Pseudospin Soliton in the $\nu = 1$ Bilayer Quantum Hall State

A. Fukuda,1 D. Terasawa,2 M. Morino,2 K. Iwata,3 S. Kozumi,2 N. Kumada,4 Y. Hirayama,2,4 Z. F. Ezawa,2 and A. Sawada1

1Research Center for Low Temperature and Materials Sciences, Kyoto University, Kyoto 606-8502, Japan
2Graduate School of Science, Department of Physics, Tohoku University, Sendai 980-8578, Japan
3Graduate School of Science, Department of Physics, Kyoto University, Kyoto 606-8502, Japan
4NTT Basic Research Laboratories, NTT Corporation, 3-1 Morinosato-Wakamiya, Atsugi 243-0198, Japan

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We investigate a domain structure of pseudospins, a soliton lattice in the bilayer quantum Hall state at total Landau level filling factor $\nu = 1$, in a tilted magnetic field, where the pseudospin represents the layer degree of freedom. An anomalous peak in the magnetoresistance $R_{xx}$ appears at the transition point between the commensurate and incommensurate phases. The $R_{xx}$ at the peak is highly anisotropic for the angle between the in-plane magnetic field $B_{\parallel}$ and the current, and indicates a formation of the soliton lattice aligned parallel to $B_{\parallel}$. Temperature dependence of the $R_{xx}$ peak reveals that the dissipation is caused by thermal fluctuations of pseudospin solitons. We construct a phase diagram of the bilayer $\nu = 1$ system as a function of $B_{\parallel}$ and the total electron density. We also study effects of density imbalance between the two layers.

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Two-dimensional electron gas (2DEG) in a strong magnetic field is an ideal system to investigate many-body phenomena. Since the quantization of electron motion into Landau levels (LLs) quenches the kinetic energy, electron-electron interactions dominate the physics. When two or more LLs are brought close in energy near the Fermi level, the Coulomb interaction leads to a broken-symmetry state, which can be described as a new class of ferromagnet [1,2]. This is best illustrated in the bilayer quantum Hall (QH) state at total LL filling factor $\nu = 1$. When two 2DEGs are set close, even in the limit of zero tunneling energy, strong interlayer interactions produce a broken-symmetry state with spontaneous interlayer phase coherence [1, 2]. A number of interesting phenomena, such as Josephson-like interlayer tunneling [3] and vanishing Hall resistance for counterflowing currents in the two layers [4, 5], have been observed. This state can be viewed in several ways, including Bose condensate of interlayer excitons [6] and pseudospin ferromagnet [1, 2, 7], where the pseudospin represents the layer degree of freedom, in which the pseudospin up and down denotes electrons in the front and back layers, respectively.

In-plane magnetic field $B_{\parallel}$ has been used to change pseudospin properties. Murphy et al. showed evidence of a $B_{\parallel}$-induced phase transition in the bilayer $\nu = 1$ QH state: as $B_{\parallel}$ is increased, the activation energy gap drops when $B_{\parallel}$ is smaller than a critical value $B_{\parallel}^{C}$ and then stays almost at a constant value for larger $B_{\parallel}$ [8]. This phase transition is understood as a commensurate-incommensurate (C-IC) transition [7]. The presence of $B_{\parallel}$ periodically shifts the interlayer phase difference of electrons between the two layers $\phi$. In pseudospin language, while the $z$-component of pseudospin, $P_{z}$, vanishes at the balanced density configuration, the in-plane components of the pseudospin, $P_{x}$ and $P_{y}$, are related to the interlayer phase difference: $\phi = \arctan(P_{y}/P_{x})$. For $B_{\parallel} < B_{\parallel}^{C}$, pseudospins rotate along the planar direction following the periodically shifting $\phi$. This is the C phase, where the tunneling energy is minimized. In the C phase, since neighboring pseudospins are no longer parallel, the pseudospin exchange energy increases with $B_{\parallel}$. In the limits of large $B_{\parallel}$, pseudospins are uniformly polarized to minimize the exchange energy. This is the IC phase in the large $B_{\parallel}$ limit. Pseudospin configurations in these phases are illustrated in Fig. 4. Theories have suggested that in the IC phase for any finite $B_{\parallel} > B_{\parallel}^{C}$ there exists a domain structure of pseudospins [9, 10, 11, 12, 13, 14, 15] (also illustrated in Fig. 4). A domain structure is theoretically derived from the sine-Gordon equation, as well as from an isolated soliton solution. Thus we call the domain structure a "soliton lattice" and the domain wall a "pseudospin soliton". At the pseudospin soliton, a direction of pseudospin $\phi$ slip by $2\pi$ around a magnetic flux penetrating between the two layers. Therefore $\phi$ has a repetitive stepwise position of the function. An abrupt change of $\phi$ over the small distance at the domain wall costs the large gradient energy and causes repulsive interactions between solitons, which stabilize the pseudospin soliton into a soliton lattice in the low temperature limit. The formation and properties of the soliton lattice are directly related to the pseudospin ferromagnetism, and their experimental investigation is essential for understanding the bilayer $\nu = 1$ QH state.

In this Letter, we report the observation of an anomalous peak in the longitudinal resistance $R_{xx}$ with a well-developed QH plateau in the Hall resistance $R_{xy}$ around the C-IC transition point in the bilayer $\nu = 1$ QH state. The $R_{xx}$ at the peak changes with the angle $\phi$ between the direction of $B_{\parallel}$ and the current $I$, following a sinusoidal function. We interpret this anisotropic transport as a formation of the soliton lattice aligned parallel to $B_{\parallel}$. Temperature dependence of the $R_{xx}$ peak reveals that the dissipation is caused by thermally fluctuating pseudospin solitons. We construct a phase diagram of the bilayer $\nu = 1$ QH state as a function of $B_{\parallel}$ and the total electron density $n_{T}$. We also show that pseudospin solitons disappear when the bilayer system is off-balanced.

We used two double-quantum-well samples with 20-nm-wide GaAs quantum wells. The tunneling energy is $\Delta_{SAS} = 11$ K for sample A and 8 K for sample B [16]. Low-temperature mobility is $1.0 \times 10^{2} \text{m}^{2}/\text{Vs}$ at $n_{T} = 1.0 \times 10^{15} \text{m}^{-2}$ for both samples. By adjusting the front- and back-gate biases, we can independently control $n_{T}$ and the density imbalance $\sigma \equiv$...
define the tilting angle $\theta$ a goniometer with a superconducting stepper motor [17]. We apply perpendicular magnetic field. To investigate anisotropic transport, we placed sample B on a two-axis goniometer, for which the samples were tilted in the magnetic field $B_\parallel$ given in the inset of Fig. 2(a)). Figure 2(b) shows the magnetoresistance at the peak $R_{xx}^{\text{peak}}$ as a function of $\phi$. The data is well fitted by a sinusoidal function: $R_{xx}^{\text{peak}} = A \cos 2\phi + B$. The amplitude $A = [R_{xx}(\phi = 90^\circ) - R_{xx}(\phi = 0^\circ)]/2$ is related to the anisotropic ratio $|R_{xx}(\phi = 90^\circ) - R_{xx}(\phi = 0^\circ)|/R_{xx}(\phi = 0^\circ)$. As $T$ is decreased, although $A$ decreases, $R_{xx}(\phi = 0^\circ)$ decreases more rapidly and thus the anisotropic ratio increases

In Figs. 1(a), (c), and (e), we present $R_{xx}$ as a function of $B_{\text{tot}}$ and $\nu_T$ near the $\nu = 1$ QH state for three tilted angles in a balanced density condition ($\sigma = 0$). Yellow areas indicate small $R_{xx}$ and thus QH states. Dashed lines lie just on the filling factor $\nu = 1$. The $R_{xx}$ at $\nu = 1$ (along the dashed lines) is plotted as a function of $\nu_T$ in Figs. 1(b), (d), and (f). When $\theta$ is small (Figs. 1(a) and (b)), the bilayer $\nu = 1$ QH state collapses as $\nu_T$ is increased. This transition from the bilayer $\nu = 1$ QH state to the compressible state is known to be induced by strong intralayer interactions for larger $\nu_T$ [8]. The QH state corresponds to the C phase because $B_\parallel$ is applied perpendicular to $\nu_1$ and $B_\perp$. Temperature is 130 mK for sample A. Decreases, $C$-IC phase transition point by the $\nu_1$ QH state to the compressible state is known to be induced by strong intralayer interactions for larger $\nu_T$ [8]. The QH state corresponds to the C phase because $B_\parallel$ is applied perpendicular to $\nu_1$ and $B_\perp$. Temperature is 130 mK for sample A. When $\theta$ is increased, a peak in $R_{xx}$ grows and becomes maximum when $I$ is orthogonal to $B_\parallel$ ($\phi = 90^\circ$). Figure 2(b) shows the magnetoresistance at the peak $R_{xx}^{\text{peak}}$ as a function of $\phi$. The data is well fitted by a sinusoidal function: $R_{xx}^{\text{peak}} = A \cos 2\phi + B$. The amplitude $A = [R_{xx}(\phi = 90^\circ) - R_{xx}(\phi = 0^\circ)]/2$ is related to the anisotropic ratio $|R_{xx}(\phi = 90^\circ) - R_{xx}(\phi = 0^\circ)|/R_{xx}(\phi = 0^\circ)$. As $T$ is decreased, although $A$ decreases, $R_{xx}(\phi = 0^\circ)$ decreases more rapidly and thus the anisotropic ratio increases

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(\nu_T - \nu_B)/\nu_T$ between the two layers, where $\nu_T$ ($\nu_B$) denotes the electron density in the front (back) layer. The samples were mounted in the mixing chamber of a dilution refrigerator with a base temperature of 40 mK. Measurements were performed using standard low-frequency AC lock-in techniques. To apply $B_{\text{tot}}$, the samples were tilted in the magnetic field $B_{\text{tot}}$ by a goniometer with a superconducting stepper motor [17]. We define the tilting angle $\theta$ as $\tan \theta = B_{\text{tot}}/B_\perp$, where $B_\perp$ is the perpendicular magnetic field. To investigate anisotropic transport, we placed sample B on a two-axis goniometer, for which both $\theta$ and $\phi$ can be controlled independently (the angles are given in the inset of Fig. 2(a)).

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as a function of
increases, a clear peak appears around
dence of
of pseudospins, i.e. the soliton lattice. When
pseudospin solitons, we measured the temperature (T)
of the carriers is maximized when the magnetic moments of
although in this system anisotropic spin-dependent scattering
ventional spin-induced giant magnetoresistance (GMR) [19],
pseudospin soliton. This anisotropy is reminiscent of the con-
indicates that electrons are backscattered when they crossa
flows parallel to pseudospin solitons. As
for several temperatures at
T = 300 mK [Fig. 3(b)], showing that the anomalous peak in
R_{xx} occurs in the QH regime.

The temperature dependence of R_{xx} at T = 300 mK [Fig. 3(b)], showing that the anomalous peak in
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We construct a phase diagram for the bilayer v = 1 QH state in the B_{1} - n_{T} plane at a finite temperature T = 130 mK (Fig. 4). The C-IC phase boundary (solid line) is obtained by collecting (B_{1}, n_{T}) plane at a finite temperature
that gives a local minimum
R_{xx}(n_{T}) in the IC phase. At
G_{IC} into two regions, that is, the non-dissipative and
dissipative regions. The boundary (dashed line) between the
two regions is defined by (B_{1}, n_{T}) that gives a local minimum
of the derivative of R_{xx} with respect to n_{T} (dashed arrow in
Fig. 4(f)). The narrow dissipative region appears along the boundary to the C phase.

We discuss the B_{1} dependence of R_{xx} in the IC phase. At
a finite temperature, R_{xx} in the IC phase is determined by the
stiffness of the soliton lattice, which is related to the density of
soliton n_{S}. Near the phase boundary to the C phase, n_{S} is small
and the lattice is soft. Therefore, at a finite temperature, the
fluctuations of solitons are large, leading to large R_{xx}. As B_{1} is
increased, the stiffness increases with n_{S} and, at some point, the
lattice of solitons is formed. Thus we refer to the dissipative
and non-dissipative regions as a dissipative soliton (DS)
region and a non-dissipative soliton lattice (NDSL) region, respectively.
The phase diagram shows that the DS region appears narrowly along the boundary to the C phase. Theories
show that \( n_S \) starts to increase at \( B_\parallel = B_\parallel^C \) and proliferates rapidly until the distance between solitons becomes comparable to the width of a soliton. The rapid increase in \( n_S \) explains the narrow DS region along the phase boundary. Once the spacing between solitons is equal to the domain width, the interlayer phase difference of electrons is constant at every place, pseudospins are polarized and the system is regarded as a pure incommensurate phase, illustrated in Fig. 4. Since the \( R_{xx} \) in the pure incommensurate phase also vanishes, it is observed experimentally in the NDSL region. Note that the Kosterlitz-Thouless (K-T) transition between the soliton lattice and liquid was theoretically predicted[14]. According to the theory, it may be possible to translate the DS region into a soliton liquid phase. However, our \( R_{xx} \) data show no criticality. This may be due to the particularity of the K-T transition that any thermodynamic quantity does not jump at the transition point. More detailed theoretical work for the \( n_S \) and \( T \) dependence of \( R_{xx} \) would clarify the existence of the K-T transition.

Finally, we investigate effects of the density imbalance \( \sigma \) between the two layers. Figure 5 shows \( R_{xx} \) in a surface plot as a function of \( \sigma \) and \( n_\parallel \). The data were taken by sweeping both \( \sigma \) and \( n_\parallel \) while keeping the filling factor \( \nu = 1 \) at \( \theta = 57.9^\circ \) and \( \phi = 90^\circ \). Pseudospin solitons appear as a peak in \( R_{xx} \) around \( \sigma = 0 \) and \( n_\parallel = 0.61 \times 10^{15} \text{m}^{-2} \). The inset of Fig. 5 shows the slice at \( n_\parallel = 0.61 \times 10^{15} \text{m}^{-2} \). For \( |\sigma| > 0.2 \), \( R_{xx} \) almost vanishes, which indicates that pseudospin solitons are unstable. The instability would be due to the reduction of the pseudospin stiffness proportional to \( 1 - \sigma^2 \)[10, 14]. However, this dependence is not sufficient to explain the observed strong \( \sigma \) dependence of \( R_{xx} \). Further quantitative theoretical investigation is needed to reveal the structure of pseudospin solitons in an off-balanced system.

In conclusion, we have carried out magnetotransport measurements around the C-IC transition in the bilayer \( \nu = 1 \) QH state. We found an anomalous peak in \( R_{xx} \) near the C-IC transition point. This peak has a highly anisotropic nature, which indicates that pseudospin solitons are formed along the direction of \( B_\parallel \). The temperature dependence of \( R_{xx} \) and \( R_{xy} \) reveals that thermally fluctuated pseudospin solitons solidify into a rigid soliton lattice at low temperature. The phase diagram constructed experimentally in the \( n_\parallel-B_\parallel \) plane shows that the dissipation occurs only in a narrow region just near the C phase. We also found that pseudospin solitons are very sensitive to the charge imbalance.

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[1] S. M. Girvin and A. H. MacDonald. Perspectives in Quantum Hall Effects. Wiley, New York, 1997. edited by A. Pinczuk and S. Das Sarma.
[2] Z. F. Ezawa. Quantum Hall Effects. Field Theoretical Approach and Related Topics. World Scientific, Singapore, 2000.
[3] I. B. Spielman et al. Phys. Rev. Lett., 84:5808, 2000.
[4] M. Kellogg et al. Phys. Rev. Lett., 93:036801, 2004.
[5] E. Tutuc et al. Phys. Rev. Lett., 93:036802, 2004.
[6] J. P. Eisenstein and A. H. MacDonald. Nature (London), 432:691, 2004, and references therein.
[7] K. Yang et al. Phys. Rev. Lett., 72:732, 1994.
[8] S. Q. Murphy et al. Phys. Rev. Lett., 72:728, 1994.
[9] N. Read. Phys. Rev. B, 52:1926, 1995.
[10] R. Côté et al. Phys. Rev. B, 51:13475, 1995.
[11] K. Yang et al. Phys. Rev. B, 54:11644, 1996.
[12] L. Brey et al. Phys. Rev. B, 54:16888, 1996.
[13] Z. F. Ezawa. Chapter 23 in Ref. [2].
[14] C. B. Hanna et al. Phys. Rev. B, 63:125305, 2001.
[15] S. Park et al. Phys. Rev. B, 66:153318, 2002.
[16] We obtained qualitatively the same results from the two samples with slightly different \( \Delta_{QH} \). Quantitatively, overall features occur at higher \( \theta \) in the sample with larger \( \Delta_{QH} \).
[17] M. Suzuki et al. Cryogenics, 37:275, 1997.
[18] A rotation of the sample in the mixing chamber increases the temperature, preventing the detailed experiment around the C-IC transition by changing \( \theta \) with fixed \( n_\parallel \). Accordingly, most of the data are taken by changing \( n_\parallel \) and \( B_{\parallel} \) with fixed \( \theta \).
[19] M. N. Baibich et al. Phys. Rev. Lett., 61:2472, 1988.