Manipulation of local nuclear spin polarization in quantum Hall systems

Tomoki Machida [1], Tomoyuki Yamazaki, Susumu Komiyama

Department of Basic Sciences, University of Tokyo, Komaba 3-8-1-16-622, Meguro-ku, Tokyo 153-8902, Japan

Abstract

We demonstrate a spatially resolved detection of dynamic nuclear polarization (DNP) in integer quantum Hall systems. A continuous-wave radio-frequency (rf) magnetic field is generated by transmitting rf electrical current through micro-metal strips fabricated on top of a Hall bar device. Nuclear magnetic resonance (NMR) in a limited region along edge channels is detected via the edge-channel transport. Systematic difference of the NMR amplitudes from different regions provides an evidence of the local detection of DNP.

Key words: Quantum Hall effect; Edge channels; Dynamic nuclear polarization

Nuclear-spin polarization has recently been found to have striking effects on electron transports in quantum Hall systems [1-7]. Nuclear spins are dynamically polarized through the hyperfine interaction with electron spins, and the induced dynamic nuclear polarization (DNP), in turn, affects the transport properties of the electron systems. The spatial distribution of the DNP is thus a key issue for the better understanding of the spin-dependent phenomena. Nevertheless, local detectability of the DNP has not been demonstrated.

In this work, we present a spatially resolved detection of DNP along edge channels in integer quantum Hall (IQH) systems. By generating a continuous-wave radio-frequency (rf) magnetic field using micro-metal strips, we observe nuclear magnetic resonance (NMR) in a limited region along the edge channels. By exciting NMR in two adjacent but separated regions, we demonstrate the local detectability of nuclear-spin polarization via the all-electrical means.

A schematic representation of the Hall bar studied here and a scanning electron micrograph of its central region are shown in Figs. 1(a) and 1(b). The devices are fabricated on an $Al_{0.3}Ga_{0.7}As/GaAs$ single heterostrucure crystal with a two-dimensional electron gas (2DEG) of an electron mobility 30 m^2/Vs and a sheet electron density 3.5×10^{15} m^{-2} at 4.2 K. The 2-μm-wide metal strips (MS1 and MS2), terminating the coplanar waveguides, are aligned along one boundary of the 2DEG region. The four-terminal differential Hall resistance, $R'_{\rm H} \equiv \partial V_{\rm H}/\partial I$, is studied by superposing a small ac current $I_{\rm ac} = 1$ nA (18 Hz) on the dc current $I_{\rm dc}$ at a temperature of 50 mK in a ^{3}He-^{4}He dilution refrigerator.

The Landau-level filling factor in the bulk 2DEG region and the gated regions are adjusted to $\nu_{\rm B} = 2$ and $\nu_{\rm G} = 1$, respectively, so that the potential barriers underneath the gates transmit the outer spin-up edge channel while reflecting the inner spin-down edge channel as schematically shown in Fig. 1(a). The edge channels along the upper boundary between the two gates are unequally populated. In this condition, the value of $R'_{\rm H}$ gives a sensitive measure of the inter-edge-channel scattering rate: $R'_{\rm H}$ is quantized to h/e^2 when the inter-edge-channel scattering is completely suppressed, while $R'_{\rm H} = h/2e^2$ in a fully equilibrated transport regime.

When the electrochemical potential of electrons in

[1] Corresponding author. Also at Solution Oriented Research for Science and Technology (SORST), Japan Science and Technology Corporation (JST). E-mail: machida@mujin.c.u-tokyo.ac.jp

the source μ_S is higher than that of the drain μ_D, the up-to-down spin-flip scattering takes place along the edge channel as schematically shown in Fig. 1(c). Owing to the hyperfine interaction with nuclear spins, the up-to-down flip processes of electron spin cause down-to-up flops of nuclear spin in the host material, leading to a positive DNP, $I_z > 0$ [3-7]. The DNP in turn reduces the effective Zeeman energy, and the inter-edge-channel scattering is thereby self-accelerating. When I_{dc} is maintained at a positive value ($\mu_S > \mu_D$), R'_H decreases due to the enhancement of the inter-edge-channel scattering with a very long relaxation time of a few minutes as reported in Ref. 6. The slow evolution of R'_H represents the development of a positive DNP.

Utilizing this technique, we prepare an initial condition for NMR by maintaining $I_{dc} = 4$ nA until R'_H decreases to a steady value, i.e. the positive DNP fully develops. We then transmit rf current through one of the metal strips MS1. The rf current generates a rf magnetic field B_{rf} exclusively at the nuclear spins underneath MS1 in the direction parallel to the 2DEG [Fig. 1(d)]. The distribution of B_{rf} is local, and rapidly decays outside the region beneath MS1. As the frequency f of B_{rf} is scanned, a distinct resonance peak is found in R'_H at the NMR frequency for ^{75}As as shown by the solid line in Fig. 2(a). The resonance structure in the curve of R'_H versus f arises because the nuclear spins underneath MS1, positively polarized in the initial condition, is depolarized by the NMR. Similar NMR spectra have been found at the NMR frequencies for ^{69}Ga and ^{71}Ga. Additional experiments carried out with $I_{dc} < 0$ provide similar NMR signals with the opposite polarity for all the nuclei of GaAs.

To prove the locality of the present NMR, we make similar experiments using another metal strip MS2. Similar NMR signal is obtained but the amplitude of the signal is slightly smaller than that obtained from MS1 as shown in Fig. 2(a). This is because MS2 is located in a downstream of the electron propagation along the edge channels, as schematically shown in Fig. 1(a): The degree of unequal population between the edge channels, i.e. thereby the degree of DNP, is smaller in the region underneath MS2 than those underneath MS1. When the propagation direction of electrons in the edge channels is reversed by reversing the polarity of B_{ext} and exchanging the role of the contacts (S, D, and V), the NMR signals exchange the relative amplitudes between MS1 and MS2 as displayed in Fig. 2(b). The systematic difference of the NMR amplitude demonstrates that the rf magnetic field exclusively affects the nuclear spins located underneath the metal strip.

In summary, we have locally excited and detected nuclear spin polarization by transmitting rf current through the micro-metal strips deposited above edge channels. This technique makes possible a spatially resolved detection of nuclear-spin polarization in quantum Hall systems.

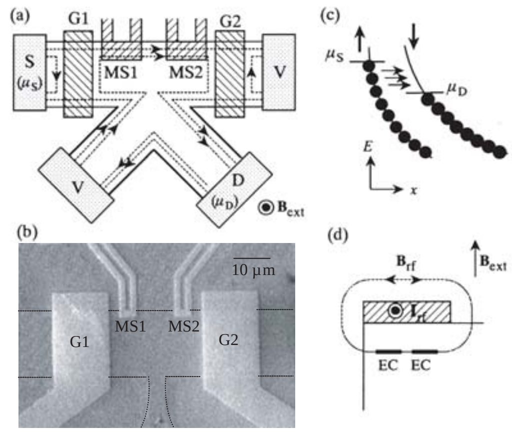

Fig. 1. (a) Schematic representation of a Hall-bar device. The dashed lines represent IQH edge channels. (b) Scanning electron micrograph of the device. (c) Unequally populated edge channels ($\mu_S > \mu_D$). (d) RF magnetic fields and edge channels on a cross section of the device.

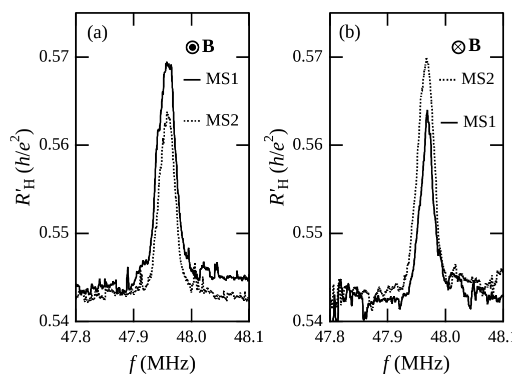

Fig. 2. NMR spectra obtained by transmitting rf current through MS1 (solid lines) and MS2 (dotted lines) for the opposite polarities of the external magnetic field. (a) $B_{ext} > 0$. (b) $B_{ext} < 0$.

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