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Reentrant quantum Hall effect in bilayer system at high filling factors

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Abstract

We report on the measurements of the quantum Hall effect states in double quantum well structures at the filling factors $\nu = 4N + 1$ and $4N + 3$, where N is the Landau index number, in the presence of the in-plane magnetic field. The quantum Hall states at these filling factors vanish and reappear several times. Repeated reentrance of the transport gap occurs due to the periodic vanishing of the tunneling amplitude in the presence of the in-plane field. When the gap vanishes, the transport becomes anisotropic. The anisotropy persist at half-odd filling factors, when bilayer quantum Hall states are recovered with increase of the tilt angle.

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1. Introduction

The two-dimensional electron gas in a GaAs double quantum wells separated by thin layer demonstrates many exotic properties in the strong magnetic field [1]. For example, such quantum Hall bilayer system can exhibit a many-body phase in the absence of tunneling due to spontaneous interlayer coherence at total Landau filling factor $\nu = 1$. The states in the quantum Hall bilayers are best described in the pseudospin language where the right (left) well is associated with a pseudospin up (down) state. When the electron might be in either layer, the system is described as a linear combination of pseudospin up and down states. The resulting state is aligned along arbitrary direction determined by angle ϕ in the pseudospin XY plane. When the magnetic field is tilted away from perpendicular direction, the transport gap at $\nu = 1$ is reduced, which was explained as commensurate–incommensurate (CI) transition in the pseudospin configuration [2]. At small parallel magnetic field, the pseudospins rotate commensurately with the effective Zeeman field. The resulting state is called the commensurate liquid. However, when the in-plane field increases the pseudospin no longer rotates with field, because the local field tumbles too rapidly, and a phase transition to an incommensurate liquid state occurs, where pseudospins are spatially uniform [1].

Recently, it has been shown that in high Landau level the tunneling amplitude oscillates with in-plane field, which results not only one but several (reentrant) CI transitions at filling factors $\nu = 4N + 1$. At these filling factors electrons are equally distributed in two layers as at $\nu = 1$. In-plane field induces very rich phase diagram with a complex sequence of the phase transitions in bilayer quantum Hall system [3].

In this paper we report on the observations of reentrant quantum Hall effect in high mobility GaAs double well structures in the presence of the in-plane field. We observe strong anisotropy of the resistance $\nu = 5$, which indicates that this state can be stripe state. Stripe states in a single well system in a perpendicular magnetic field have been

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observed in transport experiments for quantum Hall systems at half-filled Landau filling factors [4]. In this phase, electrons cluster into parallel stripes of the alternative integer filling factor, and longitudinal resistance exhibits large anisotropy. The in-plane field induces the transport anisotropy, for example, stabilizes the preferred direction or nematic phase at $\nu = 4N + 1$.

2. Experimental results and discussions

The samples are symmetrically doped GaAs double quantum wells separated by tunneling $Al_xGa_{x-1}As$ barrier with different width varied from 1.4 to 5 nm. The width of the GaAs well is 14 nm. Sample has high total density $9 \times 10^{11}\,cm^{-2}$ ($4.5 \times 10^{11}\,cm^{-2}$ in each layer), and average mobility $\mu = 1 \times 10^6\,cm^2/V\,s$. The energy separation between bonding and antibonding subbands is varied from 3.2 to 0.4 meV. We measure longitudinal and Hall resistances for different tilt angle Θ between magnetic field and normal to the surface at $T = 50\,mK$ up to 15 T. Fig. 1 shows the longitudinal resistances as a function of inverse Landau filling factor for double wells with different barrier thickness for magnetic field normal to double quantum wells. Arrows indicate the resistance minimum due to corresponding energy gaps in the spectrum.

Fig. 2 shows the phase diagram, or the plot of the longitudinal resistance R_{xx} as a function of the perpendicular component of the magnetic field B and the tilt angle Θ for Hall bar containing double well structure with $d_b = 2.0\,nm$. We may see that the minima in the resistance corresponding to the filling factors $\nu = 4N + 1$ and $\nu = 4N + 3$ vanish, when the magnetic field is tilted. The vanishing of the resistance minima occurs in small range of the tilt angle and is accompanied by vanishing of the Hall

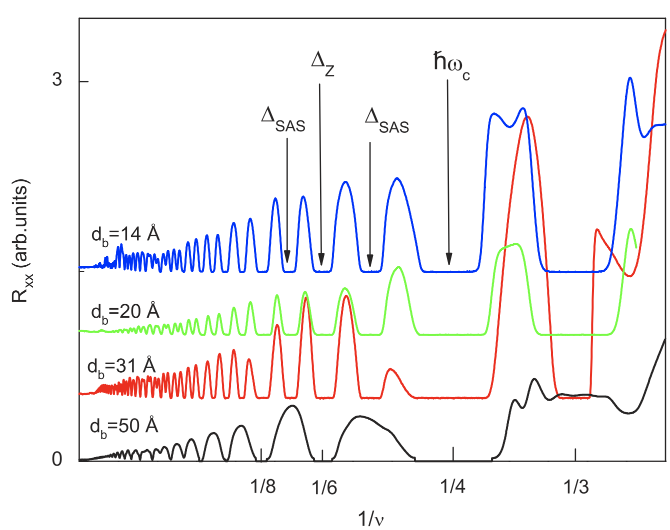

Fig. 1. Longitudinal resistance for double quantum wells with different barrier thickness at $T = 50\,mK$ as a function of the inverse filling factor (magnetic field). Magnetic field is normal to bilayers. Minima with corresponding gaps are indicated. $\hbar\omega_c$ is the cyclotron energy, Δ_z is the Zeeman energy, and Δ_{SAS} is the tunneling energy.

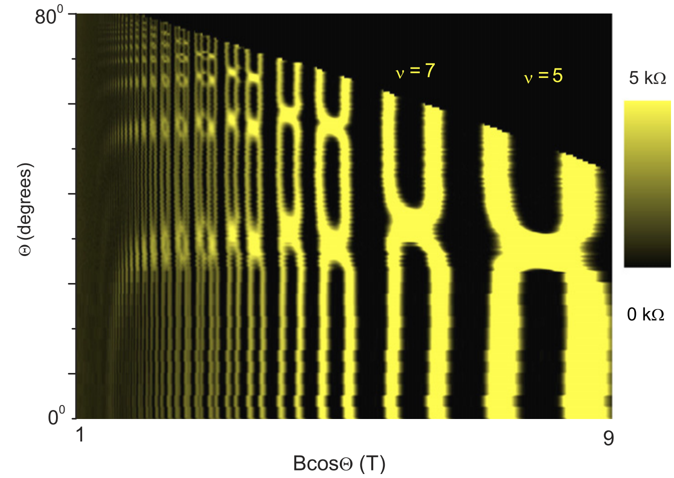

Fig. 2. Experimentally determined plot of the resistance in the magnetic field–tilt angle plane for double well structure with barrier thickness $d_b = 2\,nm$. Filling factors determined from Hall resistance are labeled. Filling factors $\nu = 4N + 1$ and $\nu = 4N + 3$ correspond to the tunneling gap. The figure demonstrates vanishing and reentrance of $\nu = 4N + 1$ and $\nu = 4N + 3$ minima for $N > 1$ Landau levels with tilt angle.

quantization. The value of the tilt angle, when the minima starts to disappear, is slightly different for different N. When Θ increases, the energy gap at $\nu = 4N + 1$ and $\nu = 4N + 3$ vanishes and re-establishes several times for $N = 2, 3, 4, 5 \ldots$.

In the tight-binding approximation it has been predicted that the tunneling amplitude is given by [5]

$$T_N = \Delta_{SAS} \exp\left(-\frac{Q^2 l_\perp^2}{4}\right) L_N^0\left(\frac{Q^2 l_\perp^2}{2}\right), \tag{1}$$

where L_N^0 is a generalized Laguerre's polynomial, the wave vector Q is defined as $Q = d/l_\parallel^2$, where $l_\perp = \sqrt{\hbar c/eB_\perp}$ and $l_\parallel = \sqrt{\hbar c/eB_\parallel}$ magnetic lengths associated with the perpendicular and the parallel magnetic field consequently. For $N = 1, 2, 3 \ldots$ the tunneling amplitude oscillates with $B_\parallel$ and becomes negative in some range of the tilt angle. We compare resistance fluctuations at filling factors $\nu = 4N + 1$ and $\nu = 4N + 3$ as a function of the in-plane magnetic field with Eq. (1). Indeed the tunneling amplitude vanishes, when the longitudinal resistance has a maximum in agreement with tight-binding approximation [5].

In order to probe the anisotropic states associated with CI transitions in the regions, when the tunneling gaps vanishes, we perform the transport tilt field measurements in the samples with square van der Paw geometry. The resistance anisotropy is strongly enhanced in this geometry, since an anisotropy in the resistivities causes an inhomogeneous current density distribution in the sample.

In Fig. 3a,b we show a measurements of the longitudinal resistance for the current flowing in the perpendicular directions and for different tilt angles. No significant anisotropy is observed in the perpendicular magnetic field. However, in the tilted field the resistance shows pronounced anisotropy at $\nu = 5$, when the tunneling gap

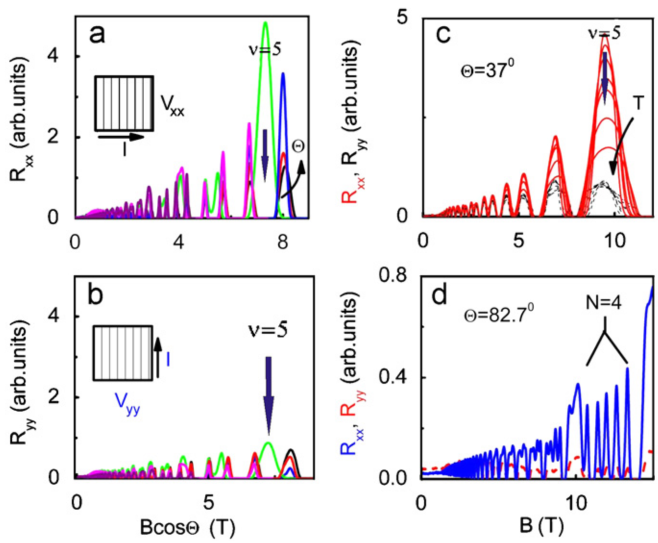

Fig. 3. Longitudinal resistance measurements in the van der Paw geometry for sample with barrier thickness $d_b = 2.0$ nm with current directed along hard axes (a) and easy axis (b) for different tilt angles Θ: 0° (black), 38.7° (green), 50.6° (red), 57.6° (blue). (c) R_{yy} (dashed lines) and R_{xx} (red lines) at $\Theta = 37°$ as a function of the magnetic field for different temperatures T (K): 1.3, 0.7, 0.57, 0.45, 0.25, 0.1. (d) Longitudinal resistance for $\Theta = 82.7°$ for $N > 4$.

vanishes. Following the literature, we use the expressions "hard-axis" and "easy-axis" for the directions of the current flowing along the axis with large and low resistances, consequently. Fig. 3a,b shows low field R_{xx} and R_{yy} traces for different tilt angles. The angle Θ is along x (hard) axis. We may see that the resistance anisotropies at large filling factors occurs at sufficiently high tilt angles. Fig. 3c shows the R_{xx} and R_{yy} traces for different temperatures. We may see that the hard-axes resistance R_{xx} increases with decreasing temperature, whereas R_{yy} remains the same. We measure resistance anisotropy at half integer filling factors, when longitudinal resistance exhibits the peaks, and at $\nu = 4N + 1$, when tunneling gap vanishes in the presence of the in-plane field. Note that anisotropy occurs not only at filling factors $\nu = 2N + 1$, but at half filling factors too. We are not able to distinguish between commensurate and incommensurate anisotropic phases, predicted in work [3]. However, it is worth noting that, the energies of the stripe states are very close, so when the finite layer width is taken into account, some of these states may be favored energetically. It is very likely that, just experiments can indicate more favorable configuration. We find the stripes aligned perpendicular to the parallel magnetic field. It is consistent with "isospin skyrmion stripe phase".

We also observe anisotropy of states at $\nu = \frac{9}{2} \ldots \frac{13}{2} \ldots \frac{17}{2} \ldots$ (see Fig. 2c). The bilayer system with total half-odd integer filling factor can be regarded as two separate quantum Hall states with filling factors $\nu = \frac{1}{4}$ in the absence of the tunneling. We may speculate that interlayer interaction can lead to an modulated stripe state or anisotropic Wigner crystal at these filling factors.

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References

[1] S. Das Sarma, A. Pinzuk (Eds.), Perspectives in Quantum Hall Effects, Wiley, New York, 1997.
[2] S.Q. Murphy, et al., Phys. Rev. Lett. 72 (1994) 728.
[3] R. Cote, H.A. Fertig, J. Bourassa, D. Bouchiha, Phys. Rev. B 66 (2002) 205315.
[4] M.P. Lilly, K.B. Cooper, J.P. Eisenstein, L.N. Pfeiffer, K.W. West, Phys. Rev. Lett. 82 (1999) 394.
[5] J. Hu, A.H. MacDonald, Phys. Rev. B 46 (1992) 12554.