Pulsed-mode operation of nuclear spin polarization in integer quantum Hall systems

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Abstract

We demonstrate pulsed-mode control of nuclear-spin polarization in integer quantum Hall systems. Nuclear spins in a limited region along edge channels of a quantum Hall conductor are initially polarized through the hyperfine interaction with electron spins. The initialized nuclear-spin polarization is then manipulated with pulsed nuclear magnetic resonance using a micro-metal strip fabricated on top of the edge channels. The nuclear-spin polarization is probed by the Hall resistance.

Key words: Quantum Hall effect; Edge channels; Pulsed-mode nuclear magnetic resonance

Quantum computers can in principle perform computations far more rapidly than classical ones by employing a quantum-mechanical superposition of a two-level system as a quantum bit (qubit) [1]. Recently, a quantum algorithm has been realized in a solution of molecules using nuclear magnetic resonance (NMR) [2, 3], where the nuclear spins are coherently controlled by applying a pulse radio-frequency (rf) magnetic field. In order to explore expansion of the number of qubits, coherent control of nuclear spins in a solid-state device is desired [4].

Quantum Hall systems are interesting elements for designing a device in which nuclear-spin polarization is manipulated with an all electrical means [5-10]. Nuclear spins along integer quantum Hall (IQH) edge channels can be dynamically polarized through the hyperfine interaction with electron spins [5-10], and the induced dynamic nuclear polarization (DNP) is detected with NMR via resistance of the device. However, the existing experiments [5-10] have been limited to continuous-wave NMR. Therefore, a technique of pulsed-mode NMR has to be developed for coherent control of nuclear spins in quantum Hall devices.

In this work, we demonstrate local control of nuclear-spin polarization via *pulsed-mode* NMR. Nuclear spins of GaAs nuclei along IQH edge channels is initially polarized by selectively populating spin-resolved edge channels. By generating a local rf magnetic field using a micro-metal strip, nuclear-spin polarization is controlled in a limited region along the edge channels.

The Hall-bar device studied are shown in Figs. 1(a) and 1(b). The device is fabricated on an $Al_{0.3}Ga_{0.7}As/GaAs$ single heterostrucure with a two-dimensional electron gas (2DEG) of an electron mobility 330 m^2/Vs and a sheet electron density 1.3×10^{15} m^{-2} at 1.6 K. The 2-μm-wide metal strip (MS) aligned along a boundary of the 2DEG region generates a rf magnetic field. The four-terminal differential Hall resistance, $R'_H \equiv \partial V_H/\partial I$, is studied with a standard lock-in technique by superposing a small ac current I_{ac} = 1 nA (18 Hz) on a dc current I_{dc} at a temperature of 50 mK in a ^3He-^4He dilution refrigerator.

It has been established that nuclear spins are dynam-

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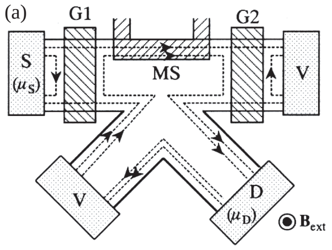

Fig. 1. (a) Schematic representation of a Hall-bar device. The dashed lines represent IQH edge channels. (b) A micrograph of a central region of the device.

ically polarized through the hyperfine interaction with electron spins when spin-resolved edge channels are selectively populated [5-9]: When an up-spin (down-spin) edge channel is overpopulated, a positive (negative) DNP, $I_z > 0$ ($I_z < 0$), is induced, leading to an enhancement (suppression) of the inter-edge-channel scattering due to the reduction (increase) of the effective Zeeman splitting. We adopt this process for initializing the nuclear-spin polarization.

We adjust the Landau level filling factor in the bulk and gated regions to $\nu_B = 2$ and $\nu_G = 1$, respectively, so that the potential barriers underneath the gates transmit the outer spin-up edge channel while reflecting the inner spin-down edge channel [Fig. 1(a)]. The edge channels along the upper boundary sandwiched by the two gates are unequally populated [11]. When I_{dc} is maintained at $I_{dc} = -4$ nA, where the electrochemical potential of electrons in the source μ_S is lower than that of the drain μ_D, a negative DNP, $I_z < 0$, is induced. R'_H consequently increases due to the suppression of the inter-edge-channel scattering with a long relaxation time of 200 seconds as reported in Ref. 8.

After the initialization of nuclear-spin polarization, we transmit a pulse rf current with a duration of 150 μs through the metal strip MS. The rf current generates a rf magnetic fields B_{rf} exclusively at the nuclear spins underneath MS in the direction parallel to the 2DEG. Figure 2 shows a pulsed-NMR spectrum for ^{71}Ga in a 3-dimensional plot of R'_H as the frequency f of B_{rf} is scanned. At the NMR frequency of ^{71}Ga nuclei, R'_H decreases rapidly after the pulse application (at t = 60 s) and decays slowly with a decay constant of 200 seconds. Additional experiments carried out with $I_{dc} > 0$ provide similar NMR signals with the opposite polarity. Similar NMR spectra have been found at the NMR frequencies for ^{69}Ga and ^{75}As.

Observations of the distinct NMR signals demonstrate a controllability of local nuclear-spin polarization with a *pulsed* NMR. This technique has advantages in designing a nuclear-spin solid-state device: (i) nuclear-spin polarization can be initialized to a fully polarized state, (ii) nuclear-spin polarization in a *local* region below the metal strip can be exclusively con-

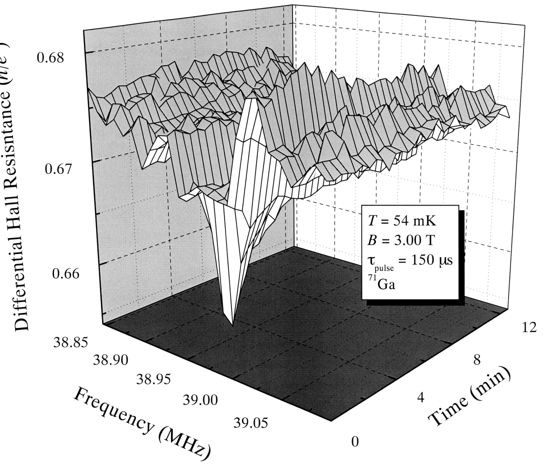

Fig. 2. NMR spectra of ^{71}Ga nuclei obtained by transmitting a pulse rf current (pulse duration of 150 μs) through a micro-metal strip.

trolled, and (iii) the device is furnished with a flexible design capability. Therefore, this technique will open up a possibility of coherently controlling local nuclear-spin polarization in quantum Hall devices, and the experimental challenge in the next step will be to demonstrate the coherent evolution of nuclear-spin state.

This work is supported by Grant-in-Aid for Specially Promoted Research from the Japanese Ministry of Education, Culture, Sports, Science and Technology.

References

[1] D. Deutsch, Proc. R. Soc. London A **400** (1985) 97.

[2] I. L. Chuang, L. M. K. Vandersypen, X. Zhou, D. W. Leung, and S. Lloyd, Nature **393** (1998) 143.

[3] J. A. Jones, M. Mosca, and R. H. Hansen, Nature **393** (1998) 344.

[4] B. E. Kane, Nature **393** (1998) 133.

[5] B. E. Kane, L. N. Pfeiffer, and K. W. West, Phys. Rev. B **46** (1992) 7264.

[6] K. R. Wald, L. P. Kouwenhoven, P. L. McEuen, N. C. van der Vaart, and C. T. Foxon, Phys. Rev. Lett. **73** (1994) 1011.

[7] D. C. Dixon, K. R. Wald, P. L. McEuen, and M. R. Melloch, Phys. Rev. B **56** (1997) 4743.

[8] T. Machida, S. Ishizuka, T. Yamazaki, S. Komiyama, K. Muraki, and Y. Hirayama, Phys. Rev. B **65** (2002) 233304.

[9] T. Machida, T. Yamazaki, and S. Komiyama, Appl. Phys. Lett. **80** (2002) 4178.

[10] K. Hashimoto, K. Muraki, T. Saku, and Y. Hirayama, Phys. Rev. Lett. **88** (2002) 176601.

[11] In this condition, the value of R'_H is a sensitive probe of the inter-edge-channel scattering rate: $R'_H = h/e^2$ in an adiabatic transport regime, while $R'_H = h/2e^2$ in a fully equilibrated one.