Phase Transition to Insulating State from Quantum Hall State by Current-Induced Nuclear Spin Polarization

S. Tsuda1†, Minh-Hai Nguyen1, D. Terasawa2, A. Fukuda2, and A. Sawada3

1Department of Physics, Graduate School of Science, Kyoto University, Kyoto 606-8502, Japan
2Department of Physics, Hyogo College of Medicine, Nishinomiya 663-8501, Japan
3Research Center for Low Temperature and Materials Sciences, Kyoto University, Kyoto 606-8501, Japan

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We investigate the resistance enhancement state (RES) where the magnetoresistance of the ν = 2/3 fractional quantum Hall state (FQHS) is increased with dynamic nuclear spin polarization (DNP) induced by a large electric current. After inducing DNP, we measure the temperature dependence of the magnetoresistance by a small current over a short period of time. We find that the FQHS makes a phase transition to an insulating state. By measuring the Hall resistance in the insulating state, we find that the RES exhibits a quantized Hall resistance. We discuss the RES in association with the Anderson localization.

KEYWORDS: semiconductor, quantum Hall state, fractional quantum Hall state, nuclear spin polarization, domain, Wigner crystal, insulator, Anderson localization

When subjected to a strong perpendicular magnetic field at low temperatures, a two-dimensional electron system (2DES) displays novel collective states arising from the dominance of the Coulomb interaction energy over the kinetic energy and the degree of freedom of the spins. Under a high magnetic field, when the electrons occupy the lowest Landau level, the 2DES exhibits fractional quantum Hall states (FQHSs). The FQHSs show not only a variety of phenomena originating from Coulomb interaction but also spin-related phenomena due to the spin degree of freedom.1,2 For example, the ν = 2/3 quantum Hall state (QHS) has two ground states with different spin polarizations.3 At the spin phase transition point of the ν = 2/3 QHS, an anomalous magnetoresistance $R_{xx}$ peak with hysteretic transport was observed by Kronmüller et al.4 The RF-irradiation experiment with a nuclear magnetic resonance and relaxation measurements has suggested that the enhancement of the magnetoresistance at the ν = 2/3 QHS is proportional to the degree of nuclear spin polarization. Thereafter, resistively detected nuclear magnetic resonance and relaxation measurements became excellent techniques for the study of the spin state of various exotic QHSs such as the Goldstone mode of the Skyrmion lattice near the ν = 1 QHS,5 the canted antiferromagnetic phase in the bilayer ν = 2 QHS,7 and the spin polarization in the even-denominator fractional ν = 5/2 non-Abelian QHS.8

Up to now, the mechanism of the $R_{xx}$ enhancement has been understood as follows: at the spin transition point, the two fractional quantum Hall states with different spin polarizations degenerate energetically in the composite Fermion model,5,9 and an electronic domain structure is formed.4,10,11 It is believed that when a current passes across a domain boundary, electron spins flip-flop scatter nuclear spins causing dynamic nuclear spin polarization (DNP), which in turn affects the domain formation and increases the length of the domain boundaries.10,11 In addition, an anisotropy of the hysteretic transport for the angle between current direction and in-plane magnetic field around the transition point in a tilted magnetic field was found.12 This suggests that the dynamics of electron spin domains is affected by the current direction for the in-plane field. However, details of the domain structure are still unclear, and the real cause of the magnetoresistance enhancement remains a riddle even now.

A previous experiment has shown that the resistance-enhanced state (RES) is not stable and decays over roughly several hundred seconds.12 In this work, the measurement of the resistance is performed much faster than the decay time of RES. In order to avoid the heating effect due to the current, we change the measuring current to a sufficiently small value. Moreover we measure the temperature dependence of the $R_{xx}$ of RES within a short time after pumping the nuclear spin polarization with a large current of 60 nA. With this new method, we find that the magnetoresistance of RES has a negative temperature gradient. By investigating the $R_{xx}$ and the Hall resistance $R_{xy}$ in the RES as a function of ν, the RES is found to indicate a quantized Hall resistance. We explain the quantized Hall resistance as the property of the FQHS domain surrounded by the Anderson localized state.

The sample employed in our experiments consists of two 20-nm-thick GaAs/AlGaAs quantum wells that have been processed into a 50-μm-wide Hall bar with a voltage probe distance of 180 μm. We use the front layer and deplete electrons in the back layer. This sample was previously used for the experiment on interlayer diffusion of the nuclear spins.13 The electron density n is controlled by the gate voltage. The low temperature mobility is $2.2 \times 10^6$ cm²/V·s with n = $2.0 \times 10^{11}$ cm⁻². The sample is placed inside a mixing chamber filled with liquid helium in a dilution refrigerator with a base temperature of 62 mK. We measure the $R_{xx}$ and $R_{xy}$ with a standard low-frequency AC lock-in technique at a frequency of 37.7 Hz. The magnetic field is applied by a superconduct-
ing magnet with a maximum field of 13.5 T. The measurement is performed at 7.19 T; therefore, the phase transition of the ν = 2/3 QHSs just arise. A RuO₂ resistance calibrated in the magnetic field is used as a thermometer, and a heater is placed near the sample immersed in the liquid helium of the mixing chamber.

Figure 1(a) shows the hysteretic behavior of Rₓₓ around the ν = 2/3 QHS. The front gate voltage is swept to change ν. The thick red (blue dotted) line shows Rₓₓ as a function of ν around ν = 2/3 with an AC current of 5 nA and a upward (downward) sweep speed of dv/dt = 1 × 10⁻² s⁻¹. No hysteretic behavior is seen, and the Rₓₓ peak of the spin phase transition point is clearly observed. The thin red (blue broken) line represents the upward (downward) sweep with dv/dt = 1 × 10⁻⁴ s⁻¹ and a large current, I = 30 nA. The hysteretic behaviors of Rₓₓ are seen around the spin transition point with slow sweep and high current.

These results are similar to previous reports about the hysteretic behavior. At ν = 0.65 (the dotted straight line in Fig. 1(a), where the enhancement of Rₓₓ is large, we perform DNP with a 60 nA current continuously and at 1,800 s change the current to 5 nA. By pumping nuclear spin polarization, Rₓₓ increases for about 500 s and saturates. After pumping, sudden change of the measuring current to small value of 5 nA to avoid the self-heating effect, the Rₓₓ is enhanced by a factor of two (the blue square in Fig. 1(b))

In the next step, to investigate the temperature dependence of the Rₓₓ in the RES, we increase quickly the temperature of the mixing chamber containing the sample with the heater within 50 s after DNP. The solid blue triangles represent the temperature dependence of Rₓₓ before DNP. The slope gives an activation energy gap of about Δ = 15 mK when analyzed with the Arrhenius formula. The red squares are the data after DNP with a current of 60 nA and 37.7 Hz AC current. The notable feature is that the data after DNP indicate a negative gradient for the temperature dependence.

To determine which explanation is more appropriate, we measure the temperature dependence of Rₓₓ in a different way, using the self-heating effect of the probing current. Figure 3(a) shows the Rₓₓ in the RES as a function of the probing current. The reference current for measuring Rₓₓ is 5 nA. The measurement procedure is as follows: 1) set ν = 0.65 and pump DNP at 60 nA for 1,800 s; 2) decrease the current to 5 nA and measure Rₓₓ; 3) change the current to arbitrary values I_meas; 4) measure Rₓₓ for several different values of I_meas in a total time of about 20 s; 5) decrease the current to 5 nA and measure Rₓₓ; 6) reset the RES using the Goldstone mode of the Skyrmion crystal state, where the polarization quickly relaxes to the equilibrium value when the filling factor is changed to ν = 0.85; 7) go back to 1) and repeat. Because the values measured at the reference current in steps 2) and 5) are in good agreement, the RES does not change during the measurements for the various currents. The sample temper-
The temperature of the 2DES is estimated under the assumption that the same energy input yields the same temperature increase in any kind of QHS. To get the relation between the power $P$ and the sample temperature $T$, we use the $\nu = 1/3$ QHS. The procedure is as follows: 1) we measure the temperature dependence of $R_{xx}$ at 1 nA by increasing the temperature of the mixing chamber; 2) we measure $R_{xx}$ for various currents; and 3) we compare 1) and 2) to determine the power dependence of the sample temperature $T_{\text{eff}}(P)$. The inset of Fig. 4(a) shows the plot of the $T_{\text{eff}}$ against the resistive heating $P = R_{xx}I^2$. Fig. 4(b) shows the result of calibrating the electric power to the sample temperature for Fig. 3. We assume that same $R_{xx}$ value is associated with the same temperature value, for instance, 300 mK in Fig. 2 corresponds to 240 mK in Fig. 4(b). Here the temperature difference is 20%. One cause of this difference is likely to be the lack of the thermal equilibrium between the sample and the thermometer, which is a potential difficulty, in any experiment using a heater. As for other cause, the calibration curve of $T_{\text{eff}}(P)$ may be inaccurate at the insulating phase. The inspections of the calibration curve are nice result checked in the $R_{xx}$ of any quantum Hall state (Fig. 4(a)). But it may be necessary to inspect whether it is possible under the conditions to have the characteristic of an insulating state, because the RES indicate the negative temperature gradient. Although there is a discrepancy of 20%, both measurements indicate that the temperature derivative of the magnetoresistance is negative.

To clarify the intrinsic properties of the RES at $\nu = 2/3$, we measure the magnetoresistance and the Hall resistance simultaneously in the RES as a function of the filling factor. In Fig. 5, the $R_{xx}$ before and after DNP are plotted for measuring current values of 5 nA and 60 nA. The broken vertical line is located at $\nu = 0.65$, where the DNP is carried out. For the entire range of $\nu$, the $R_{xx}$ before DNP with 5 nA is lower than the one with 60 nA. Since the sample temperature is proportional to the heating effect by the DNP current, the QHS is developed for the entire range of $\nu$ before DNP. However, after DNP, the differential coefficient of $R_{xx}$ to the temperature takes negative values for $0.5 \leq \nu \leq 0.68$; that is, the novel insulator state arises. In Fig. 5(b), the Hall resistance coincides approximately with a quantized value of $3h/2e^2$, not only in the QHS but also in the insulating state of the RES.

Here, we discuss the mechanism for the insulating properties of the RES. One of the candidates for the insulating phase is a Wigner crystal that manifests itself at $\nu < 1/7$ using the high mobility samples. The RES is induced by effectively increasing the disorder caused by the nuclear spin polarization that acts as electron scattering centers. Since this disorder destroy the long-range order of the Wigner crystal, the possibility of the Wigner crystal forming in this experiment is quite low. Another candidate is a stripe phase, which has the same temperature dependence as the insulating phase. However, it is unlikely that the stripe phase will appear, because it grows in a unidirectional potential or an in-plane magnetic field only in high mobility samples. The Mott insulator is also a candidate for the insulating phase. Since $R_{xy}$ diverges in the Mott insulator, this state is eliminated as a candidate. Now we try to find another possibility. Kagalovsky...
The localization length can be derived using Eq. (2), where plotting the data of Figs. 4 as log \( R \) versus \( T^{-1/2} \) for DNP. After DNP, the FQHS puddles disappear, and the Anderson insulating phase extends all over the 2DES. A similar state has been observed in the low mobility 2DES\(^{20}\) and is called the quantized Hall insulator.

In summary, we measured the temperature dependence of the enhanced magnetoresistance pumped by the electric current. Our results indicate that the enhanced resistance state is a novel insulating phase that appears as a result of a phase transition from the QHS induced by dynamic nuclear spin polarization. Anderson localization is enhanced by a number of tiny polarized nuclear spins acting as impurities. By investigating the magnetoresistance and the Hall resistance in the RES, the insulating state is found to be the quantized Hall resistance. We explained the quantized Hall resistance by a model in which FQHS puddles are surrounded by an Anderson insulating phase.

Acknowledgments

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\[ C = 6 \] in a 2DES\(^{20}\) Thus the localization length is estimated to be approximately \( 1.1 \mu m \). As the localization length is much smaller than the size of the Hall bar, a strongly localized system dominates, namely an insulating state.

Lastly, we discuss the quantization of the Hall resistance in the insulating state. Shimshoni and Auerbach\(^{29}\) interpreted the coexistence of the quantized \( R_{xx} \) and insulating \( R_{xx} \) with a model in which FQHS "puddles" are surrounded by an insulating phase and connected to one another by tunnel junctions.

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1) Z. F. Ezawa: Quantum Hall Effects: Field Theoretical Approach and Related Topics (World Scientific, Singapore, 2000).
2) S. M. Girvin and A. H. MacDonald: in Perspectives in Quantum Hall Effects, ed. A. Pinczuk and S. Das Sarma (Wiley, New York, 1997).
3) J. P. Eisenstein, H. L. Stormer L. N. Pfeiffer and K. W. West: Phys. Rev. B 41 (1990) 7910.
4) S. Kronmüller, W. Dietsche, J. Weiss, K. von Klitzing, W. Wegscheider and M. Bichler: Phys. Rev. Lett. 81 (1998) 2526.
5) S. Kronmüller, W. Dietsche, K. von Klitzing, G. Denninger, W. Wegscheider and M. Bichler: Phys. Rev. Lett. 82 (1999) 4070.
6) K. Hashimoto, K. Muraki, T. Saku and Y. Hirayama: Phys. Rev. Lett. 88 (2002) 176601.
7) N. Kumada, K. Muraki and Y. Hirayama: Science 313 (2006) 329.
8) L. Tiemann, G. Gamez, N. Kumada and K. Muraki: Science 335 (2012) 828.
9) N. Kumada D. Terasawa, Y. Shimoda, H. Aizuha, A. Sawada, Z.F. Ezawa, K. Muraki, T. Saku and Y. Hirayama: Phys. Rev. Lett. 89 (2002) 116802.
10) O. Stern, N. Freytag, A. Faye, W. Dietsche, J. H. Smet, K. von Klitzing, D. Schuh and W. Wegscheider: Phys. Rev. B 70 (2004) 075318.
11) S. Kraus, O. Stern, J.G.S. Lok, W. Dietsche, K. von Klitzing, M. Bichler, D. Schuh and W. Wegscheider: Phys. Rev. Lett 89 (2002) 266801.
12) K. Iwata, M. Morino, A. Fukuda, N. Kumada, Z. F. Ezawa, Y. Hirayama...
13) M. H. Nguyen, S. Tsuda, D. Terasawa, A. Fukuda, Y. D. Zheng, and A. Sawada: cond-mat/1309.5185.
14) K. Hashimoto, K. Muraki, N. Kumada, T. Saku and Y. Hirayama: Phys. Rev. Lett. 94 (2005) 146601.
15) J. G. S. Lok, S. Kraus, O. Stern, W. Dietshe, K. von Klitzing, W. Wegscheider, M. Bichler and D. Schuh: Physica E 22 (2004) 138.
16) V. Bayot, E. Grivei, S. Melinte, M. B. Santos and M. Shayegan: Phys. Rev. Lett. 76 (1996) 4584.
17) J. Amrit and J. P. Thermeau: Proc. 25th Int. Conf. on Low Temperature Physics J. Phys. Conf. Ser 150 (2009) 032002.
18) K. Yang, F. D. M. Haldane and E. H. Rezayi: Phys. Rev. B 64 (2001) 081301.
19) V. J. Goldman, M. Shayegan and D. C. Tsui: Phys. Rev. Lett. 61 (1988) 881.
20) N. Shibata and D. Yoshioka: J. Phys. Soc. Jpn. 72 (2002) 664.
21) T. Okamoto, K. Hosoya, S. Kawaji and A. Yagi: Phys. Rev. Lett. 82 (1999) 3875.
22) M. P. Lilly, K. B. Cooper, J. P. Eisenstein, L. N. Pfeiffer and K. W. West: Phys. Rev. Lett. 82 (1999) 394.
23) A. Endo, N. Shibata and Y. Iye: J. Phys. Soc. Jpn. 79 (2010) 103707.
24) S. Kivelson, D. H. Lee and S. C. Zhang: Phys. Rev. B 46 (2001) 2223.
25) V. Kagalovsky and I. Vagner: Phys. Rev. B 75 (2007) 113 304.
26) Y. Ono: J. Phys. Soc. Jpn. 51 (1982) 237.
27) G. Ebert, K. von Klitzing, C. Probst E. Schubert, K. Ploog and G. Weimann: Solid State Commun. 45 (1983) 625.
28) N.L. Nguen Van Lien: Sov. Phys. Semicond. 18 (1984) 207.
29) E. Shimshoni and A. Auerbach: Phys. Rev. B 55 (1997) 9817.
30) M. Hilke, D. Shahar, S.H. Song, D.C. Tsui, Y.H. Xie and Don Monroe: Nature 395 (1998) 675.