Insulating phases induced by crossing of partially filled Landau levels in a Si quantum well

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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.

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 ω_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.[1–3] 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 ν, it is predicted that the ground state is the ferromagnetic state with easy-axis (Ising) anisotropy.[2,3] 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. 4–9) and discussed in association with domain wall between $m_z=+1$ and $m_z=-1$ regions of the sample.[10] On the other hand, the pseudospin configuration has not been studied for the intermediate region between integer QH states. In the case of real spin systems, the ground state was found to be spin unpolarized for various noninteger values of ν when the bare Zeeman splitting is sufficiently small.[11–17] 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 ν 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 lo-

calized at the coincidence where the pseudospin is expected to be unpolarized. The ν dependence of the dip width implies that the pseudospin-unpolarized phase develops as ν 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.[18] The electrons are provided by a Sb-δ-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 μm 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.[19] 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.[9,20] HB-X (HB-Y) is 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 μ are $1.38(1.43)\times10^{11}$ cm^{-2} and $2.6(2.8)\times10^5$ cm^2/V s, respectively, for HB-X (HB-Y).[21] The sample was mounted on a rotary stage in a ^{3}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($\uparrow$,0)] and the spin-down LL with $n=1$[LL($\downarrow$,1)]. We assign $m_z=+1$ to LL($\uparrow$,0) and $m_z=-1$ to LL($\downarrow$,1). The Fermi level ε_F is inside these degenerate LLs when the Landau-level filling factor ν is in the range between 2 and 6 as shown in Fig. 1(b). Note that we have a twofold valley degeneracy for a 2DES formed on the Si(001) surface.[22] In our experimental setup, the tilt angle θ can be continuously varied while the temperature T is kept constant at a fixed value. Furthermore, simultaneous control of θ and the total magnetic field B_{tot} allows us to measure the B_{tot} dependence for a constant value of the perpendicular component $B_\perp=B_{tot}\cos\theta$, which is proportional to ν.
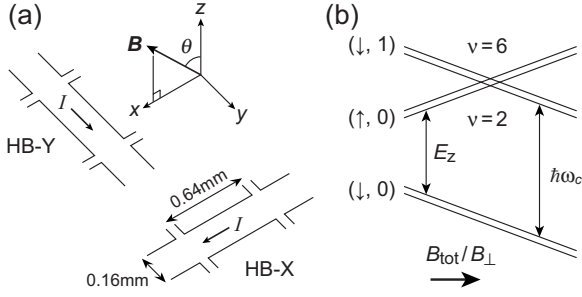
FIG. 1. (a) Schematic of the Hall bars. The current direction is along the x axis in HB-X and the y axis in HB-Y. The magnetic field is tilted from the z axis in the x direction by an angle θ. (b) Landau levels in a tilted magnetic field. The ratio of the Zeeman energy E_z to the cyclotron energy $\hbar\omega_c$ increases with θ. E_z and $\hbar\omega_c$ are approximately proportional to the total magnetic field B_{tot} and the perpendicular component $B_\perp = B_{tot}\cos\theta$, respectively.

Figure 2 shows ρ_{xx} and ρ_{yx} as functions of $B_\perp$ in the range between the QH states of $\rho_{yx}=h/3e^2$ and $h/2e^2$. Data for different fixed values of B_{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_{tot} increases. In the QH region near $\nu=3$ (e.g., $B_\perp \approx 1.87$ T and $B_{tot} = 4.42$ T), ρ_{xx} exhibits a sharp spike which is attributed to domain-wall resistance in Ising QH ferromagnets.[5–9] On the other hand, a pronounced dip is observed in the intermediate region (e.g., $B_\perp \approx 2.15$ T and $B_{tot}=5.23$ 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 $B_\perp \approx 2.0$ T. While the structure of the longitudinal resistivity at the coincidence is sensitive to ν, the change in ρ_{yx} is always positive in this range. The position of the peak center is in good agreement with the center of the ρ_{xx} dip in the intermediate region.

As reported in previous studies on Si/SiGe heterostructures in the vicinity of $\nu=4$,[9,20] 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.[23] The anisotropy has been discussed in terms of a stripelike domain structure of the Ising QH ferromagnet oriented perpendicular to the in-plane magnetic field.[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 ε_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 ρ_{xy} in the vicinity of the LL coincidence is shown. The sign of the change in ρ_{xy} is positive for $\nu<4$ and negative for $\nu>4$. Similar behavior was observed for ρ_{yx}. 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.[24] The dip in the longitudinal resistivity ac-
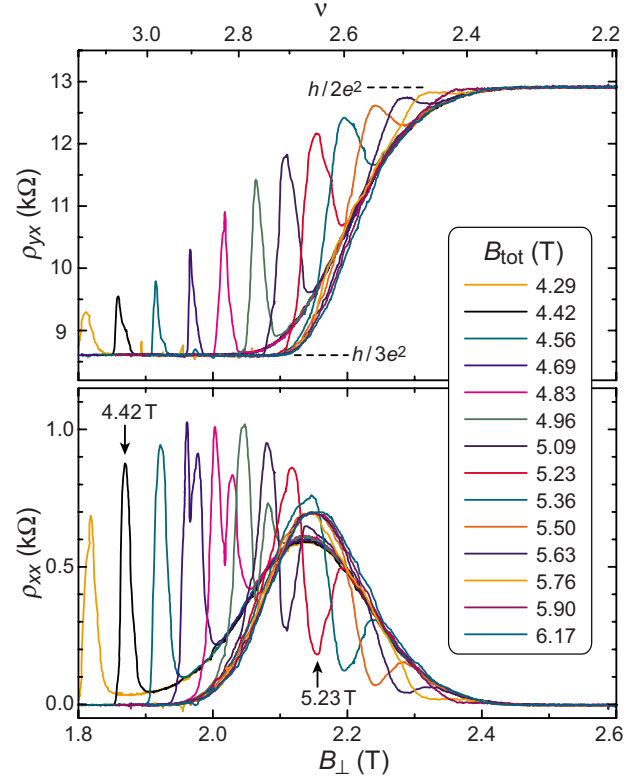

FIG. 2. (Color online) $B_\perp$ dependence of ρ_{xx} and ρ_{yx} for different fixed values of B_{tot}. The data were obtained for HB-X by decreasing $B_\perp$ at 70 mK. The position of the peak or dip shifts to higher $B_\perp$ as B_{tot} increases. The peak for $B_{tot}=4.42$ T and the dip for $B_{tot}=5.23$ T are indicated by arrows.

companied with the Hall resistivity change reminds us of insulating phases in spin-resolved high LLs of high-mobility GaAs 2DESs,[25–27] which are interpreted as bubble phases of electrons or holes.[28–33] 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 $\nu=4$,[9] 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 ρ_{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 $\nu=$ 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 ν, 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 ΔB_{tot} of the insulating state determined from the dip in the longitudinal resistivities is shown. It decreases almost linearly with increasing ν 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 pseu-
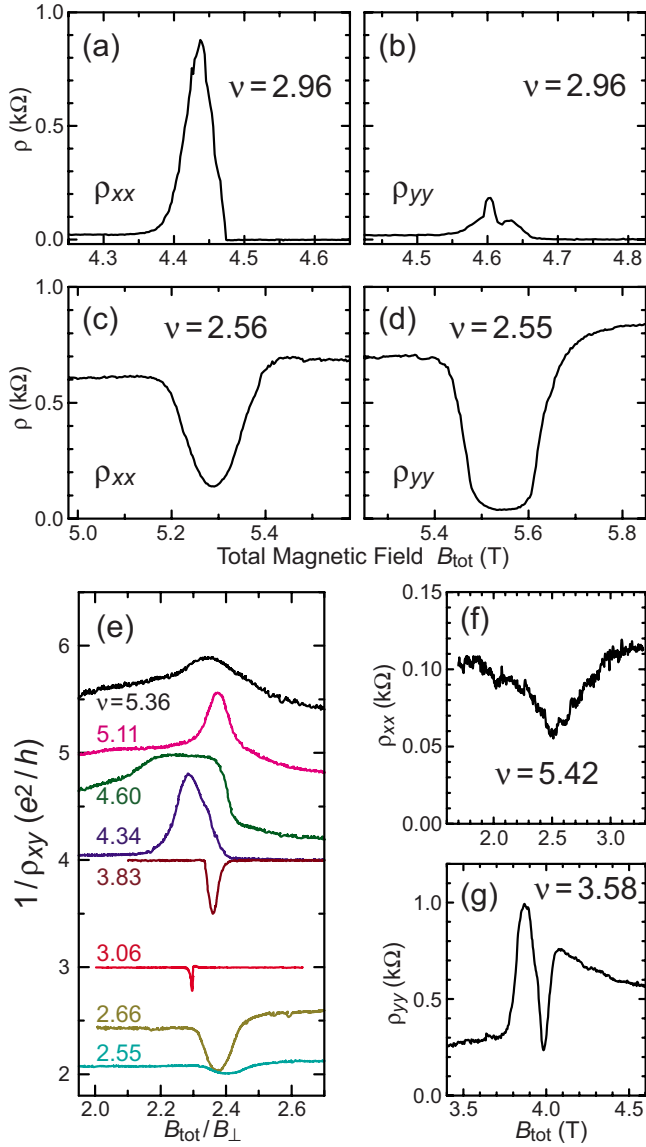
FIG. 3. (Color online) [(a)–(d), (f), (g)] Longitudinal resistivities as functions of B_{tot} for different fixed values of ν. (e) Inverse of the Hall resistivity vs $B_{tot}/B_\perp$. All the data were obtained by decreasing B_{tot} at 70 mK. HB-X was used for (a), (c), and (f). HB-Y was used for (b), (d), (e), and (g).
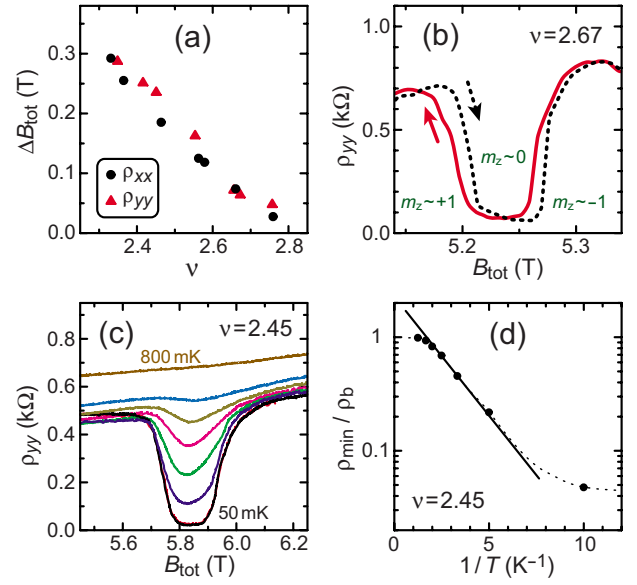

FIG. 4. (Color online) (a) The full width at half maximum of the dip in ρ_{xx} or ρ_{yy} measured at 70 mK. Since hysteresis was observed, the mean values are plotted. (b) Hysteresis of B_{tot} dependence of ρ_{yy} at 70 mK and $\nu=2.67(B_\perp=2.21$ T). Solid curve (red): the downward sweep with $dB_{tot}/dt=-0.5$ mT/s. Dashed curve (black): the upward sweep with $dB_{tot}/dt=+0.7$ mT/s. (c) B_{tot}-dependence of ρ_{yy} at $\nu=2.45(B_\perp=2.41$ T) for $T=50,100,200,300,400,500,600,$ and 800 mK (from bottom to top). The data were obtained by decreasing B_{tot}. (d) Logarithm plot of the ρ_{yy} minimum, divided by the baseline value ρ_b, is shown as a function of the inverse temperature. The solid straight line represents an Arrhenius temperature dependence $\rho_{yy}/\rho_b \propto \exp(-\Delta/2$ T), where $\Delta=1.0$ K is the energy gap. The dotted line is a guide for the eyes.

dospin field. The ν dependence of ΔB_{tot} implies that the pseudospin-unpolarized phase with $|m_z|<1$ develops as ν 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_{tot} and low-B_{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 ρ_{yy} at $\nu=2.45$ are shown in Fig. 4(c). If we assume an Arrhenius temperature dependence, the energy gap is deduced to be $\Delta \sim 1$ K as exemplified in Fig. 4(d).

The state with small m_z corresponds to a configuration in which the LL($\uparrow,0$) and LL($\downarrow,1$) are nearly equally popu-

lated. 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.[34] 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 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 $\nu^* \lesssim 0.3$ while the results are not conclusive for higher ν^*.

In summary, we have performed the magnetotransport measurements on a high-mobility Si 2DES in the vicinity of the coincidence of LL($\uparrow,0$) and LL($\downarrow,1$). In contrast to the QH region where ρ_{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 ν dependence of ΔB_{tot} implies that the pseudospin-unpolarized phase develops as ν 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 $\Delta \sim 1$ K from the Arrhenius plot of the longitudinal resistivity.

[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. Shayegan, 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. Shayegan, 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] E. P. De Poortere, E. Tutuc, and M. Shayegan, Phys. Rev. Lett. **91**, 216802 (2003).

[8] J. C. Chokomakoua, N. Goel, S. J. Chung, M. B. Santos, J. L. Hicks, M. B. Johnson, and S. Q. Murphy, Phys. Rev. B **69**, 235315 (2004).

[9] K. Toyama, T. Nishioka, K. Sawano, Y. Shiraki, and T. Okamoto, Phys. Rev. Lett. **101**, 016805 (2008).

[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. Shayegan, Phys. Rev. B **45**, 3418 (1992).

[15] S. E. Barrett, G. Dabbagh, 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. Shayegan, 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 $V_{\text{BG}}=0$ V with $N_s=2.3 \times 10^{11}$ cm^{-2} and $\mu=6 \times 10^5$ cm^2/V 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).