magnetic field component  $B_{\text{norm}}$  at different tilt angles  $\alpha$ :  $0^\circ$  (dash),  $19^\circ$  (solid),  $28^\circ$  (dots),  $51^\circ$  (dash-dot).

model calculations [13] is equal to  $\Delta_{\text{SAS}} = 1.3$  meV. Samples were prepared from two different wafers (A and B) with close growth parameters.

The samples were patterned in quasi-Corbino geometry [14] with the gate area about  $0.5 \text{ mm}^2$ . Ohmic contacts are made to both parts of the well in double-layer samples. We trace the dissipative conductivity minimum near the fractional  $\nu = 2/3$  for single-layer samples and near the integer  $\nu = 2$  for double-layer ones in the  $(n_s, B)$ -plane by usual magnetoresistance and magnetocapacitance measurements. The experiment is performed at the temperature of 30 mK for different tilt angles of the magnetic field with respect to normal to the interface.

An example of the fan chart in  $(n_s, B)$ -plane for single layer structure is shown in Fig. 1. The fan chart lines for integer and fractional quantum Hall states at  $\nu = 4/3; 1; 1/3$  do not show any peculiarities. In contrast, the ground state at  $\nu = 2/3$  is changing at the electron density  $n_s^{\text{tr}} = 8.77 \times 10^{10} \text{ cm}^{-2}$ . The comparison of this value with the known from the previous experiments [1, 3] demonstrates that electron density at the transition point  $n_s^{\text{tr}}$  is sample dependent. It is not surprising, because the electron–electron interaction depends on the wave function extension in the direction normal to the interface, which varies from sample to sample. As expected, the transition point shifts towards the lower electron density while increasing the parallel to the interface field component  $B_{\text{par}}$ . From our experimental data the derivative  $dn_s^{\text{tr}}/dB_{\text{par}}$  can be estimated as  $10^{10} (\text{cm}^2 \text{ T})^{-1}$ .

In the vicinity of the transition point two minima in  $\sigma_{xx}$  are observable, see Fig. 2. One of them, corresponding to the upper branch in Fig. 1, is the continuation of the  $\nu = 2/3$  line at low electron density, the second is connected with this  $\nu = 2/3$  line at high density. In some region near the transition point  $n_s^{\text{tr}}$  two minima in the dissipative conductivity can be found in  $\sigma_{xx}(n_s)$  sweep at fixed  $B$  (see Fig. 2a) or on in  $\sigma_{xx}(B)$  sweep at fixed  $n_s$  (see Fig. 2b).



**Fig. 3** Positions of the dissipative conductivity minima (open circles) as function of gate voltage  $V_g$  (which controls the electron concentration) and perpendicular magnetic field component  $B_{\text{norm}}$  for two different wafers A (a) and B (b, c). Solid lines show the exact positions of integer filling factors  $\nu$ . The tilt angle of magnetic field with respect to normal to the sample plane equals  $\alpha = 45^\circ$  (a) and  $\alpha = 50^\circ, 53^\circ$  (b, c). The phase transition at  $\nu = 2$  takes place at  $n_s^{\text{tr}} = 3.63 \times 10^{11} \text{ cm}^{-2}$ .

At the first glance, the behavior of the double-layer system is very similar, see Fig. 3. The phase transition is observed in tilted magnetic fields for samples from wafers A (Fig. 3a) and B (Fig. 3b, c). Under the same conditions no peculiarities are found at filling factors  $\nu = 3, 4$ . At tilt angles  $45^\circ, 50^\circ, 53^\circ$  the ground state for  $\nu = 2$  is changing at the electron density  $n_s^{\text{tr}} = 3.63 \times 10^{11} \text{ cm}^{-2}$ . The density  $n_s^{\text{tr}}$  is also sample dependent, nevertheless, qualitatively all observations are sample independent, as it is easy to see from comparison of Fig. 3a)–c). The derivative  $dn_s^{\text{tr}}/dB_{\text{par}} \sim 4 \times 10^{10} (\text{cm}^2 \text{ T})^{-1}$ . The same order of the value  $dn_s^{\text{tr}}/dB_{\text{par}}$  as in the FQHE case means that we deal with similar competition between Coulomb and Zeeman energy in both cases.

Remarkably, the symmetry of  $\sigma_{xx}$ -minima positions in Figs. 1 and 3 is totally different. In Fig. 3 the upper branch is the continuation of the  $\nu = 2$  line at high electron density and the bottom one is connected with this line at low density. Such a scenario is totally different from the FQHE case.

We have to mention that the existence of two minima in the  $(B, n_s)$ -plane is non-trivial and needs an explanation. We propose here the explanation, based on the consideration of domain structure in the vicinity of the transition point  $n_s^{\text{tr}}$ . It is well known and clearly shown experimentally, that in both cases the complicated domain structure does exist in the vicinity of the transition point. The area covered by domains of one phase is a function of the filling factor  $\nu$ . At the points  $n_s^{\text{tr}}$ , the areas covered by different phases are equal and the system demonstrates non-zero dissipative conductivity due to the percolation in phase boundaries. One can expect the appearance of the deep minimum in  $\sigma_{xx}$  if the domains, belonging to one of the phase, would create an infinite cluster. Because the Zeeman splitting is smaller in weak magnetic fields, it is natural to expect that domains with low-field configuration prevails at filling factors above  $\nu = 2/3$  and  $\nu = 2$ . Such the way of explanation seems to give an adequate description for the diagrams corresponding to filling factor  $\nu = 2/3$  in the single layer 2DES, but hardly can describe the obser-

vation at  $\nu = 2$  in double layer systems. It may be because of isospin degree of freedom in double-layer systems.

In conclusion, we investigate the ground state competition at the transition from the spin unpolarized to spin ordered phase at filling factor  $\nu = 2/3$  in single layer heterostructure and at  $\nu = 2$  in double layer quantum well. To trace the quantum Hall effect phase we use the minimum in the dissipative conductivity  $\sigma_{xx}$ . We observe two different transition scenarios in two investigated situations. For one of them we propose a qualitative explanation, based on the domain structure evolution in the vicinity of the transition point. The origin for the second scenario, corresponding to the experimental situation at  $\nu = 2$  in double layer 2DES, still remains unclear.

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