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Pulsed-Mode Manipulation of Nuclear Spin Polarization in Integer Quantum Hall Devices

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1. Introduction

A nuclear spin system is one of the most attractive elements in spin electronics, in particular for designing quantum computation devices [1]. We use $Al_{0.3}Ga_{0.7}As/GaAs$ Hall bars in integer quantum Hall (IQH) effect to manipulate and detect nuclear spin polarization locally. A micro metal wire is fabricated along an edge region of two-dimensional electron gas (2DEG). The radio-frequency (*rf*) pulse magnetic fields are generated by transmitting *rf* pulse electrical currents through the micro wire, which causes nuclear magnetic resonance (NMR) in a limited region along IQH edge channels. The resulting change of the nuclear spin polarization is detected via Hall resistance of the device.

2. IQH device with a micro-metal wire

A schematic representation of the Hall bar is shown in Fig. 1(a) and an optical micrograph of a central region of the device is shown in Fig. 1(b). The device is fabricated on an $Al_{0.3}Ga_{0.7}As/GaAs$ single heterostructure crystal with 2DEG of an electron mobility $\mu = 30\ m^2/Vs$ and a sheet electron density $n_s = 3.5 \times 10^{15}\ m^{-2}$ at 4.2 K, located 100 nm beneath the crystal surface. Schottky cross gates (G) and a micro wire are prepared by depositing a layer of 150-nm-thick Au and 10-nm-thick Ti on the crystal surface. The micro wire is aligned along one boundary of the 2DEG in a region sandwiched by the two cross gates. The device is studied at a temperature of 60 mK in a ^3He-^4He dilution refrigerator. The four-terminal differential Hall resistance, $R'_H \equiv \partial V_H / \partial I$, is studied by applying both a small ac-current $I_{AC} = 1$ nA (18 Hz, Lock-in technique) and dc-current I_{DC}. The Landau level filling factor in the bulk 2DEG is adjusted to $\nu_B = 2$ by applying a magnetic field of $B_{ext} = 7.3$ T, while that in the two gated regions is tuned to $\nu_G = 1$ by biasing gate voltage, -0.2 V. The potential barriers underneath the gates transmit the outer spin-up edge channel while reflecting the (inner) spin-down edge channel as shown in Fig. 1(a): The edge channels along the upper boundary in the region between the two gates are unequally populated. In this condition, R'_H is a sensitive measure of the inter-edge-channel (IEC) scattering.

3. Dynamic nuclear polarization (DNP) along IQH edge channels

The spin-flip scattering of electrons between $\nu = 1$ edge channel and $\nu = 2$ one dynamically polarizes nuclear spins [2-4] through the hyperfine interaction, the Hamiltonian of which is written as

$$AI \cdot S = \frac{1}{2}A\left[I_+S_- + I_-S_+\right] + AI_ZS_Z ,$$

where the first term within the brackets corresponds to the simultaneous flip-flop of the electron spin and the nuclear spin, and the second term is the hyperfine splitting, with A: the hyperfine constant, I: the nuclear spin, and S: the electron spin.

The polarity of DNP is initialized in either parallel or anti-parallel direction to the external magnetic field by selecting the polarity of source-drain current. That is, when $I_{DC} < 0$ ($I_{DC} > 0$), electrons in the outer (inner) IQH edge channel are scattered into the inner (outer) one, up-to-down (down-to-up) electron spin-flip processes cause down-to-up (up-to-down) nuclear-spin flops, producing DNP; $I_Z > 0$ ($I_Z < 0$). This DNP in turn generates an effective magnetic field, B_{int}, to the electron system, which widens (narrows) spin splitting energy gap. As a result, IEC scattering is suppressed (enhanced) by the DNP. This enhancement (suppression) of IEC scattering manifest itself as very slow time evolution of R'_H in a time scale of a few minutes [3].

4. Pulsed-mode nuclear magnetic resonance

By transmitting *rf* pulse currents (pulse width 250 μs) through a micro-sized metallic wire, fabricated just above the IQH edge channels, *rf* pulse magnetic fields is applied to the nuclear spins underneath the wire in a direction parallel to the 2DEG, and NMR depolarizes the nuclear spins. The resulting change of DNP is detected by the change of differential Hall resistance. The R'_H shows distinct increases at NMR frequencies of all the nuclei of GaAs, i.e. ^{69}Ga, ^{71}Ga, and ^{75}As, as shown in Figs. 2 a), b), and c). The NMR response of R'_H decays with a time constant around 1 min.

5. Conclusions

We have exited and detected nuclear spins in local region by transmitting rf pulse currents to micro metal wire deposited above edge channels in IQH systems. The pulsed-mode NMR in local area along edge channels is opening up new possibilities of utilizing nuclear spins in solid-state devices.

References

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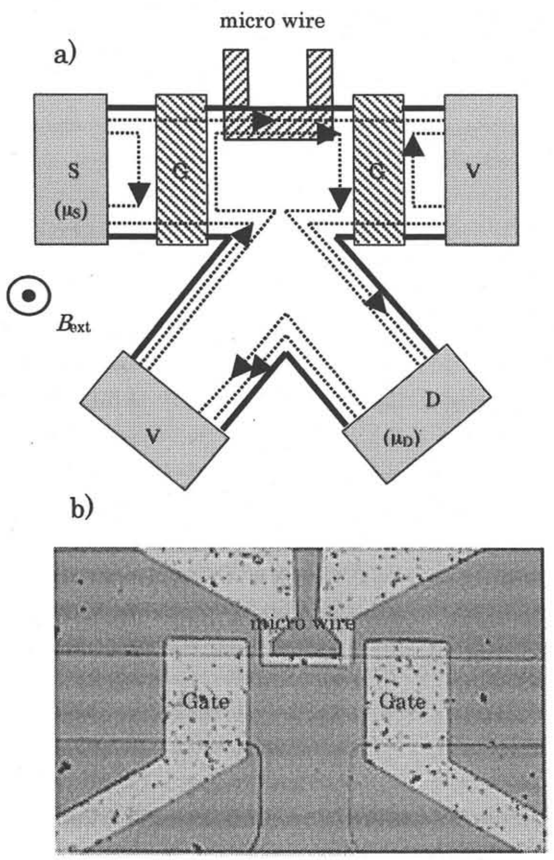

Figure 1 a) Schematic representation of a Hall bar device. The dashed lines stand for IQH edge channels. b) Optical micrograph of the device.

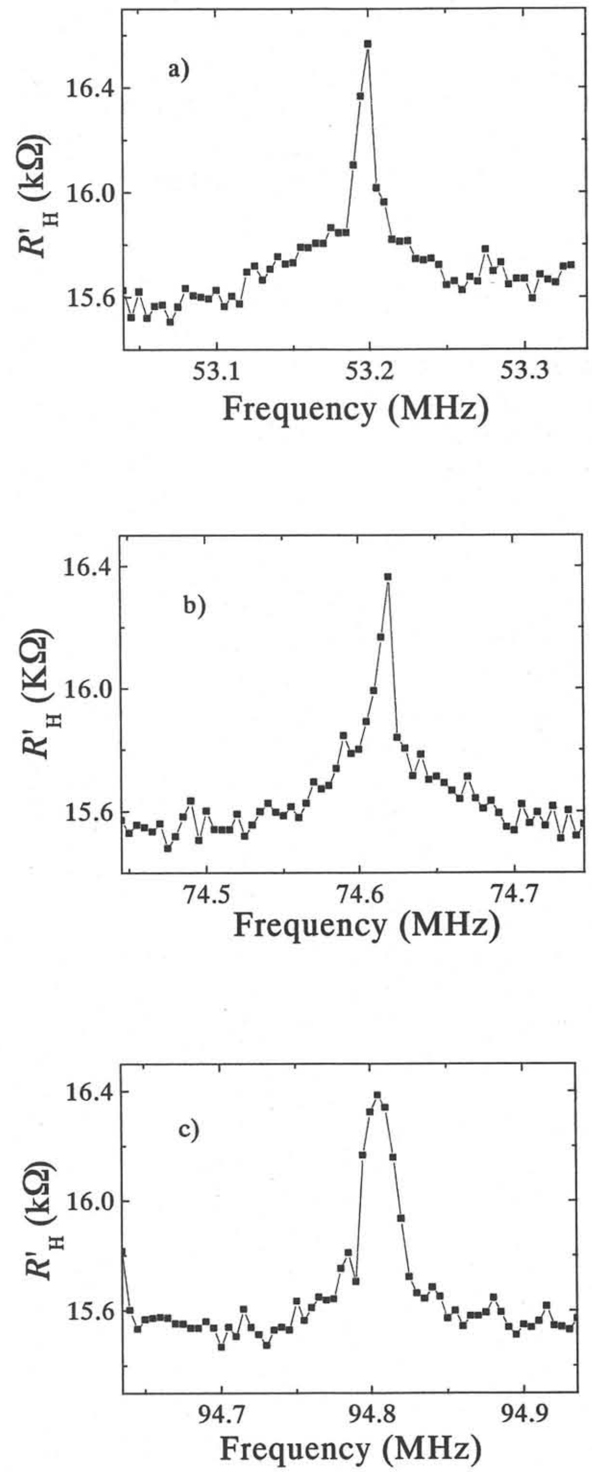

Figure 2 Pulsed-mode NMR spectra for each nuclei of GaAs, a) ^{75}As, b) ^{69}Ga, and c) ^{71}Ga, detected via the change of differential Hall resistance.