Coherent manipulation of nuclear spins in GaAs using electrical spin injection

Tetsuya Uemura
Graduate School of Information Science and Technology, Hokkaido University, Sapporo, Japan

Nuclear spins in semiconductors are an ideal system for implementing quantum bits (qubits) for quantum computation because of an extremely long coherence time. Dynamic nuclear polarization (DNP) through hyperfine interaction with electron spins and control of nuclear spin states by nuclear magnetic resonance (NMR) in semiconductors provide basic technologies for implementing nuclear-spin based qubits. In this study, we have developed a novel NMR system that uses spin injection from a highly polarized spin source (Fig. 1). The nuclear spins in a semiconductor channel are initialized through a DNP technique using spin-polarized electrons injected from contact-2. The nuclear spin states are then manipulated through the NMR by irradiation of a radio-frequency (rf) magnetic field. The manipulated nuclear-spin states can be readout through the detection of the Larmor precession of electron spins induced by nuclear field by measuring the nonlocal voltage (V_{NL}).

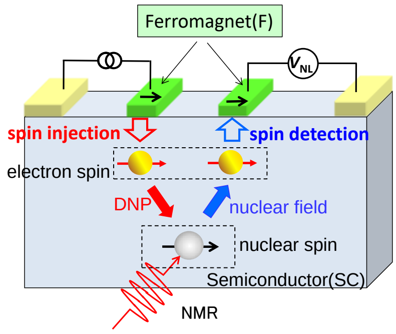

Fig. 1. A novel NMR system using a spin injection.

We demonstrated a clear spin injection from Co_2MnSi into GaAs and the resultant DNP for Ga and As atoms [1,2]. Moreover we demonstrated coherent manipulation of nuclear spins of ^{69}Ga through the observation of Rabi oscillation [3] and spin-echo signals [4] by combining the NMR techniques. Figure 2 plots ΔV_{NL} measured at 4.2 K as a function of pulse duration (τ_p) of the rf-magnetic field, where ΔV_{NL} is a change in V_{NL} by rf-pulse irradiation. We observed a clear oscillation of ΔV_{NL} as a function of τ_p. This indicates that the nuclear spins coherently rotate between nuclear-spin levels (Rabi oscillation), which is a key factor for nuclear-spin based qubits.

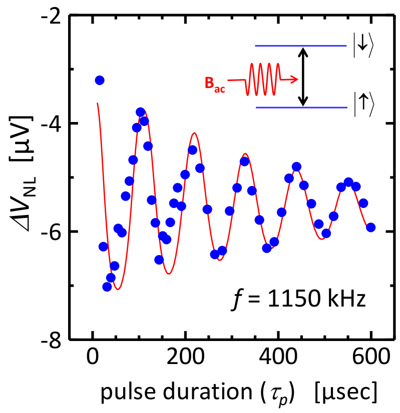

Fig. 2. Rabi oscillation for ^{69}Ga [3].

In order to estimate the intrinsic phase coherence time (T_2) in GaAs, a spin-echo signal was also measured, in which a series of pulses consisting of π/2, π, and π/2 pulses (Fig. 3(a)) was applied. The first π/2 pulse rotates the total nuclear spin into the *x*-*y* plane, and the nuclear spin starts to dephase. After a time of *τ*/2, the nuclear spins flip to the opposite side in the *x*-*y* plane by application of a π pulse, and they start to refocus during the period of τ/2. Then, a complete refocusing, or spin echo, occurs after *τ*/2. Finally, the second π/2 pulse rotates the nuclear spin back to the *z*-axis for readout. ΔV_{NL} shows an exponential dependence on *τ*, as shown in Fig. 3(b). The intrinsic dephasing time T_2 (= 167 μs) obtained from the fitting was consistent to the value obtained from the Rabi oscillation.

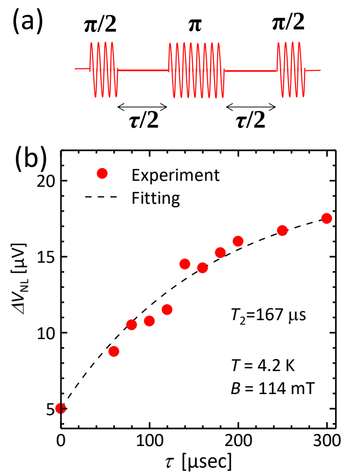

Fig. 3. (a) Spin-echo pulse sequence. (b) τ dependence of ΔV_{NL} [4].

*Email:uemura@ist.hokudai.ac.jp

References

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