Insulating Phases Induced by Crossing of Partially Filled Landau Levels in a Si Quantum Well

Tohru Okamoto, Kohei Sasaki, Kiyohiko Toyama, Ryuichi Masutomi, Kentarou Sawano, and Yasuhiro Shiraki

1Department of Physics, University of Tokyo, 7-3-1, Hongo, Bunkyo-ku, Tokyo 113-0033, Japan
2Research Center for Silicon Nano-Science, Advanced Research Laboratories, Tokyo City University, 8-15-1 Todoroki, Setagaya-ku, Tokyo 158-0082, Japan

(Dated: 3 March 2009)

We study magnetotransport in a high mobility Si two-dimensional electron system by in situ tilting of the sample relative to the magnetic field. A pronounced dip in the longitudinal resistivity is observed during the Landau-level crossing process for noninteger filling factors. Together with a Hall resistivity change which exhibits the particle-hole symmetry, this indicates that electrons or holes in the relevant Landau levels become localized at the coincidence where the pseudospin-unpolarized state is expected to be stable.

PACS numbers: 73.43.Nq, 73.40.Lq, 73.43.Qt, 75.60.-d

In a strong magnetic field, the single-particle energy spectrum of a two-dimensional electron system (2DES) is quantized into Landau levels (LLs) and the spin degeneracy is lifted due to the Zeeman effect. The ratio of the Zeeman energy $E_z$ to the cyclotron energy $\hbar\omega_c$ can be controlled by tilting the magnetic field with respect to the sample normal, where $\omega_c$ is the cyclotron frequency. A crossing of LLs with different orbital and spin indices occurs when $E_z$ becomes comparable to $\hbar\omega_c$. In the vicinity of the coincidence, where the two LLs are nearly degenerate in the single-particle energy, the electron-electron interaction plays an essential role in determining the ground-state configuration. To study many-body states and quantum phase transitions, it is convenient to relabel the two crossing LLs in terms of pseudospin. The $z$ component of the pseudospin magnetization unit vector can be defined as $m_z = +1$ ($-1$) when all the relevant electrons reside in the first (second) LL. For integer LL filling factors $\nu$, it is predicted that the ground state is the ferromagnetic state with easy-axis (Ising) anisotropy. The magnetization jumps discontinuously at a point where the $m_z = +1$ and $m_z = -1$ states are degenerate, i.e., the zero point of the pseudospin field. Experimentally, resistance spikes and hysteresis have been observed for several 2DESs (Refs. [1,2,3,4,5,6,7,8,9]) and discussed in association with domain wall between integer and noninteger states. In the case of real spin systems, the ground state was found to be spin unpolarized for various noninteger values of $\nu$ when the bare Zeeman splitting is sufficiently small. It is likely that an unpolarized ground state would also occur in pseudospin systems for $\nu \neq$ integer and small pseudospin field. The pseudospin configuration with $|m_z| < 1$ corresponds to a new quantum state characterized by an admixture of electrons with different orbital wave functions.

In this paper, we report magnetotransport measurements on a high-mobility Si 2DES in the vicinity of the coincidence of LLs. In situ tilting of the sample relative to the magnetic field allows independent control of $\nu$ and $E_z/\hbar\omega_c$. In the intermediate region, we observe a pronounced dip in the longitudinal resistivity and a Hall resistivity change which exhibits the particle-hole symmetry. The results indicate that electrons or holes in the relevant Landau levels become localized at the coincidence where the pseudospin is expected to be unpolarized. The $\nu$ dependence of the dip width implies that the pseudospin-unpolarized phase develops as $\nu$ decreases from an integer. Hysteresis behavior that occurs around the dip is interpreted as evidence for the first-order transition between the pseudospin-unpolarized and pseudospin-polarized states.

We used a Si/SiGe heterostructure with a 20-nm-thick strained Si channel sandwiched between relaxed Si$_{0.8}$Ge$_{0.2}$ layers. The electrons are provided by a Si-$\delta$-doped layer 20 nm above the channel. The electron concentration $N_s$ can be controlled by varying bias voltage $V_{BG}$ of a p-type Si(001) substrate 2.1 $\mu$m below the channel at 20 K. Electron spin resonance measurements have shown that the spin-orbit interactions and the electron-nuclear spin (hyperfine) coupling are very small in the present 2DES. Two Hall bars, denoted by HB-X and HB-Y, were fabricated on the same chip as illustrated in Fig. 1(a) to study the anisotropy with respect to the in-plane magnetic field direction. The Fermi level $\delta$-$\text{He}^4$He dilution refrigerator and the in-plane magnetic field was oriented along the $x$ direction $(y$ direction) and used for the measurements of the longitudinal resistivity $\rho_{xx}$ ($\rho_{yy}$) and the Hall resistivity $\rho_{yx}$ ($\rho_{xy}$). After brief illumination of a red light emitting diode with $V_{BG} = -4.2$ V, $N_s$ and low-temperature mobility $\mu$ are 1.38 (1.43) $\times 10^{11}$ cm$^2$/Vs and 2.6 (2.8) $\times 10^6$ cm$^2$/Vs, respectively, for HB-X (HB-Y). The sample was mounted on a rotary stage in a $\delta$-$\text{He}^4$He dilution refrigerator and the in-plane magnetic field was oriented along the $x$ direction. To avoid the heating effect, a small ac current of 1.0 nA was used in a standard low-frequency (11.7 Hz) lock-in technique.

Here we focus on the coincidence of the spin-up LL with an orbital index of $n = 0$ [LL$(\{1,0\})$ ] and the spin-down LL with $n = 1$ [LL$(\{1,1\})$]. We assign $m_z = +1$ to LL$(\{1,0\})$ and $m_z = -1$ to LL$(\{1,1\})$. The Fermi level $\varepsilon_F$ is inside these degenerate LLs when the Landau-level filling factor $\nu$ is in the range between 2 and 6 as shown.
in Fig. 1(b). Note that we have a two-fold valley degeneracy for a 2DES formed on the Si(001) surface.\textsuperscript{22} In our experimental setup, the tilt angle \( \theta \) can be continuously varied while the temperature \( T \) is kept constant at a fixed value. Furthermore, simultaneous control of \( \theta \) and the total magnetic field \( B_{\text{tot}} \) allows us to measure the \( B_{\text{tot}} \)-dependence for a constant value of the perpendicular component \( B_\perp = B_{\text{tot}} \cos \theta \), which is proportional to \( \nu \).

Figure 2 shows \( \rho_{xx} \) and \( \rho_{yx} \) as functions of \( B_\perp \) in the range between the QH states of \( \rho_{xx} = h/3e^2 \) and \( h/2e^2 \). Data for different fixed values of \( B_{\text{tot}} \) are presented. An anomalous structure arising from the LL crossing is clearly seen in each curve and the position shifts to higher \( B_\perp \) as \( B_{\text{tot}} \) increases. In the QH region near \( \nu = 3 \) (e.g., \( B_\perp \approx 1.87 \text{ T and } B_{\text{tot}} = 4.42 \text{ T} \)), \( \rho_{xx} \) exhibits a sharp spike which is attributed to domain wall resistance in Ising QH ferromagnets.\textsuperscript{5,6,7,8,8} On the other hand, a pronounced dip is observed in the intermediate region (e.g., \( B_\perp \approx 2.15 \text{ T and } B_{\text{tot}} = 5.23 \text{ T} \)). We believe that the dip has a different origin than the spike and is related to the occurrence of the pseudospin-unpolarized phase discussed later. It appears even in the spike and leads to the apparent double-peak structure around \( B_\perp \approx 2.0 \text{ T} \). While the structure of the longitudinal resistivity at the coincidence is sensitive to \( \nu \), the change in \( \rho_{yx} \) is always positive in this range. The position of the peak center is in good agreement with the center of the \( \rho_{xx} \) dip in the intermediate region.

As reported in previous studies on Si/SiGe heterostructures in the vicinity of \( \nu = 4 \),\textsuperscript{9,10,20} the resistivity spike in the QH region exhibits a strong anisotropy with respect to the in-plane magnetic field. In Figs. 3(a) and 3(b), results for \( \nu \approx 3 \) are shown.\textsuperscript{23} The anisotropy has been discussed in terms of a stripe-like domain structure of the Ising QH ferromagnet oriented perpendicular to the in-plane magnetic field.\textsuperscript{9,20} However, the dip in the intermediate region does not show a well-defined anisotropy. Typical data set obtained for the range of \( 2 < \nu < 3 \) is presented in Figs. 3(c) and 3(d). This also supports that the origin of the dip is different than that of the spike in the Ising QH ferromagnet.

In the range of \( 2 < \nu < 6 \) where \( \epsilon_F \) is inside the four degenerate LLs, particle-hole symmetry centered at \( \nu = 4 \) is expected to occur. It appears clearly in a Hall resistivity change. In Fig. 3(e), the inverse of \( \rho_{xy} \) in the vicinity of the LL coincidence is shown. The sign of the change in \( \rho_{xy} \) is positive for \( \nu < 4 \) and negative for \( \nu > 4 \). Similar behavior was observed for \( \rho_{xx} \). This indicates that the number of mobile electrons or holes that carry the Hall current is reduced at the LL coincidence. As shown in Fig. 3(f), the longitudinal resistivity exhibits a dip also for \( 5 < \nu < 6 \) where the hole picture is useful.\textsuperscript{24} The dip in the longitudinal resistivity accompanied with the Hall resistivity change reminds us of insulating phases in spin-resolved high LLs of high-mobility GaAs 2DESs,\textsuperscript{25,26,27} which are interpreted as bubble phases of electrons or holes.\textsuperscript{28,29,30,31,32,33} Although the mechanism leading to the insulating state is unclear for our system, the results strongly suggest that electrons or holes become localized at the LL coincidence at least for \( 2 < \nu < 3 \) and \( 5 < \nu < 6 \).

In the ranges of \( 3 < \nu < 4 \) and \( 4 < \nu < 5 \), peculiar behaviors are observed possibly due to the valley degeneracy [e.g., Fig. 3(g)]. As discussed in our previous work for \( \nu = 4 \),\textsuperscript{23} the bare valley splitting is estimated to be
very small in the present 2DESs. At \( \nu = 4 \), the LL crossing is observed as a single narrow spike in \( \rho_{xx} \), indicating that the valley degeneracy is not lifted. On the other hand, the many-body effect strongly enhances the valley splitting and stabilizes the QH state at \( \nu = \text{odd} \). The valley polarization in the intermediate region between \( \nu = 4 \) and \( \nu = 3 \) (or 5) is unclear and might be altered during the LL crossing process. In fact, the shape of the resistivity change, which is sensitive to \( \nu \), is not simple in these ranges. In the following, we shall not further discuss the valley state, and restrict ourselves to the range of \( 2 < \nu < 3 \).

In Fig. 4(a), the width \( \Delta B_{\text{tot}} \) of the insulating state determined from the dip in the longitudinal resistivities is shown. It decreases almost linearly with increasing \( \nu \) and goes to zero. At \( \nu = 3 \), the Ising QH ferromagnetic state with \( m_z = +1 \) or \( m_z = -1 \) is expected to be stable even for zero pseudospin field. The \( \nu \) dependence of \( \Delta B_{\text{tot}} \) implies that the pseudospin-unpolarized phase with \( |m_z| < 1 \) develops as \( \nu \) decreases in the range of \( 2 < \nu < 3 \). As shown in Fig. 4(b), the transition between conducting and insulating states exhibits hysteresis, which is a common feature of first-order transitions. Since the hysteresis loops for high-\( B_{\text{tot}} \) and low-\( B_{\text{tot}} \) transitions are similar to each other, it is expected that the jumps in \( m_z \) are also comparable. This means that the pseudospin magnetization is small in the insulating region. The dip in the longitudinal resistivity disappears as \( T \) is raised. The data for \( \rho_{yy} \) at \( \nu = 2.45 \) are shown in Fig. 4(c). If we assume an Arrhenius temperature dependence \( \rho_{yy}/\rho_e \propto \exp(-\Delta/2T) \), where \( \Delta = 1.0 \) K is the energy gap. The dotted line is a guide for the eyes.

The state with small \( m_z \) corresponds to a configuration in which the LL(\( \perp \), 0) and LL(\( \parallel \), 1) are nearly equally populated. Akera, MacDonald, and Yoshioka have studied the ground state of a double-layer system in which a higher LL (\( n = 4 \) or 5) in one layer is degenerate with the ground LL (\( n = 0 \) ) in the other. It was shown that the ground state can be pseudospin unpolarized for small values of the effective filling factor \( \nu^* = \nu - n \) in the limit of zero layer separation, where the system is equivalent to a single-layer system with the spin degree of freedom and nonzero Zeeman splitting. By an approach using the analytical model wave function, the pseudospin-unpolarized ground state was found to be an

![FIG. 3](image-url)  (Color online) [(a)-(d), (f), (g)] Longitudinal resistivities as functions of \( B_{\text{tot}} \) for different fixed values of \( \nu \). (e) Inverse of the Hall resistivity vs \( B_{\text{tot}}/B_\perp \). All the data were obtained by decreasing \( B_{\text{tot}} \) at 70 mK. HB-X was used for (a), (c), and (f). HB-Y was used for (b), (d), (e), and (g).

![FIG. 4](image-url)  (Color online) (a) The full width at half maximum of the dip in \( \rho_{xx} \) or \( \rho_{yy} \) measured at 70 mK. Since hysteresis was observed, the mean values are plotted. (b) Hysteresis of \( B_{\text{tot}} \)-dependence of \( \rho_{yy} \) measured at 70 mK and \( \nu = 2.67 \) \( (B_\perp = 2.21 \text{ T}) \). Solid curve (red): the downward sweep with \( dB_{\text{tot}}/dt = -0.5 \text{ mT/s} \). Dashed curve (black): the upward sweep with \( dB_{\text{tot}}/dt = +0.7 \text{ mT/s} \). (c) \( B_{\text{tot}} \)-dependence of \( \rho_{yy} \) at \( \nu = 2.45 \) \( (B_\perp = 2.41 \text{ T}) \) for \( T = 50, 100, 200, 300, 400, 500, 600, \) and 800 mK (from bottom to top). The data were obtained by decreasing \( B_{\text{tot}} \). (d) Logarithm plot of the \( \rho_{yy} \) minimum, divided by the baseline value \( \rho_e \), is shown as a function of the inverse temperature. The solid straight line represents an Arrhenius temperature dependence \( \rho_{yy}/\rho_e \propto \exp(-\Delta/2T) \), where \( \Delta = 1.0 \) K is the energy gap. The dotted line is a guide for the eyes.
electron crystal, which is composed of two interpenetrating square sublattices. In order to study the ground-state pseudospin polarization in our system, we extend the calculations in Ref. [34] to the case of \( n = 1 \) for the higher LL. Although effects of layer thickness, LL mixing, and the valley degree of freedom might be important, we do not consider them for simplicity. Exact diagonalizations on finite clusters with four electrons have shown that the pseudospin-unpolarized phase occurs at least for \( \nu > \frac{3}{2} \) while the results are not conclusive for higher \( \nu^* \).

In summary, we have performed the magnetotransport measurements on a high-mobility Si 2DES in the vicinity to the QH region where \( \rho_{xx} \) shows a narrow spike, we found a pronounced dip in the intermediate region. The sign of the Hall resistivity change is positive for \( \nu < 4 \) and negative for \( \nu > 4 \). These results indicate that electrons or holes in the relevant Landau levels become localized at the coincidence where the pseudospin is expected to be unpolarized. The \( \nu \) dependence of \( \Delta B_{\text{tot}} \) implies that the pseudospin-unpolarized phase develops as \( \nu \) decreases in the range of \( 2 < \nu < 3 \). Hysteresis loops observed around the dip were interpreted as evidence for the first order transition between the pseudospin-unpolarized and pseudospin-polarized states. The energy gap was deduced to be \( \Delta \sim 1 \text{ K} \) from the Arrhenius plot of the longitudinal resistivity.

This work has partly supported by Grant-in-Aids for Scientific Research (B) (Grant No. 18340080), (A) (Grant No. 21244047) and Grant-in-Aid for Scientific Research on Priority Area “Physics of New Quantum Phases in Superclean Materials” (Grant No. 20029005) from MEXT, Japan.

1 A. H. MacDonald, P. M. Platzman, and G. S. Boebinger, Phys. Rev. Lett. 65, 775 (1990).
2 T. Jungwirth, S. P. Shukla, L. Smrčka, M. Shavegan, and A. H. MacDonald, Phys. Rev. Lett. 81, 2328 (1998).
3 T. Jungwirth and A. H. MacDonald, Phys. Rev. B 63, 035305 (2000).
4 V. Piazza, V. Pellegrini, F. Beltram, W. Wegscheider, T. Jungwirth, and A. H. MacDonald, Nature (London) 402, 638 (1999).
5 E. P. De Poortere, E. Tutuc, S. J. Papadakis, and M. Shavegan, Science 290, 1546 (2000).
6 J. Jaroszyński, T. Andrearczyk, G. Karczewski, J. Wróbel, T. Wojtowicz, E. Papis, E. Kamińska, A. Piotrowska, D. Popović, and T. Dietl, Phys. Rev. Lett. 89, 266802 (2002).
7 A. H. MacDonald, P. M. Platzman, and G. S. Boebinger, Phys. Rev. B 69, 235315 (2004).
8 K. Toyama, T. Nishio, K. Sawano, Y. Shiraki, and T. Okamoto, Phys. Rev. Lett. 101, 016805 (2008).
9 J. C. Chokomakou, N. Goel, S. J. Chung, M. B. Santos, J. L. Hicks, M. B. Johnson, and S. Q. Murphy, Phys. Rev. B 69, 235315 (2004).
10 T. Jungwirth and A. H. MacDonald, Phys. Rev. Lett. 87, 216801 (2001).
11 J. P. Eisenstein, R. Willett, H. L. Stormer, D. C. Tsui, A. C. Gossard, and J. H. English, Phys. Rev. Lett. 61, 997 (1988).
12 R. G. Clark, S. R. Haynes, A. M. Suckling, J. R. Mallett, P. A. Wright, J. J. Harris, and C. T. Foxon, Phys. Rev. Lett. 62, 1536 (1989).
13 J. P. Eisenstein, H. L. Stormer, L. Pfeiffer, and K. W. West, Phys. Rev. Lett. 62, 1540 (1989).
14 L. W. Engel, S. W. Hwang, T. Sajoto, D. C. Tsui, and M. Shavegan, Phys. Rev. B 45, 3418 (1992).
15 S. E. Barrett, G. Dabagh, L. N. Pfeiffer, K. W. West, and R. Tycko, Phys. Rev. Lett. 74, 5112 (1995).
16 R. R. Du, A. S. Yeh, H. L. Stormer, D. C. Tsui, L. N. Pfeiffer, and K. W. West, Phys. Rev. Lett. 75, 3926 (1995).
17 N. Freytag, M. Horvatić, C. Berthier, M. Shavegan, and L. P. Lévy, Phys. Rev. Lett. 89, 246804 (2002).
18 A. Yutani and Y. Shiraki, Semicond. Sci. Technol. 11, 1009 (1996); J. Cryst. Growth 175/176, 504 (1997).
19 J. Matsunami, M. Ooya, and T. Okamoto, Phys. Rev. Lett. 97, 066602 (2006).
20 U. Zeitler, H. W. Schumacher, A. G. M. Jansen, and R. J. Haug, Phys. Rev. Lett. 86, 866 (2001).
21 Qualitatively similar experimental results were obtained for \( V_{BG} = 0 \text{ V} \) with \( N_s = 2.3 \times 10^{11} \text{ cm}^{-2} \) and \( \mu = 6 \times 10^4 \text{ cm}^2/V \text{ s} \).
22 T. Ando, A. B. Fowler, and F. Stern, Rev. Mod. Phys. 54, 437 (1982).
23 We have also performed measurements in a magnetic field where the in-plane component is aligned parallel to the \( y \) direction. It was confirmed that the transport anisotropy in the QH region is dominated by the direction of the in-plane magnetic field with respect to the current channel, not by the crystallographic anisotropy.
24 The range of \( 5 < \nu < 6 \) for holes corresponds to the range of \( 2 < \nu < 3 \) for electrons.
25 M. P. Lilly, K. B. Cooper, J. P. Eisenstein, L. N. Pfeiffer, and K. W. West, Phys. Rev. Lett. 82, 394 (1999).
26 R. R. Du, D. C. Tsui, H. L. Stormer, L. N. Pfeiffer, K. W. Baldwin, and K. W. West, Solid State Commun. 109, 389 (1999).
27 K. B. Cooper, M. P. Lilly, J. P. Eisenstein, L. N. Pfeiffer, and K. W. West, Phys. Rev. B 60, R11285 (1999).
28 A. A. Koulakov, M. M. Fogler, and B. I. Shklovskii, Phys. Rev. Lett. 76, 499 (1996).
29 M. M. Fogler, A. A. Koulakov, and B. I. Shklovskii, Phys. Rev. B 54, 1853 (1996).
30 R. Moessner and J. T. Chalker, Phys. Rev. B 54, 5006 (1996).
31 F. D. M. Haldane, E. H. Rezayi, and K. Yang, Phys. Rev. Lett. 85, 5396 (2000).
32 N. Shibata and D. Yoshioka, Phys. Rev. Lett. 86, 5755 (2001).
33 R. M. Lewis, P. D. Ye, L. W. Engel, D. C. Tsui, L. N. Pfeiffer, and K. W. West, Phys. Rev. Lett. 89, 136804 (2002).
34 H. Akera, A. H. MacDonald, and D. Yoshioka, Physica B 212, 273 (1995).