Dynamic Nuclear Polarization in a Quantum Hall Corbino Disk

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Electrical polarization of nuclear spins is studied in a Corbino disk under a breakdown regime of the quantum Hall effect (QHE). Since the edge channels are completely absent in the Corbino disk, we conclude that the electric current flowing in the bulk channel of a quantum Hall conductor is relevant to dynamic nuclear polarization (DNP). A pump and probe measurement demonstrates that DNP emerges near the critical voltage of the QHE breakdown. The agreement of the onset voltage of DNP with that of the QHE breakdown indicates that the underlying origin of DNP is closely related to that of the QHE breakdown.

KEYWORDS: quantum Hall effect breakdown, dynamic nuclear polarization, hyperfine interaction

Breakdown of the quantum Hall effect (QHE) has been a subject of research interest not only for developing a QHE resistance standard but also for understanding fundamental physics of electron transport in quantum Hall (QH) systems. When the electric field applied to a two-dimensional electron gas (2DEG) exceeds a critical value $E_c$, the QH conductor becomes unstable against the excitation of electron-hole ($e$-$h$) pairs, leading to avalanche-type multiplication of the $e$-$h$ pairs. As a result, the dissipationless QH state breaks down and the longitudinal resistivity increases abruptly. According to the earlier works on QHE breakdown, the multiplication of $e$-$h$ pairs occurs due to inter-Landau-subband impact ionization; the electrons accelerated in the upper Landau subband collide with the other electrons in the lower subband and excite them to the upper subband (Fig. 1).

In our earlier work, we showed that dynamic nuclear polarization (DNP) is created in the breakdown regime of an odd-integer QHE. We observed hysteretic voltage-current characteristic curves and detected nuclear magnetic resonance by measuring the longitudinal voltage. As observed in the other experiments on DNP pumping, DNP is probably induced by the flip-flop process of electron spin $S$ and nuclear spin $I$ through the hyperfine interaction $\mathcal{H}_{\text{hyperfine}} = AS \cdot I = A(S^+I^- + S^-I^+)/2 + AS_zI_z$, where $A$ is the hyperfine constant. However, the detailed mechanism of DNP in QHE breakdown regimes has not been understood yet.

In order to discuss the mechanism of DNP, at least the following two important aspects of DNP should be clarified experimentally. The first question that arises is where is DNP created, and the second question that arises is whether DNP is created only in the QHE breakdown regime. It is natural to suppose that DNP is created in the bulk part of the 2DEG because electric current mainly flows in the QH bulk channel under the breakdown regime. On the other hand, however, it is well established that the nuclear spins can be polarized by scattering of electrons between the spin-resolved QH edge channels. Therefore, it is crucial to distinguish which channel is relevant to the DNP observed in the QHE breakdown regime. It is also important to clarify whether DNP is created only in the breakdown regimes or whether it is created in the QH regimes as well. If DNP is associated with the QHE breakdown, DNP should be created only when the bias electric field exceeds $E_c$. Thus, the bias electric field dependence of DNP gives a clue regarding the mechanism of DNP.

In this paper, we report that DNP is created in a QH Corbino disk where the edge channel transport is completely absent and that DNP emerges near the critical voltage of the QHE breakdown. The creation of DNP in the Corbino disk directly shows that DNP is created in the inner bulk part of the 2DEG and that the bulk channel current is relevant to DNP. Furthermore, the agreement of the onset voltage of DNP with that of the QHE breakdown suggests that the underlying origin of DNP is closely related to that of the QHE breakdown.

Experiments were conducted using a sample with Corbino geometry fabricated photolithographically from a wafer of GaAs/Al$_0.3$Ga$_0.7$As single heterostructure...
The temperature of 20 mK. An external magnetic field was applied perpendicular to the 2DEG plane by using a superconducting solenoid. The current between the inner and outer electrodes was measured using a standard dc method. A single-turn coil around the device was used to irradiate radio-frequency (rf) magnetic fields.

Figures 2(a)-2(c) show the current-voltage (I-V) curves at Landau level filling factors $\nu = 1.05$ ($B = 8.95$ T), $\nu = 1.82$ ($B = 5.15$ T), and $\nu = 3.09$ ($B = 3.04$ T), respectively. The currents are obtained by sweeping the voltage in the positive (blue) and negative (red) directions at a sweep rate of 0.67 mV/s. Shifts of the I-V curves toward the smaller voltage sides indicate that DNP accelerates the QHE breakdown by reducing the energy gaps of the odd-integer QH states. Since the odd-integer QH states are stabilized by the spin-splitting energy for electrons $\Delta_n = |g^*|\mu_B B - A/L_z$, where $g^*$ is the effective g-factor for electrons and $\mu_B$ is the Bohr magneton, the acceleration of the QHE breakdown indicates that the nuclear spins are polarized upward ($L_z > 0$).

In Fig. 3(c), the shifts of the I-V curves ($\Delta V$) defined at $I = 2 \mu A$ are plotted against $\nu$ in the range of the QH plateau of $\nu = 3$. The amount of shift increases with $\nu$. This trend is similar to that observed in Hall-bar devices. Although the origin of the trends is not understood, the observation of similar filling-factor dependence in both Corbino and Hall-bar samples suggests that the filling-factor dependence reflects the nature of the bulk channel.

Fig. 2. (Color online) I-V curves obtained by sweeping the bias voltage in the positive (blue) and negative (red) directions at (a) $\nu = 1.05$ ($B = 8.95$ T), (b) $\nu = 1.82$ ($B = 5.15$ T), and (c) $\nu = 3.09$ ($B = 3.04$ T). Inset in (a): micrograph of the Corbino device.
mV, the value of $\Delta I$ is almost zero. The value of $\Delta I$ increases abruptly at about $V_{\text{pump}} = 45$ mV and saturates above $V_{\text{pump}} = 60$ mV. These results show that DNP is not created in QH states with vanishing longitudinal conductance where $V_{\text{pump}}$ is smaller than $V_c$. DNP emerges near $V_{\text{pump}} = V_c$ and saturates for larger $V_{\text{pump}}$. Similar results were obtained in a Hall-bar sample used in Ref. 13. These suggest that the underlying origin of DNP is closely related to that of the QHE breakdown.

Since the QHE breakdown is induced by the avalanche-multiplication of $e$-$h$ pairs due to inter-Landau-level impact ionization, it can be surmised that avalanche-multiplication is relevant to DNP. In the case of impact ionization in an odd-integer QH state, electrons are excited from the up-spin subband to the down-spin subband, as indicated by the arrow $b\rightarrow b'$ in Fig. 1. This process is accompanied by the up-to-down flip of electron spin. The up-to-down flips of electron spins can cause the down-to-up flips of nuclear spins via the hyperfine interaction. As a result, the nuclear spins are expected to be polarized upward ($\langle I_z \rangle > 0$), thereby reducing the spin-splitting energy $\Delta_s$. This is consistent with the observation of the shifts of the $I$-$V$ curves toward the smaller voltage sides [Figs. 2(a) and 2(c)]. From these results, we infer that DNP is induced by the spin-flip process of electrons in the inter-Landau-level impact ionization during the avalanche multiplication of $e$-$h$ pairs.

To summarize, we have experimentally demonstrated that the nuclear spins are polarized in the QH Corbino disk under QHE breakdown regimes. The pumping voltage dependence of DNP shows that DNP starts to increase near the critical voltage for the QHE breakdown. The presence of DNP in the Corbino disk strongly suggests that the nuclear spin polarization in the bulk channel of the 2DEG is pumped and detected. The agreement of the onset voltage of DNP with that of the QHE breakdown suggests that the underlying origin of DNP is closely related to that of the QHE breakdown. We suggest that DNP possibly originates due to the electron spin flip process in inter-Landau-level impact ionization during the avalanche multiplication of $e$-$h$ pairs.

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