PHYSICAL REVIEW B **78**, 233305 (2008)

Observation of an in-plane magnetic-field-driven phase transition in a quantum Hall system with SU(4) symmetry

G. P. Guo,[1] Y. J. Zhao,[1] T. Tu,[1,*] X. J. Hao,[1] X. C. Zhang,[2] G. C. Guo,[1] and H. W. Jiang[2,†]
[1]*Key Laboratory of Quantum Information, Chinese Academy of Sciences, University of Science and Technology of China, Hefei 230026, People's Republic of China*
[2]*Department of Physics and Astronomy, University of California–Los Angeles, 405 Hilgard Avenue, Los Angeles, California 90095, USA*
(Received 22 July 2008; revised manuscript received 20 October 2008; published 9 December 2008)

We focus on the magnetotransport study of a two-subband GaAs/AlGaAs two-dimensional electron system in a regime where there are four closely spaced energy levels, with a filling factor around $\nu=4$. As we increase the in-plane magnetic field, we found that the conventional pseudospin quantum Hall ferromagnetic states with SU(2) symmetry collapsed rapidly into an unexpected state with SU(4) symmetry. Within a narrow tilting range angle of 0.5°, the activation energy increases as much as 12 K. While the origin of this puzzling observation remains to be exploited, we discuss the possibility of a long-sought pairing state of electrons with a fourfold degeneracy.

DOI: 10.1103/PhysRevB.78.233305 PACS number(s): 73.43.Nq, 72.20.My, 73.21.−b

In condensed-matter physics, the study of electronic states with SU(N) symmetry has attracted considerable and growing attention in recent years, as systems with such a symmetry can often have a spontaneous symmetry-breaking effect giving rise to a different ground state. For example, in a bilayer quantum Hall system, in which two Landau levels can be brought close to degeneracy, leading to a SU(2) symmetry by varying magnetic field, pseudospin quantum Hall ferromagnetic states with various anisotropy have been realized.[1] In the past several years, the exploration of collective states in other multicomponent quantum Hall systems has emerged.[2–5]

The studies of multicomponent quantum Hall systems so far have been limited to systems with a SU(2) symmetry. Very recently, interest has been further extended to systems with a higher-order symmetry, such as SU(4), motivated mainly by the surge of research in graphene, where the twofold spin and twofold valley degeneracy lead to a fourfold degeneracy.[6,7] The SU(4) symmetry can be readily created in a multicomponent quantum Hall system. For a typical two subband semiconductor heterostructure, where both the symmetric and antisymmetric subbands of the confined quantum well are occupied, two distinct sets of Landau levels are present. Through varying the density or magnetic field, levels with different Landau orbital indices originating from the two subbands can be brought into degeneracy. Due to the very small energy difference of the spin splitting in GaAs,[2,3,8–10] the system can provide us with the desired SU(4) symmetry. The experimental studies presented in this Brief Report are specifically focused on this interesting physical regime.

The sample was grown by molecular-beam epitaxy and consists of a symmetrical modulation-doped 24-nm-wide single GaAs quantum well bounded on each side by Si δ-doped layers of AlGaAs with doping level $n_d=10^{12}$ cm^{-2}. Heavy doping creates a very dense two-dimensional electron gas (2DEG), resulting in the filling of two subbands in the well. As determined from the Hall resistance data and Shubnikov–de Haas oscillations in the longitudinal resistance, the total density is $n=8.0\times10^{11}$ cm^{-2}, where the first and the second subbands have densities of $n_1=6.1\times10^{11}$ cm^{-2} and $n_2=1.9\times10^{11}$ cm^{-2}, respectively. The sample has a low-temperature mobility $\mu=4.1\times10^5$ cm^2/V s, which is extremely high for a 2DEG with two filled subbands. The samples are patterned into Hall bars using standard lithography techniques. A NiCr top gate is evaporated on the top of the sample approximately 350 nm away from the center of the quantum well. By applying a negative gate voltage on the NiCr top gate, the electron density can be varied continuously. Magnetotransport measurements were carried out in an Oxford top-loading dilution refrigerator with a base temperature of 15 mK and an *in situ* motorized rotating stage. The calibration of the angles was done against the classical Hall resistance at high temperatures. To measure the longitudinal and Hall resistances R_{xx} and R_{xy}, we used a standard ac lock-in technique with electric current ranging from 10 to 100 nA at a frequency of 11.3 Hz. Two devices from the same wafer were studied and they have produced remarkably identical results. For consistency, however, we present the data from only one sample.

In this experiment, we have concentrated our study around $\nu=4$, where four energy levels are filled. In the absence of an in-plane magnetic field (i.e., with zero tilting angle), the three-dimensional (3D) plot of longitudinal resistance R_{xx} in the density(n)-perpendicular magnetic-field ($B_\perp$) plane exhibits a squarelike structure around $\nu=4$, as shown in Fig. 1(a).[3,10] Here, point B corresponds to the degeneracy point of $|(S,1,\downarrow)\rangle$ and $|(A,0,\uparrow)\rangle$ while point C corresponds to that of $|(S,1,\uparrow)\rangle$ and $|(A,0,\downarrow)\rangle$, as illustrated schematically in Fig. 1(f). Here we label the single-particle levels (i,N,σ), and $i(=S,A)$, N, and $\sigma(=\uparrow,\downarrow)$ are the subband, orbital, and spin quantum numbers. One prominent feature is the disappearance of the extended states (i.e., bright lines) that complete the two arms of the square. The disappearance is due to the pseudospin gaps of easy-axis quantum Hall ferromagnetic states where the electrons are suddenly transferred from $(S,1,\downarrow)$ to $(A,0,\uparrow)$ and from $(S,1,\uparrow)$ to $(A,0,\downarrow)$ or vice versa.[2,10,11]

Now we turn our attention to the behavior of the phase diagram in the tilted magnetic field. The

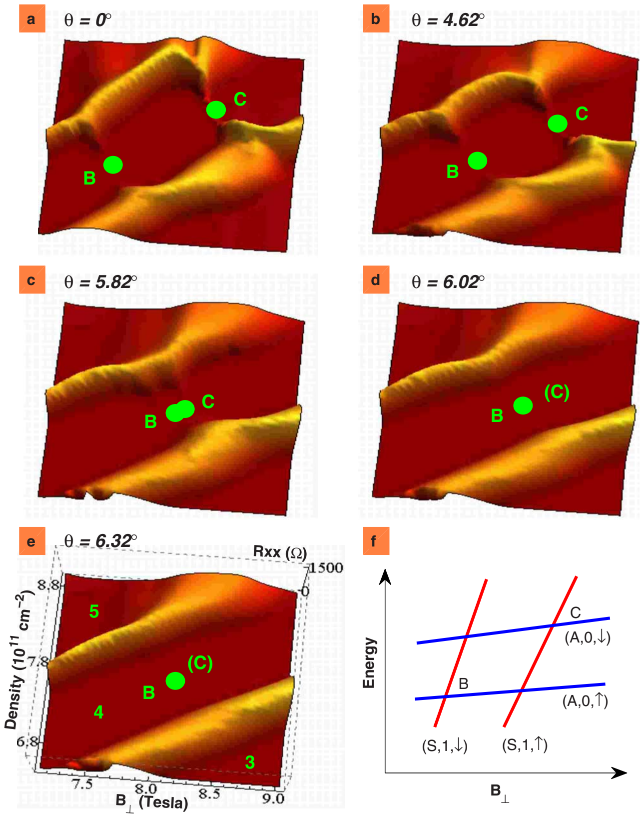

FIG. 1. (Color online) The longitudinal resistance R_{xx} as a function of density n and perpendicular $B_\perp$ at filling factor $\nu=4$ with the tilted angle θ from 0° to 7°, which are measured at the base temperature $T \simeq 15$ mK. [(a)–(e)] $n-B_\perp$ phase diagram at tilted angle $\theta=0°$, 4.62°, 5.82°, 6.02°, and 6.32°. (f) Schematic drawing of the crossing between different subband and spin indices Landau levels in two corresponding places marked by B and C in (a)–(e).

density(n)-perpendicular magnetic-field ($B_\perp$) phase diagrams of R_{xx} at several tilted angles $\theta=0°$, 4.62°, 5.82°, 6.02°, and 6.32° for $\nu=4$ are shown in Fig. 1. Here the angle θ is defined as $\tan\theta = \frac{B_\parallel}{B_\perp}$. When the titling angle is increased to 4.62° [Fig. 1(b)], the size of the square, a measure of the energy separation between the two degeneracy points, shrinks only slightly. However, to increase merely another 1° ($\theta_c=5.82°$), the two "arms" of the square structure almost collapse together [Fig. 1(c)] and become one point at slightly larger angles [Figs. 1(d) and 1(e)]. The evolution of the positions of the anticrossing points B and C (roughly in the middle of each of the "arms" of the square structure at $\nu=4$, also the local minimum of energy gap in the anticrossing region) are plotted in Fig. 2 as a function of the tilting angle.[12] One can clearly visualize that the two points get close with each other in a narrow range of tilting angle and emerge as one point when θ is increased, which implies four Landau levels are brought into degeneracy. In other words, the two degeneracy points with a SU(2) symmetry become a single degeneracy point with a SU(4) symmetry.

Since there seems to be a drastic change in the characteristics of the phase diagram, in a very narrow range of the in-plane magnetic field, it is natural to obtain a measurement of the energy scale of the associated energy gaps there. In

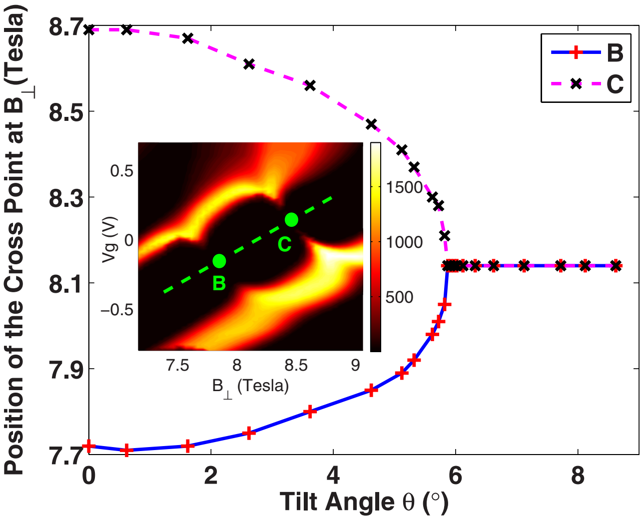

FIG. 2. (Color online) Evolution of the positions of the degenerate points B and C as a function of the tilted angle θ. The corresponding in-plane magnetic field are displayed on the top axis. Insert: indication of the points that are measured.

Fig. 3, the longitudinal resistance R_{xx} at points B and C is plotted on a log scale as a function of the inverse temperature $1/T$, for various tilting angles. R_{xx} clearly follows a thermally activated behavior $R_{xx} \sim \exp(-E_a/2T)$ over a few decades, and the thermally activated gap E_a can be extracted. In Fig. 4, we present the θ dependence of the energy gap E_a at two points B and C marked by the dots in Fig. 1. The energies are found to be nearly constant, ≈ 4 K (at point B) and ≈ 2 K (at point C) before $\theta_c=5.82°$. While after $\theta_c=5.82°$ points B and C overlap as one point, the energy gap increases sharply for a small angle region into a rough angle-independent region ≈ 15 K. At this tilt angle, the applied parallel magnetic field is only $B_\parallel \approx 0.8$ T. Without any assistance from theoretical analysis, the raw data strongly suggest a phase transition.

Before we speculate on the physical origin of the observations, we would like to compare the current experiment with others in similar 2DEG systems in the presence of an in-plane magnetic field. There are indeed examples of in-plane magnetic-field-induced phase transitions in multicomponent quantum Hall systems. The system studied by Murphy *et al.*,[13] a strongly coupled double quantum well at a filling factor $\nu=1$, showed a relatively large energy-gap change when the tilted angle was increased. It is now commonly believed that this change reflects a commensurate to an incommensurate phase transition in the pseudospin field. However, in this case, only the two lowest Landau levels are involved before and after this quantum phase transition; in contrast to four Landau levels degeneracy in our system. In a recent study of Si-SiGe heterostructures by Lai *et al.*,[4] the $\nu=3$ and 5 valley gaps rise rapidly when the angle of tilting approaches at about 65°. In this experiment, the effect is driven by the coincidence of two different Landau levels when the Zeeman splitting becomes comparable to the cyclotron energy, which is not possibly consistent with our small tilting angle. In another recent study of the 2DEG in a AlAs quantum well by Vakili *et al.*,[5] the size of the energy

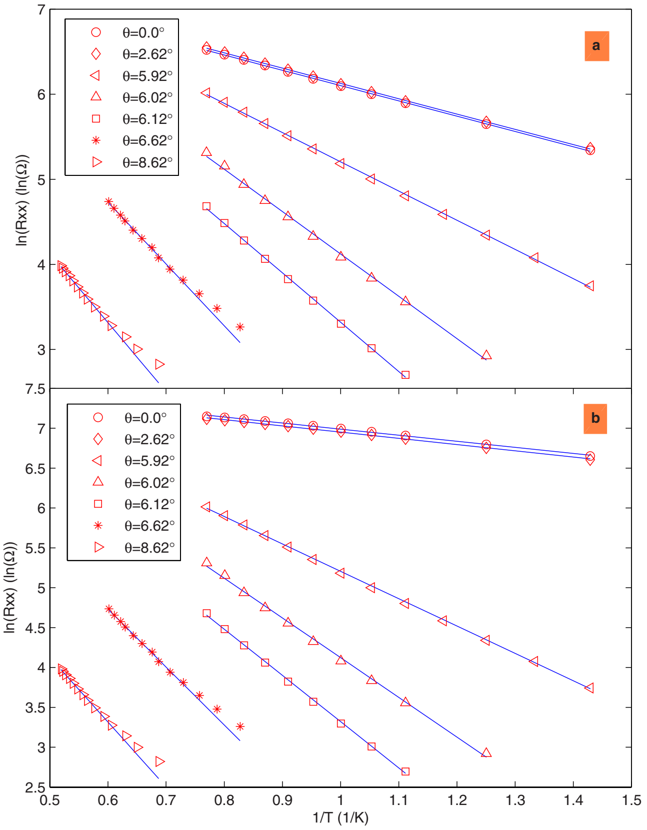

FIG. 3. (Color online) The longitudinal resistance R_{xx} at points (a) B and (b) C as a function of $1/T$ for different tilting angles θ. All data error bars (accuracy of the resistance measurement) are smaller than the symbols. The solid lines are fittings to the extraction of the thermal activation gap E_a.

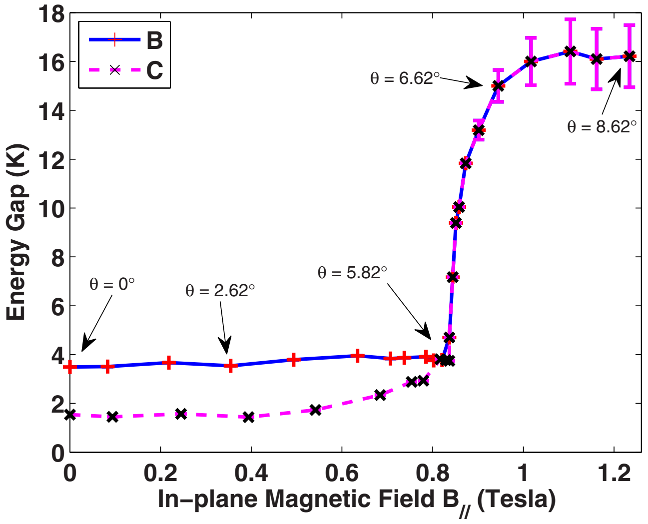

FIG. 4. (Color online) Energy gap of two anticrossing points B and C as a function of in-plane magnetic field $B_{\parallel}$.

gap of $\nu=3$ valley changed rapidly through a coincidence angle of about 65°. The change is induced also by the crossing of two different Landau levels made possible again by the large tilting angle.

Changes in the energy gap E_a normally reflect changes in the spectrum of charged excitations and the 2DEG ground state. At first sight, one might expect that the phase transition is induced by the spin flips due to variations in the Zeeman energy $g\mu_B B_{\text{tot}}$. The Zeeman energy, however, changes only about 30 mK upon tilting from $\theta=0°$ to 10° as the total magnetic field changes only about 10%, which is negligibly small compared to the observed change of 10 K in E_a. The in-plane magnetic field can also affect the magnitude of the exchange energy since the distributions of both the symmetric and antisymmetric wave functions are expected to vary considerably when the in-plane magnetic field ranges from 0 at $\theta=0°$ to 0.8 T at $\theta=8°$. However the sudden change in the activation energy cannot simply be due to the quantitative change in the exchange energy by the in-plane magnetic field. First, the experimental data of the energy gap E_a is nearly constant in a wide range of tilted angle θ at small in-plane fields, as shown in Fig. 4. We therefore expect that the energy of the pseudospin states is rather insensitive to response relative to the in-plane magnetic field. Second, the tilted field behavior at next even filling factor $\nu=6$ in samples is also examined. We found that such a phase transition is totally absent at a filling factor $\nu=6$.

We speculate that the observations involve a quantum phase transition induced by an in-plane magnetic field. There is a competition between two ground states, one of which, at $\theta<\theta_c$, takes advantage of Coulomb interactions by forming pseudospin quantum Hall ferromagnets and the other, which becomes a more favorable many-body configuration when $\theta>\theta_c$. From the energetic degeneracy of Landau levels before and after the critical point, we infer that there is a symmetry change: from SU(2) to SU(4) symmetry in our system. As shown in the standard Landau level fan diagram [Fig. 1(f)], at $\nu=4$, there is a SU(2) symmetry at crossing points B and C. Since the two crossing Landau levels have opposite spins, the exchange energy is highly pseudospin dependent and leads to an easy-axis quantum Hall ferromagnet.[2,10,11] As a result, the energy gap here represents an exchange energy penalty for a pseudospin flip. In our system, as the tilted magnetic field increases, the B and C points are close to each other, which means a total of four Landau levels with different subband, orbital, and spin indices are brought close in energy near the phase transition. Thus there is a SU(4) symmetry at the region where B and C overlapped. Coupling of all fourfold levels may give rise to a more complex many-body state. In light of this, the energy-gap jump may be due to suppression of the low-energy excitations which originates from the formation of a new ground state. One possibility is that in this region, electrons with different spins and subbands can pair up and condensed in a pseudospin-singlet pairing state of fourfold Landau levels as $|S\rangle=\Pi_k[C^{\dagger}_{(S,1,\uparrow),k}+e^{i\varphi}C^{\dagger}_{(A,0,\uparrow),k}][C^{\dagger}_{(S,1,\downarrow),k}+e^{i\varphi}C^{\dagger}_{(A,0,\downarrow),k}]|0\rangle$.[14,15] Thus the energy gap of 15 K for $\theta>\theta_c$ can be taken as a measurement of the pairing strength of pseudospin. Actually for a bilayer system at $\nu=2$ where sometimes four Landau levels are close to degeneracy, the ground state is extensively studied by several groups and a similar pairing state of pseudospins or layers can become energetically favorable.[16] We speculate that similar SU(2) to SU(4) phase transition phenomenon can be observed in bilayer systems at some appropriate regions. Of course, there are possibly different competing orders, such as a stripe state with broken translational and spin symmetries, which is commonly believed to occur at very large in-plane magnetic fields.[15,17,18]

In summary, we find experimental evidence for intriguing and unexpected quantum phase transition from the typical pseudospin quantum Hall ferromagnetic states with broken SU(2) symmetry into a state with broken SU(4) symmetry driven by the in-plane magnetic field, around a filling factor of $\nu=4$ in a two-subband GaAs-AlGaAs 2DEG. While the origin of this new state is unclear, we discussed the possibility of the pairing state of electrons with different spins and subbands. More experiments, such as electrically detected nuclear magnetic resonance,[19] are needed to further investigate the microscopic aspects of this quantum phase transition.

The authors would like to thank S. Das Sarma, A. H. Macdonald, K. Yang, and S. A. Kivelson for helpful discussions. This work was funded by the National Basic Research Programme of China (Grants No. 2009CB929600 and No. 2006CB921900), the Innovation funds from Chinese Academy of Sciences, and the National Natural Science Foundation of China (Grants No. 10604052, No. 10804104, and No. 10874163). The work at UCLA was supported by the NSF under Grant No. DMR-0804794.

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[*] tutao@ustc.edu.cn
[†] jiangh@physics.ucla.edu

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