Spatial gradient of dynamic nuclear spin polarization
induced by breakdown of quantum Hall effect

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We studied spatial distribution of dynamic nuclear polarization (DNP) in a Hall-bar device in a breakdown regime of the quantum Hall effect (QHE). We detected nuclear magnetic resonance (NMR) signals from the polarized nuclear spins by measuring the Hall voltage $V_{xy}$ using three pairs of voltage probes attached to the conducting channel of the Hall bar. We find that the amplitude of the NMR signal depends on the position of the Hall voltage probes and that the largest NMR signal is obtained from the pair of probes farthest from the electron-injecting electrode. Combined with results on pump-and-probe measurements, we conclude that the DNP induced by QHE breakdown develops along the electron-drift direction.

The current-driven breakdown of the quantum Hall effect (QHE) is a phenomenon, characterized by an abrupt increase of longitudinal resistance and a deviation of Hall resistance from the quantized resistance, when the electric current passing through a quantum Hall (QH) conductor exceeds a critical current $I_c$. The QHE breakdown has gained renewed interest because of the recent development of the dynamic nuclear spin polarization (DNP) technique in QHE breakdown regimes. It was demonstrated that nuclear spins in GaAs/AlGaAs heterostructures are dynamically polarized through the hyperfine interaction between electron spins and nuclear spins when the two-dimensional electron system (2DES) embedded in the heterostructure is driven to the breakdown regime of odd-integer QHE. Given its simplicity, the DNP technique can be useful for the initialization of nuclear spin quantum bits. Moreover, the back-action of the polarized nuclear spins on electrical transport coefficients of the 2DES makes it possible to perform extremely sensitive detection of nuclear magnetic resonance (NMR). Thus, the resistively detected NMR technique can be utilized to investigate the electron spin properties of QH systems.

Although QHE breakdown has been studied both theoretically and experimentally ever since the discovery of QHE, earlier experimental studies were mainly conducted at even-integer QHE where the spin degree of freedom is unresolved. In the case of even-integer QHE, QHE breakdown does not occur homogeneously in the QH conductor but develops over a macroscopic distance (typically 100 µm) along the electron-drift direction. The development of QHE breakdown over a macroscopic distance was directly observed in recent electronic properties at the intersection of a conducting channel and a pair of voltage probes. The spatial distribution of DNP can be resolved by measurements of longitudinal voltage measurements in which the signals were averaged over a macroscopic area between the voltage probes of the Hall bar. So far, no experimental result has been reported concerning the spatial distribution of DNP. In order to reveal the spatial distribution of DNP, it is necessary to detect DNP signals locally in the Hall bar.

In this paper, we report that the DNP induced by QHE breakdown is spatially distributed in a Hall-bar device. We detected NMR signals from the polarized nuclear spins by measuring the Hall voltage $V_{xy}$ using three pairs of voltage probes attached to the conducting channel of the Hall bar. Since the Hall voltage $V_{xy}$ reflects local electronic properties at the intersection of a conducting channel and a pair of voltage probes, the spatial distribution of DNP can be resolved by measurements of $V_{xy}$. We find that the amplitude of the NMR signal depends on the position of the Hall voltage probes and that the largest NMR signal is obtained from the pair of Hall voltage probes farthest from the electron-injecting electrode. Combined with results on pump-and-probe measurements, we conclude that the DNP induced by QHE...
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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 $\mu = 107$ m$^2$/V·s and $n = 2.23 \times 10^{15}$ m$^{-2}$, respectively. The wafer was processed into a 20-µm-wide Hall bar as shown in Fig. 1(c). Three pairs of Hall voltage probes were attached to the conducting channel of the Hall bar, each separated by 155 µm. The Hall-bar device was cooled down to a temperature of $T = 1.5$ K, and a magnetic field of $B$ was applied perpendicular to the 2DES. A single-turn coil wound around the device was used to irradiate a rf-magnetic field of $B_{rf}$ for NMR measurements.

Figures 1(d)-(f) show the dependence of $\Delta V_{xy}$, which is defined by $\Delta V_{xy} = h/e^2I - V_{xy}$, on the bias current $I$.

When $I$ is smaller than the critical current $I_c$, the Hall resistance $R_H = V_{xy}/I$ is quantized to $h/e^2$ and $\Delta V_{xy}$ is zero. When $I$ exceeds $I_c$, $R_H$ deviates from the quantized value to approach the classical Hall resistance $B/ne$ and $\Delta V_{xy}$ is expected to increase. Thus, $\Delta V_{xy}$ is a good quantity to probe QHE breakdown in a local region at the intersection of the conducting channel and the voltage probes. The data in Figs. 1(d)-(f) were obtained by sweeping $I$ up and down at a rate of 13.2 nA/s using the Hall voltage probes (d) A-$A'$, (e) B-$B'$, and (f) C-$C'$ with $B = 8.65$ T ($\nu = 1.07$). On the positive current polarity side where electrons are injected from the left electrode in Fig. 1(c), the value of $\Delta V_{xy}$ at probe C-$C'$ increases sharply as $I$ exceeds a critical current of about $I_c = 0.2$ µA [Fig. 1(f)]. The value of $\Delta V_{xy}$ at probe B-$B'$ [Fig. 1(e)] also increases above $I_c$, although the change in $\Delta V_{xy}$ is smaller than that at probe C-$C'$. The change in $\Delta V_{xy}$ at probe A-$A'$ [Fig. 1(d)] is almost zero. On the negative current polarity side, the above described trends are spatially reversed with respect to the center of the Hall bar: the change in $\Delta V_{xy}$ is largest at probe A-$A'$ and almost zero at probe C-$C'$ when the current polarity is negative. These systematic differences in the $\Delta V_{xy}$-$I$ curves show that QHE breakdown is more prominent in the region farther from the electron-injecting electrode.

The origin of this dependence of the $\Delta V_{xy}$-$I$ curves on the probe position can be attributed to the spatial gradient of $T_c$ in the QHE breakdown regime, similar to the earlier studies at even-integer filling factors. In addition, we observe hysteresis in the $\Delta V_{xy}$-$I$ curves, which is a signature of the DNP induced by QHE breakdown.

The spatial distribution of DNP was investigated by measuring NMR signals using the Hall voltage probe pairs A-$A'$, B-$B'$, and C-$C'$. Since the Hall voltage $\Delta V_{xy}$ reflects local electronic properties at the intersection of the conducting channel and the pair of voltage probes, the spatial distribution of DNP can be resolved by comparing the amplitudes of NMR signals obtained from each point.
pair of Hall voltage probes. The data shown in Figs. 2(a)-c were obtained at \( B = 8.65 \, T \) according to the following procedure. First, nuclear spins were polarized by applying a current of \( I = +0.8 \, \mu A \) through hyperfine interaction. Subsequently, \( V_{xy} \) was measured under irradiation of a continuous wave rf-magnetic field of \( B_d \). As the frequency of \( B_d \) was scanned, the value of \( V_{xy} \) decreased when the frequency matched the NMR frequency of \( ^{71} \text{Ga} (\gamma = 81.58 \, \text{rad-MHz/T}) \) as shown in Figs. 2(b) and (c). The amplitude of the NMR signal is the largest at probe C-C’, intermediate at probe B-B’, and zero at probe A-A’. The dependences of the NMR spectrum amplitude for \( ^{69} \text{Ga} (\gamma = 64.21 \, \text{rad-MHz/T}) \) and \( ^{75} \text{As} (\gamma = 45.82 \, \text{rad-MHz/T}) \) show a trend similar to that of \( ^{71} \text{Ga} \).

Figure 3 shows the amplitudes of NMR signals \( V_{\text{NMR}} \) plotted against the position \( x \) of the Hall voltage probes measured from the center of the Hall bar. Data obtained at various positive and negative values of \( I \) are plotted in Figs. 3(a) and (b), respectively. At \( I = 0.5 \, \mu A \) [bottom panel in Fig. 3(a)], a slight NMR signal is visible only at probe C-C’. With increasing \( I \), the amplitude of \( V_{\text{NMR}} \) increases at probes B-B’ and C-C’. The region where the NMR signal can be observed spreads toward the small \( x \) region with increasing \( I \), as shown in Fig. 3(a). Above \( I = 0.9 \, \mu A \), the \( V_{\text{NMR}} \) at probe B-B’ reaches a value close to that at probe C-C’, and the \( V_{\text{NMR}}-x \) curve saturates with increasing \( x \). When the polarity of \( I \) is reversed \((I < 0)\), the amplitude of \( V_{\text{NMR}} \) decreases with increasing \( x \) [Fig. 3(b)]. The \( V_{\text{NMR}}-x \) characteristics for each value of \( |I| \) with opposite current polarities are almost symmetric to each of their positive-polarity counterparts with respect to the center of the Hall bar. When the polarity of the magnetic field was reversed, this pattern of \( V_{\text{NMR}}-x \) characteristics did not change significantly (not shown).

Since the spatial pattern was changed by reversing the current polarity, inhomogeneity in the 2DES is excluded as the origin of the spatial dependence of \( V_{\text{NMR}} \). The edge channel transport also does not play a significant role in the \( V_{\text{NMR}}-x \) characteristics because the characteristics was not changed by reversing the magnetic field polarity. Therefore, the observed spatial gradient of \( V_{\text{NMR}} \) is attributed to the spatially distributed nature of the DNP induced by QHE breakdown. The observed dependence on current polarity dependence indicates that the amplitude of \( V_{\text{NMR}} \) increases as the distance from the electron-injecting electrode increases and that the saturation of the \( V_{\text{NMR}}-x \) curve occurs in the region distant from the electron-injecting electrode. These features are similar to the spatial distribution of electron temperature \( T_e \) discussed in earlier studies of QHE breakdown at even-integer \( \nu \). A gradual increase in \( T_e \) over a macroscopic distance along the electron-drift direction and saturation of \( T_e \) in a region sufficiently distant from the electron-injecting electrode [Fig. 1(b)]. This similarity suggests the relevance of the avalanche multiplication of excited electrons to the spatial distribution of DNP, supporting our proposed scenario. We think that avalanche multiplication produces the spatial distribution not only of \( T_e \) but also of electron spin flip events, which in turn leads to the spatial distribution of DNP through hyperfine interaction.

Finally, in order to unambiguously confirm that the absence of NMR signals at the voltage probe near the electron-injecting electrode is not due to poor sensitivity of \( V_{xy} \) to the DNP, we performed pump-and-probe-type measurements similar to those in earlier studies. DNP was induced by applying pumping current \( I_{\text{pump}} \) for a pumping time of \( t_{\text{pump}} \). The value of \( V_{xy} \) was measured at a probe current of \( I_{\text{probe}} = -0.5 \, \mu A \) using Hall voltage probes A-A’ before and after the pumping procedure. The change in \( V_{xy} \) at \( I_{\text{pump}} = 1.0 \, \mu A \), \( \delta V_{xy}(I_{\text{pump}}) = V_{xy}(I_{\text{pump}}, t_{\text{pump}}) - V_{xy}(I_{\text{pump}}, 0) \), is induced by the DNP pumping. As shown in the inset of Fig. 4, \( \delta V_{xy} \) increases gradually with increasing \( t_{\text{pump}} \) when \( I_{\text{pump}} = -0.6 \, \mu A \), whereas the change in \( V_{xy} \) is negligibly small when \( I_{\text{pump}} = -0.6 \, \mu A \). This result suggests that nuclear spins are not polarized in the region near the electron-injecting electrode even for a pumping current \( I_{\text{pump}} \) larger than the \( I_c \) of QHE breakdown. Figure 4 shows the dependence of \( \delta V_{xy} \) on \( I_{\text{pump}} \) for \( t_{\text{pump}} = 600 \, s \). The value of \( \delta V_{xy} \) increases only for \( I_{\text{pump}} < -0.5 \, \mu A \) where electrons are injected from the electrode farther from the voltage probe. These results unambiguously show that the absence of \( V_{\text{NMR}} \) at probe A-A’ un-
To summarize, we observe NMR signals in the breakdown regime of $\nu = 1$ QHE by measuring Hall voltages using three different pairs of Hall voltage probes attached to the conducting channel of a Hall bar. We find that the amplitude of the NMR signal becomes large as the distance from the electron-injecting electrode increases. Combined with results on pump-and-probe measurements, we conclude that DNP induced by QHE breakdown has a spatial gradient along the electron-drift direction in the Hall-bar device. The similarity in the spatial distribution between NMR signals and $T_e$ supports the scenario that the electron excitation between the spin-resolved Landau levels is relevant to the DNP. In the case of the breakdown of odd-integer QHE, both hyperfine and spin-orbit interactions cause the flips of electron spins to excite them into the upper Landau sub-band with opposite spin polarity. Given that only the contribution of the hyperfine interaction is probed by the NMR measurements, models of the QHE breakdown taking both spin-orbit and hyperfine interactions into account are required for a quantitative understanding of the spatial profile of $V_{\text{NMR}}$. We think that studies on the spatial distribution of DNP will give further insight into the mechanisms of DNPs reported under various conditions of integer fractional QH systems.

FIG. 4: Dependence of $\delta V_{xy}$ on $I_{\text{pump}}$, obtained by the pump-and-probe measurement described in the text. The pump duration $t_{\text{pump}}$ is fixed at 600 s. $\delta V_{xy}$ is defined as $\delta V_{xy} = V_{xy}(I_{\text{pump}}, I_0) - V_{xy}(I_{\text{pump}}, 0)$. The inset shows the dependence of $\delta V_{xy}$ on $t_{\text{pump}}$ for the cases of $I_{\text{pump}} = \pm 0.6 \mu$A.

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