Activation study of collective excitations of the soliton-lattice phase in the $\nu=1$ double-layer quantum Hall state

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We investigate thermal excitations of the pseudospin soliton lattice in the double-layer quantum Hall (QH) state at total Landau-level filling factor $\nu=1$ by detailed measurements of the activation energy gap, where the pseudospin represents the layer degree of freedom. In a tilted magnetic field, the activation energy gap of the double-layer $\nu=1$ QH state shows a minimum near the phase transition point between the commensurate and incommensurate states. From a comparison of the in-plane field dependence of the activation energy gap with theories, we suggest that the minimum in the activation energy gap is due to collective modes of the soliton lattice.

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In a closely separated double-layer two-dimensional electron system, strong interlayer and intralayer Coulomb interactions lead to a number of unique many-body states.[1,2] In this system, quantum tunneling of electrons between layers plays a significant role to describe the macroscopic aspects. A most remarkable state is the quantum Hall (QH) state at total Landau-level filling factor $\nu=1$, which possesses a spontaneous interlayer phase coherence. In this state, unusual physical phenomena[3–6] have been observed for over a decade and these findings have invoked new concepts in the condensed-matter physics related to the superfluidity or superconductivity.[2,7] Pseudospin ferromagnet,[8] where pseudospin up (down) represents an electron in the front (back) side of the double-layer system, is one of these concepts to explain the interlayer coherence and its concomitant phenomena.

A phase transition associated with the pseudospin ferromagnetism has been observed by activation energy gap measurements under tilted magnetic field.[3] When an in-plane magnetic field $B_\parallel$ is introduced, the activation energy gap of the double-layer $\nu=1$ QH state drops dramatically before saturating at a roughly constant value for larger $B_\parallel$. This phase transition is explained by a competition between the pseudospin exchange and tunneling energies.[8] $B_\parallel$ couples to the interlayer phase difference ϕ, which corresponds to the in-plane component of the pseudospin: $B_\parallel$ generates an Aharanov-Bohm phase when electrons tunnel between the two layers, resulting in an effective Zeeman field that rotates the xy component of the pseudospin. When $B_\parallel$ is small, the direction of pseudospins is commensurate to the effective field to minimize the pseudospin Zeeman (tunneling) energy. For larger $B_\parallel$, in contrast, the cost of the exchange energy for pseudospins to align to the rotating effective field overtakes the pseudospin Zeeman energy, and thus pseudospins polarize incommensurately to the effective Zeeman field. More accurate pictures of this commensurate-incommensurate (C-IC) phase transition have suggested the existence of a domain structure of pseudospins in the IC phase, which is called a soliton-lattice (SL) phase.[2,9–15] In the SL phase, domains of the commensurate phase are separated by a pseudospin soliton, in which the pseudospin slips by 2π around a magnetic flux penetrating between the two layers. An important feature of the SL is that its translational symmetry is broken by the introduction of periodic kinks of pseudospins. As a result, the SL has collective Goldstone modes. Since thermal fluctuations of the SL are predicted to scatter electrons,[9,12–14] activation energy gap measurements would reveal the formation of the SL. Recent experiment in the double-layer $\nu=1$ QH state indicates the existence of pseudospin solitons by the observation of the anisotropic conductivity for the angle between $B_\parallel$ and detective current I.[16]

In this Brief Report, we investigate the collective excitation modes of the SL in the IC phase by detailed activation energy gap measurements under tilted magnetic fields. As a double-quantum-well sample is tilted in a magnetic field, the activation energy gap of the double-layer $\nu=1$ QH state drops rapidly in the C phase and takes a minimum near the C-IC phase transition point. For larger tilting angle, the gap gradually increases to an almost constant value in the IC phase. The R_{xx} minimum becomes deeper as the IC state becomes stable with decreasing electron density. From a comparison of these experimental results with theories, we suggest that collective excitations of the SL formed in the IC phase reduce the gap.

The sample used in this experiment consists of two 20-nm-wide GaAs quantum wells separated by a 3.1-nm-thick $Al_{0.33}Ga_{0.67}As$ barrier (center-to-center distance of $d=23.1$ nm).[17] The tunneling gap is $\Delta_{SAS}=11$ K.[18] The low-temperature mobility is $\mu=1.0\times10^6$ cm^2/V s at the total electron density $n_{tot}=1.0\times10^{11}$ cm^{-2}. By adjusting front- and back-gate biases, we can control n_{tot} and the density imbalance $\sigma\equiv(n_f-n_b)/n_{tot}$ between the two layers indepen-

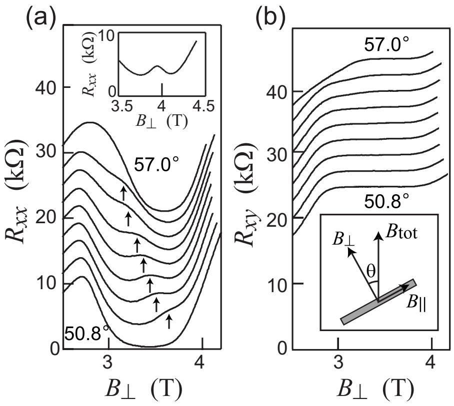

FIG. 1. (a) R_{xx} and (b) R_{xy} around $\nu=1$ at $\sigma=0$ as a function of $B_\perp$ for several values of the tilting angle. Tilting angles are $\theta=50.8°$, 52.0°, 52.8°, 53.2°, 53.6°, 54.0°, 54.6°, 55.0°, and 57.0° from the bottom to top traces. Total electron density is $n_{\mathrm{tot}}=0.9\times10^{11}$ cm^{-2}. Temperature is 250 mK. Traces are vertically offset for clarity. Arrows in (a) indicate the positions of the peak in R_{xx}. In the inset of (a), R_{xx} for another sample (see the text for details) is shown. $n_{\mathrm{tot}}=1.0\times10^{11}$ cm^{-2} and $\theta=61°$ are set at the transition point. Temperature is 355 mK. Inset of (b) shows the definition of θ.

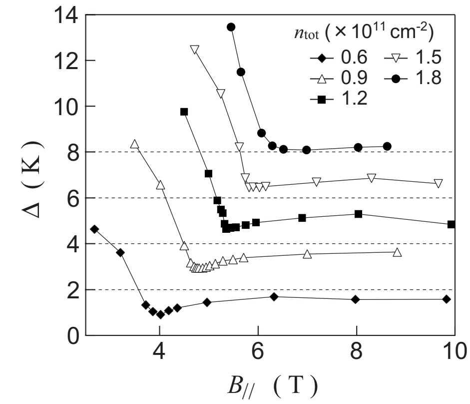

FIG. 2. Activation energy gap Δ of the double-layer $\nu=1$ QH state at $\sigma=0$ for several values of n_{tot} as a function of $B_\parallel$. Traces are vertically offset by 2 K for clarity.

dently, where n_{f} (n_{b}) denotes the electron density in the front (back) layer. The sample was mounted in a mixing chamber of a dilution refrigerator with a base temperature of 50 mK. Measurements were performed using standard low-frequency ac lock-in techniques with a current of 20 nA. To apply $B_\parallel$, we tilted the sample in the magnetic field B_{tot} by a goniometer with a superconducting stepper motor.[19] We define the tilting angle θ as $\tan\theta=B_\parallel/B_\perp$, where $B_\perp$ is the perpendicular magnetic field [inset of Fig. 1(b)]. The direction of I is normal to $B_\parallel$. In this configuration, pseudospin solitons are manifested as the increase in the magnetoresistance R_{xx}.[16]

Figures 1(a) and 1(b) show, respectively, R_{xx} and R_{xy} in the balanced density condition ($\sigma=0$) for several θ at fixed $n_{\mathrm{tot}}=0.9\times10^{11}$ cm^{-2}. When θ is small, R_{xx} at $\nu=1$ is vanishingly small, indicating a well-developed QH state in the C phase. As θ is increased, the position of the R_{xx} minimum shifts to lower field. At the same time another R_{xx} minimum appears from larger field. For larger θ, the minimum for larger field evolves into the minimum of the IC phase. This behavior demonstrates that pseudospin solitons, which appear as the peak in R_{xx} (the peak positions are indicated by arrows), exist at the C-IC phase transition point.[16] In contrast to the dramatic change in R_{xx}, the Hall plateau for the $\nu=1$ QH state is well developed even at the position where the peak appears, indicating that R_{xy} is insensitive to the existence of solitons. It is worth noting that we observe a similar behavior in another sample [inset of Fig. 1(a)] with different parameters: $\Delta_{\mathrm{SAS}}\approx 33$ K, $\mu=4.6\times10^5$ cm^2/V s, and $d=21.0$ nm. Therefore, the peak in R_{xx} is not originated in a sample-dependent property but in an intrinsic nature of the double-layer $\nu=1$ QH state.

To investigate collective excitation modes of the soliton lattice, we measured activation energy gap Δ from the temperature T dependence of R_{xx}: $R_{xx}\propto\exp(-\Delta/2T)$. In Fig. 2, we plot Δ at the exact $\nu=1$ filling point (not at the R_{xx} minimum) around the C-IC phase transition point at $\sigma=0$ for various values of n_{tot}. For smaller $B_\parallel$, the QH state is in the C phase and Δ decreases rapidly with increasing $B_\parallel$. When n_{tot} is at 1.8×10^{11} cm^{-2}, the C phase collapses into the compressible state for larger $B_\parallel$ because of strong intralayer correlations. At $n_{\mathrm{tot}}\le 1.5\times10^{11}$ cm^{-2}, interlayer correlations stabilize the QH state and the IC phase appears, in which Δ is almost constant.[3,8] Furthermore, our detailed measurements reveal another feature: Δ takes a minimum around the C-IC phase transition point and approaches a constant value with increasing $B_\parallel$. The minimum becomes more striking as the IC phase becomes more stable with decreasing n_{tot}. Since in a simple IC phase with uniform pseudospin configuration $B_\parallel$ does not affect the excitation gap, the observed $B_\parallel$ dependence of Δ in the IC phase suggests that the SL possesses lower excitation modes, particularly just after the C-IC phase transition. We compare the $B_\parallel$ dependence of Δ and R_{xx} at the exact $\nu=1$ filling point at 130 mK, which reflects a pseudospin configuration at low temperatures. Figure 3(a) shows a magnified view of Δ at $n_{\mathrm{tot}}=0.9\times10^{11}$ cm^{-2} around the C-IC phase transition point (the data are the same shown in Fig. 2). In Fig. 3(b), R_{xx} at 130 mK is plotted for the same range of $B_\parallel$ in Fig. 3(a). For lower $B_\parallel$, the system is in the C phase QH state, thus R_{xx} is vanishingly small. As $B_\parallel$ is increased, R_{xx} starts to rise abruptly at $B_\parallel=4.5$ T. This is a signal for the phase transition to the IC state, where solitons are introduced in the ground state; the critical in-plane field of the C-IC phase transition is $B_\parallel^{\mathrm{C\text{-}IC}}=4.5$ T. For larger $B_\parallel$, R_{xx} reaches a maximum at $B_\parallel=4.9$ T, and then decays gradually to zero.

We discuss the behavior of Δ and R_{xx} to compare with theories about SL. According to the theory,[2,13] no pseudospin solitons exist in the C phase. Above a critical point, the wave vector of the SL $Q_s\equiv\frac{2\pi d}{\phi_0}B_\parallel$, where ϕ_0 is a flux quantum, which is related to the number density of the pseudospin soliton, becomes finite, where Q_s is determined by a competition between a negative creation energy of solitons and a positive repulsive energy between solitons. Since the repulsive interaction is exponentially weak,[13,20] Q_s proliferates rapidly until the distance between solitons becomes comparable to the width of a soliton [inset of Fig. 3(b)]. As more solitons are introduced, the system approaches the IC phase

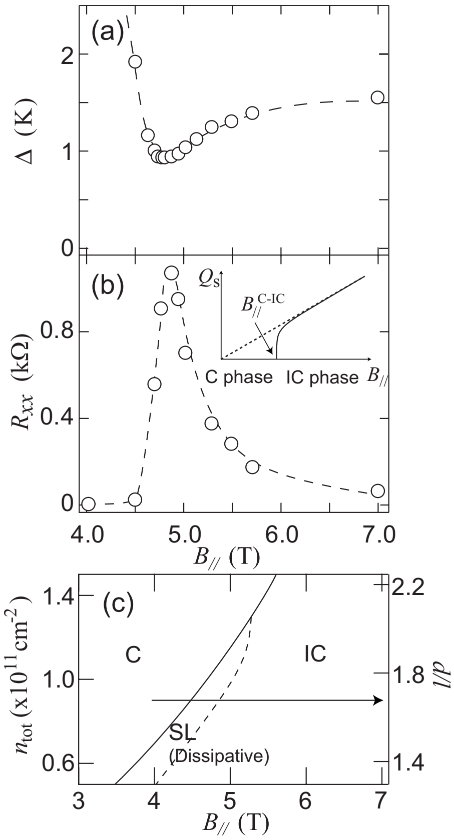

FIG. 3. (a) Activation energy gap Δ of the double-layer $\nu=1$ QH state at $\sigma=0$ as a function of $B_\parallel$. Total electron density is $n_{\text{tot}}=0.9\times10^{11}$ cm^{-2}. (b) R_{xx} at $\nu=1$ as a function of $B_\parallel$ at 130 mK. The dashed lines in (a) and (b) are guides to the eye. Inset of (b) shows illustration of the number density of the pseudospin soliton Q_s as a function of $B_\parallel$. The dashed line represents $B_\parallel d/\phi_0$, where ϕ_0 is a flux quantum. (c) A schematic phase diagram of n_{tot} and $B_\parallel$ for double-layer $\nu=1$ QH state at $\sigma=0$ (Ref. 16). d/l, where l represents the magnetic length, is also indicated on the right axis. Data in (a) and (b) are taken along the arrow in (c).

with a constant pseudospin configuration. This is consistent with the rapid increase in R_{xx} and its gradual decay with increasing $B_\parallel$ [Fig. 3(b)]. $B_\parallel=4.9$ T for the peak in R_{xx} is the in-plane field where solitons start to overlap each other. Conversely, between $B_\parallel^{\text{C-IC}}=4.5$ and 4.9 T solitons are separated and expected to cause a dissipation by the thermal fluctuation of solitons[14] (expressed as "dissipative" SL in Ref. 16).

Read[9] has suggested the behavior of the energy gap of the $\nu=1$ QH state at the C-IC transition point. Since thermal fluctuations of solitons destroy the QH state, the energy gap of the QH state is strongly affected by the charged excitation mode of the SL. In the IC phase near the C-IC transition, where Q_s is small, the arrays of solitons are soft in the direction perpendicular to the solitons. In this region, the excitation of the QH state is a collective mode of the SL that has a lower Δ.[9] As Q_s increases, the texture of the pseudospins become uniform as the SL approaches to the constant IC phase, thus the pseudospins gradually retrieve their stiffness, resulting in an increase in Δ. As a result, the calculated energy gap shows a symmetric downward square-root cusp at the transition point. This behavior is observed at higher n_{tot}

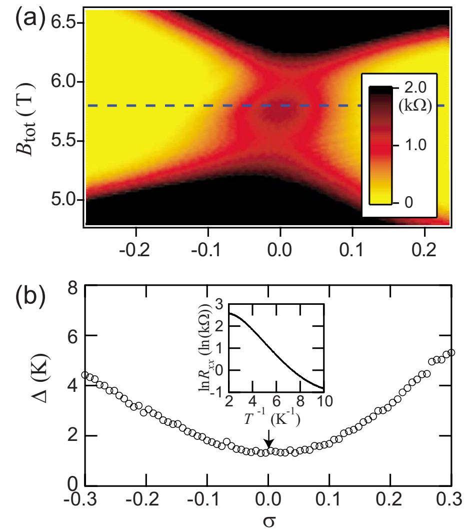

FIG. 4. (Color online) (a) Color-scale plot of R_{xx} as a function of σ and B_{tot}. Total density $n_{\text{tot}}=0.9\times10^{11}$ cm^{-2} and tilting angle $\theta=52.7°$ are fixed and the temperature is 60 mK. The yellow (light) and black (dark) regions represent small and large R_{xx}, respectively. Dashed line indicates a constant filling factor $\nu=1$. (b) Activation energy gap Δ of the $\nu=1$ QH state as a function of σ at $n_{\text{tot}}=0.8\times10^{11}$ cm^{-2} and $\theta=53.6°$. In the inset, an Arrehnius plot at $\sigma=0$ (indicated by an arrow) is presented.

area until around $n_{\text{tot}}=1.2\times10^{11}$ cm^{-2}. However, at lower n_{tot} area, this is not perfectly consistent with the observed broad minimum of Δ [Fig. 3(a)]. This inconsistency is probably due to disorder effects. Read[9] pointed out that even a small amount of disorder can destroy the long-range order of solitons and affect the charged excitation of the system especially around the transition point. Also, there exist several theoretical studies about disorder in single-layer system.[21–24] For example, Murthy[21] attributes the recent experimental result of imperfect spin polarization in the single-layer $\nu=1$ QH state[25] to disorder effects. The incompleteness of spin polarization decreases the exchange energy locally, thus the spin stiffness of the ground state is reduced. This effect can be applied to pseudospins in the double-layer $\nu=1$ state, in which pseudospin polarization is a decisive factor for the C-IC transition since the transition point is expressed as $(4/\pi)\times\sqrt{\Delta_{\text{SAS}}\pi l^2/\rho_{\text{ps}}}$, where ρ_{ps} is the pseudospin stiffness. Here, ρ_{ps} is reduced by the local incompleteness of the pseudospin polarization. Thus, microscopically, it is possible that the transition occurs independently at each local point of the sample. In Ref. 21, it is also shown that disorder reduces the energy gap of skyrmions in the $\nu=1$ QH ferromagnet. Again we can apply this effect to the charged excitation in the double layer $\nu=1$, that is, a meron pair of pseudospins. These local disturbances of the transition point and energy gap affects the macroscopic transport, therefore the cusp behavior of the energy gap becomes broad.

We also investigate effects of the density imbalance on the SL. Figure 4(a) shows R_{xx} in a color-scale plot as a function of σ and B_{tot} (Ref. 26) with n_{tot} and θ are fixed to the C-IC transition point at $\sigma=0$. The SL appears in a black (dark) region around $\sigma=0$. As σ is increased, R_{xx} at $\nu=1$ becomes smaller and the yellow (light) region for $R_{xx}\sim0$

becomes wider. At the same time, Δ gradually increases as σ increases [Fig. 4(b)]. These data indicate that the SL phase is unstable with respect to σ. Although σ suppresses ρ_{ps}, its σ dependence ($\propto\sqrt{1-\sigma^2}$) is too weak to explain the results.

A theory concerning the C-IC transition in a density imbalanced system predicts a lattice of rippled solitons in the IC phase.[27] In the rippled state, both the out-of-plane and in-plane components of pseudospins rotate around a flux. Because of the out-of-plane component of pseudospins, interactions between solitons are modified and the lattice formation may be suppressed within our experimental range. To clarify this, capacitance measurements between the layers suggested by the theory[27] are required. Furthermore, recent experiments[28–32] imply that the real spin degree of freedom is not ignorable in the double-layer $\nu=1$ system and its effect becomes more important when σ is increased.[28,31] Inclusion of the spin degree of freedom in solitons would also modify interactions between solitons, which may explain the experimental results about the σ dependence of Δ in the SL.

Finally, we briefly comment on the Kosterlitz-Thouless (KT) transition[33] of the SL. Since the SL spontaneously breaks the translational symmetry of the two-dimensional system, the KT transition is expected to appear.[9,13,15] When the temperature is higher than a critical temperature, the SL is expected to melt into a randomly distributed array because of unbound dislocations. While the melting of the lattice is suggested to be detected by an abrupt increase in R_{xx},[13,15] the temperature dependence of R_{xx} [inset of Fig. 4(b)] does not show such a critical behavior. Further investigations using various samples with different Δ_{SAS} and d for various n_{tot} are necessary to clarify this important issue.

In conclusion, we have reported the behavior of R_{xx} and Δ at the C-IC transition point in the double-layer $\nu=1$ QH state. From the $B_{\parallel}$ dependence of R_{xx} and Δ and the comparison with theories, we suggest that a pseudospin domain structure, i.e., the soliton lattice, is formed in the IC phase. The observed minimum in Δ of the $\nu=1$ QH state can be ascribed to the collective excitation mode of the SL. We have also found that the SL is unstable with respect to σ.

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