Dynamic nuclear polarization induced by breakdown of fractional quantum Hall effect

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We study dynamic nuclear polarization (DNP) induced by breakdown of the fractional quantum Hall (FQH) effect. We find that voltage-current characteristics depend on current sweep rates at the quantum Hall states of Landau-level filling factors $\nu=1$, 2/3, and 1/3. The sweep-rate dependence is attributed to DNP occurring in the breakdown regime of FQH states. Results of a pump and probe experiment show that the polarity of the DNP induced in the breakdown regimes of the FQH states is opposite to that of the DNP induced in the breakdown regimes of odd-integer quantum Hall states.

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Two-dimensional electron systems (2DESs) subjected to perpendicular magnetic fields exhibit the integer quantum Hall (QH) effect (QHE) with vanishing longitudinal resistance and quantized Hall resistance.[1] When a bias current applied to a 2DES exceeds a critical current (I_c), the quantum Hall conductor becomes unstable against the excitation of electron-hole pairs and, therefore, the longitudinal resistance increases abruptly.[2–5] This phenomenon is referred to as the QHE breakdown.

In the case of breakdown of a QH state with an odd-integer Landau-level filling factor ν, electrons in the spin-up Landau subband are excited to the spin-down subband, along with up-to-down flips of electron spins. Since electron spins $\mathbf{S}$ interact with nuclear spins $\mathbf{I}$ via the hyperfine interaction $\mathcal{H}_{\text{hyperfine}}=A\mathbf{S}\cdot\mathbf{I}=A(S^+I^-+S^-I^+)/2+AS_zI_z$, where A is the hyperfine constant, electron-spin flips cause nuclear-spin flops. Dynamic nuclear polarization (DNP) in the breakdown of odd-integer QH states has been demonstrated in our recent studies.[6,7] Nuclear spins are polarized in the bulk part of the 2DES, as shown by an experiment using a device with Corbino geometry.[8]

Recent studies have revealed that fractional quantum Hall (FQH) states also break down when a bias current exceeds I_c.[9,10] Since the origin of the FQH effect, which is Coulomb interaction, is different from that of the integer QHE, it is unclear whether DNP also occurs in the breakdown regimes of FQH states. Furthermore, in FQH states, competition between the exchange energy and the Zeeman energy leads to the production of a wide variety of ground states with different electron-spin configurations.[11] The different configurations are expected to give rise to different DNP polarities.

In this Brief Report, we report that DNP occurs in the breakdown regimes of FQH states at $\nu=2/3$ and 1/3. Results of our study indicate that voltage-current characteristics depend on current sweep rates. The relationship between DNP and the sweep-rate dependence is confirmed by nuclear-magnetic-resonance (NMR) measurements. Furthermore, we determine the polarity and amplitude of the DNP by a pump and probe experiment. The DNP polarity is unexpectedly negative ($\langle I_z\rangle<0$) and is opposite to the polarity of DNP induced in the breakdown regimes of odd-integer QH states.[6]

We used a GaAs/$Al_{0.3}Ga_{0.7}$As single heterostructure wafer with a 2DES at the interface. The mobility and sheet carrier density of the 2DES at 4.2 K were $\mu=228\ \text{m}^2\,\text{V}^{-1}\,\text{s}^{-1}$ and $n=1.59\times10^{15}\ \text{m}^{-2}$, respectively. The wafer was processed into a 20-μm-wide Hall bar covered with a front-gate electrode, as shown in Fig. 1(a). This electrode was used to change the Landau-level filling factor of the 2DES. Figure 1(b) shows a grayscale plot of the longitudinal resistance R_{xx} as a function of the external magnetic field B and Landau-level filling factor ν. The resistance peak observed in the $\nu=2/3$ FQH state at around $B=5.2$ T corresponds to the spin transition, as reported in previous studies.[12,13] The QH states on the low and high magnetic field sides of the transition are spin-unpolarized and spin-polarized phases, respectively.

The dashed curve in the inset of Fig. 2(a) represents a voltage-current (V_{xx}-I) characteristic curve at $B=6.26$ T and $\nu=1$ [D in Fig. 1(b)]. The current was increased at a rate of 6.8 nA/s. When the bias current I exceeds a critical value $I_c=1.4\ \mu$A, the longitudinal voltage V_{xx} increases abruptly. As mentioned earlier, this phenomenon is referred to as the QHE breakdown. The V_{xx}-I characteristic curve represented by the solid curve in the inset of Fig. 2(a) was obtained by increasing the current with a sweep rate of 0.4 nA/s. The QHE breaks down at a smaller I_c when the sweep rate is decreased. The sweep-rate dependence of the V_{xx}-I characteristic can be attributed to the DNP, as in the case of the hysteretic V_{xx}-I curves in our previous study:[6] in the breakdown regimes of odd-integer QH states, electrons are excited to higher Landau levels and nuclear spins are dynamically polarized by the up-to-down flips of electron spins. The polarized nuclear spins reduce the spin-splitting energy $E_s=|g^*|\mu_B B-A\langle I_z\rangle$, where g^* is the effective g factor of electrons ($g^*=-0.44$ in GaAs) and μ_B is the Bohr magneton. Since the energy gap of odd-integer QH states is given by the sum of E_s and exchange energy, the reduction in E_s accelerates the QHE breakdown resulting in the shift of V_{xx}-I curves toward the small current side.[6]

Figure 2(a) shows the V_{xx}-I curves obtained in the case of a spin-polarized FQH state at $B=6.26$ T and $\nu=2/3$ [E in Fig. 1(b)]. The current sweep rates were 6.8 and 0.05 nA/s for the dashed and solid curves, respectively. As observed at $\nu=1$, V_{xx} increases when the current exceeds a critical value.

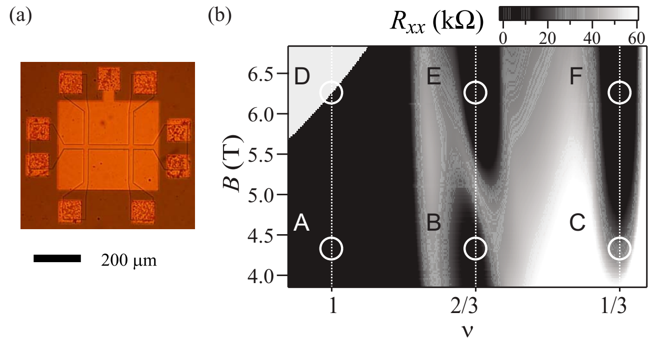

FIG. 1. (Color online) (a) Micrograph of the Hall bar device used in the present study. (b) Grayscale plot of the longitudinal resistance R_{xx} as a function of the external magnetic field B and the Landau-level filling factor ν at 20 mK. R_{xx} was measured by using a standard ac lock-in technique at an excitation current of $I_{ac}=1$ nA (18 Hz). The black regions represent quantum Hall states. Pump and probe measurements were performed at the conditions indicated by circles (A–F).

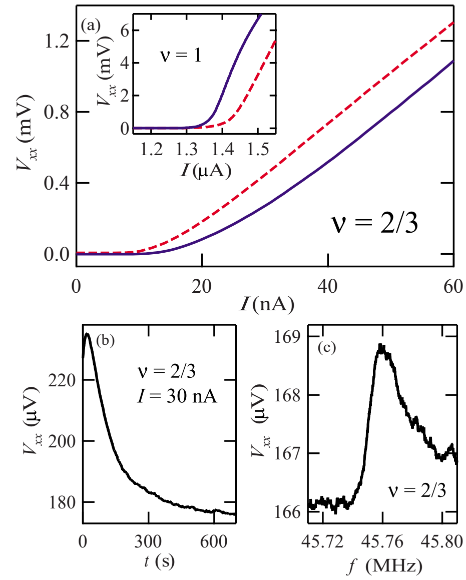

FIG. 2. (Color online) (a) V_{xx}-I curves obtained at $\nu=2/3$ and $B=6.26$ T [E in Fig. 1(b)]. The current sweep rates were 6.8 (dashed curve) and 0.05 nA/s (solid curve). The inset shows V_{xx}-I curves obtained at $\nu=1$ and $B=6.26$ T [D in Fig. 1(b)] with current sweep rates of 6.8 (dashed curve) and 0.4 nA/s (solid curve). (b) Time evolution of V_{xx} after a sudden increase in I from 0 to 30 nA. (c) NMR spectrum of ^{75}As detected by measuring V_{xx} at $\nu=2/3$ and $I=30$ nA.

This indicates the breakdown of the FQH effect. The FQH effect breaks down at a larger I_c when the sweep rate is decreased. The sweep-rate-dependent V_{xx}-I characteristics appear similar to those observed in the breakdown regime of the $\nu=1$ QH state except for the direction of the shift of the V_{xx}-I curves. Figure 2(b) shows the time evolution of V_{xx} at the $\nu=2/3$ spin-polarized FQH state after a sudden increase in I from 0 to 30 nA. The value of V_{xx} decreases slowly over a period of 600 s, which is a typical time scale for nuclear-spin-related phenomena.[6,14–16] Thus, the slow evolution of V_{xx} and the sweep-rate-dependent V_{xx}-I curves indicate that DNP occurs in the breakdown regime of the FQH state.

The relationship between the DNP and the sweep-rate-dependent V_{xx}-I characteristics and slow evolution of V_{xx} was determined by NMR measurements as follows. In order to apply a rf magnetic field B_{rf} perpendicular to the external magnetic field B (parallel to the 2DES), we wound a single-turn coil around the Hall bar device. As the frequency of B_{rf} was scanned, V_{xx} peaked at the NMR frequencies of ^{75}As, as shown in Fig. 2(c). NMR spectra of ^{69}Ga and ^{71}Ga were also obtained. Similar sweep-rate dependence in V_{xx}-I characteristics and NMR were observed at all the QH states investigated [A–F in Fig. 1(b)]. The detection of NMR by the voltage measurements definitely revealed the occurrence of DNP in the breakdown regimes of the FQH states.

It should be noted that the DNP observed in this study is different from the well-known DNP (Refs. 16–21) occurring near the spin transition at $\nu=2/3$. It has been suggested that the DNP near the spin transition is induced by electron scattering between spatially distributed spin-polarized and spin-unpolarized domains.[17,18] Therefore, the coexistence of spin-polarized and spin-unpolarized domains is considered a prerequisite for the DNP near the spin transition. In contrast, the DNP observed in this study occurs in the breakdown regime of the FQH states away from the spin transition point. In this condition, the spin configuration of the FQH system is not affected by the spin transition and the complex spin-domain structure does not exist. We think that a mechanism other than the interspin-domain scattering[17,18] is needed to understand the DNP observed in this study.

As shown in Fig. 2(a), the V_{xx}-I curves shift as the DNP occurs. The directions of the shifts at $\nu=2/3$ and $\nu=1$ are opposite to each other; this indicates that the DNP polarities are different. Therefore, in order to investigate the polarities of DNP more systematically, we conducted the pump and probe experiment. First, the 2DES was temporarily set to a breakdown state (ν_{pump},I_{pump}) for a duration τ_{pump} in order to induce DNP. Next, the bias current was turned off and the filling factor was suddenly changed to $\nu_{probe}=1$ by using the front-gate electrode. Then the I_c value of the $\nu_{probe}=1$ QH state was measured by increasing the bias current.[22] Since the I_c value is expected to change in accordance with $\langle I_z \rangle$, we can determine the polarity and amplitude of DNP induced at ν_{pump}.[23]

The inset of Fig. 3(a) shows V_{xx}-I curves obtained at $\nu=1$ after inducing DNP at $(\nu_{pump},I_{pump})=(1,1400$ nA) and $B=6.26$ T [D in Fig. 1(b)] for several values of τ_{pump}. The rightmost curve (black) represents the results obtained without inducing DNP ($\tau_{pump}=0$ s) and the leftmost curve (red) represents the results obtained after inducing DNP for $\tau_{pump}=360$ s. The horizontal shift ΔI_c of the V_{xx}-I curve defined at $V_{xx}=2$ mV is plotted as a function of τ_{pump} [closed triangles in Fig. 3(b)]. ΔI_c decreases with increasing τ_{pump}. This indicates that the decrease in ΔI_c can be attributed to the DNP.

The main panel of Fig. 3(a) shows V_{xx}-I curves obtained at $\nu=1$ after inducing DNP at $(\nu_{pump},I_{pump})=(2/3,30$ nA) and $B=6.26$ T [E in Fig. 1(b)] for several values of τ_{pump}. The curves shift to higher currents with increasing τ_{pump}. The τ_{pump} dependence of ΔI_c is indicated by solid squares in Fig. 3(b). ΔI_c increases with τ_{pump}. It should be noted that ΔI_c

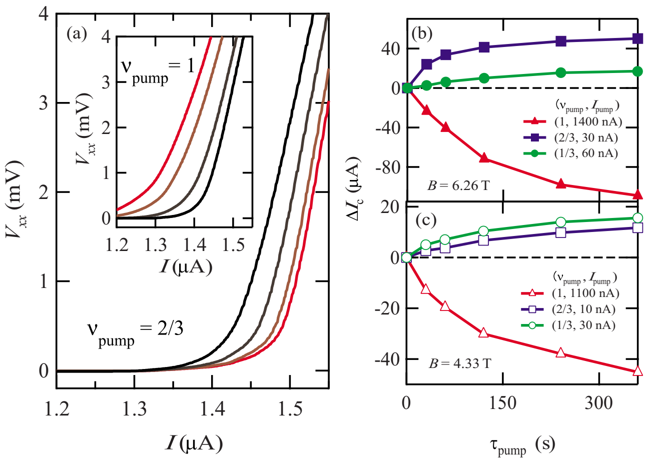

FIG. 3. (Color online) (a) V_{xx}-I curves obtained at $\nu=1$ and $B=6.26$ T after inducing DNP at $(\nu_{\text{pump}},I_{\text{pump}})=(2/3,30\ \text{nA})$ for τ_{pump} values of 0, 30, 120, and 360 s (from left to right). Inset: V_{xx}-I curves obtained at $\nu=1$ after inducing DNP at $(\nu_{\text{pump}},I_{\text{pump}})=(1,1400\ \text{nA})$. The values of τ_{pump} are 0, 30, 120, and 360 s from right to left. (b) Horizontal shift ΔI_c of V_{xx}-I curves defined at $V_{xx}=2$ mV plotted as a function of τ_{pump} at $B=6.26$ T. Results obtained at $(\nu_{\text{pump}},I_{\text{pump}})=(1,1400\ \text{nA})$, (2/3,30 nA), and (1/3,60 nA) are represented by solid triangles, solid squares, and solid circles, respectively. (c) Similar data obtained at $B=4.33$ T. Results obtained at $(\nu_{\text{pump}},I_{\text{pump}})=(1,1100\ \text{nA})$, (2/3,10 nA), and (1/3,30 nA) are represented by open triangles, open squares, and open circles, respectively.

decreases when an rf magnetic field with NMR frequency is applied. Therefore, the nonzero values of ΔI_c indicate that DNP occurs in the breakdown regimes of the FQH states.[24] The data obtained on the spin-unpolarized phase at $B=4.33$ T [B in Fig. 1(b)] are shown by open squares in Fig. 3(c). The sign of ΔI_c is also positive for $B=4.33$ T. Similar data obtained for $\nu_{\text{pump}}=1/3$ at $B=6.26$ T [F in Fig. 1(b)] are shown by solid circles in Fig. 3(b). In this case also, ΔI_c increases with τ_{pump}.

Figure 4(a) shows V_{xx}-I curves obtained after inducing DNP at $(\nu_{\text{pump}},B)=(1/3,4.33\ \text{T})$ and several values of I_{pump} for $\tau_{\text{pump}}=600$ s. The V_{xx}-I curves shift horizontally with increasing I_{pump}. The values of ΔI_c are plotted as a function of I_{pump} in Fig. 4(c) (open circles). The horizontal shift ΔI_c is maximum at $I_{\text{pump}}=30$ nA. Qualitatively similar data are obtained for $(\nu_{\text{pump}},B)=(2/3,4.33\ \text{T})$, (2/3,6.26 T), and (1/3,6.26 T), as shown in Figs. 4(b), 4(d), and 4(e), respectively. In all cases, the amplitude of DNP increases steeply when I_{pump} exceeds I_c and is maximum when I_{pump} is slightly greater than I_c. The I_{pump} dependence of DNP in the breakdown regime of FQH states is similar to that observed in the breakdown regime of odd-integer QH states.[8] This similarity indicates that the origin of DNP occurring in the breakdown regimes of both FQH and odd-integer QH states is the same.

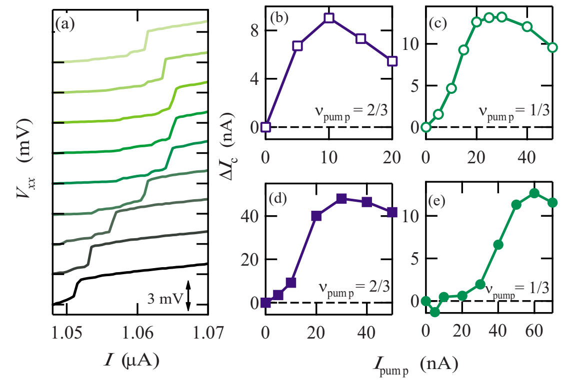

FIG. 4. (Color online) (a) V_{xx}-I curves obtained after inducing DNP at $(\nu_{\text{pump}},B)=(1/3,4.33\ \text{T})$ and $\tau_{\text{pump}}=600$ s with different pump currents $I_{\text{pump}}=0$, 5, 10, 15, 20, 25, 30, 40, and 50 nA (from bottom to top). The curves are offset vertically for clarity. (b)–(e) Horizontal shift ΔI_c of V_{xx}-I curves plotted as a function of I_{pump} at $(\nu_{\text{pump}},B)=(2/3,4.33\ \text{T})$, (1/3,4.33 T), (2/3,6.26 T), and (1/3,6.26 T), respectively.

We discuss the polarities of the DNPs occurring in the breakdown regimes of the FQH states. The positive signs of the ΔI_c values for $\nu_{\text{pump}}=2/3$ and 1/3 are opposite to those for $\nu_{\text{pump}}=1$. The positive sign of ΔI_c value shows that the energy gap of the $\nu_{\text{probe}}=1$ QH state increases due to DNP. Since $E_s=|g^*|\mu_B B-A\langle I_z\rangle$ increases due to negative DNP ($\langle I_z\rangle<0$), DNP with negative polarity is deduced from the positive ΔI_c value. The results in Figs. 3(b) and 3(c) show that DNPs with negative polarities are induced in the breakdown regimes of $\nu_{\text{pump}}=1/3$ and $\nu_{\text{pump}}=2/3$.

The negative DNPs for $\nu_{\text{pump}}=1/3$, opposite to the DNPs for $\nu_{\text{pump}}=1$ are unexpected because electron spins are fully polarized in both ground states. Furthermore, for $\nu_{\text{pump}}=2/3$, the signs of DNPs are the same (negative) both on the spin-unpolarized phase at 4.33 T and on the spin-unpolarized phase at 6.26 T [B and E in Fig. 1(b), respectively] despite of the difference in electron-spin configurations in the ground states. These results suggest that neither electron-spin configurations in the FQH ground states nor spin transitions are relevant to the polarity of DNP occurring in the breakdown regimes. In the breakdown regime, a number of electron-hole pairs are excited in the 2DES and the electron-spin configurations of the FQH ground states, which is based on subtle electron-electron correlation, are probably not maintained. We infer that spin dynamics of these excitations plays an important role to understand the mechanism of the DNPs occurring in the breakdown regimes.

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[22] The current was increased rapidly, so that DNP during the current sweep was negligible.
[23] DNPs induced at various ν_{pump} were detected at the fixed $\nu_{\mathrm{probe}}=1$, so that we can discuss the relative polarities and amplitudes of the DNPs.
[24] Electron heating effect leads to a decrease in the critical current I_c, whereas I_c increases in the present experiment.