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学　位　論　文　内　容　の　要　旨

博士の専攻分野の名称　　博士（工学）　　氏名　林　志超

学　位　論　文　題　名

Detection of nuclear spin coherence in GaAs through spin-echo measurements using electrical spin injection

（電気的スピン注入を用いたスピンエコー測定による GaAs 中の核スピンコヒーレンスの検出）

Nuclear spins are promising implementations for quantum bits (qubits) because they have extremely long coherence times. The nuclear magnetic resonance (NMR) technique enables the control and detection of nuclear-spin-based qubits. However, the sensitivity of the conventional NMR technique is limited by the low magnetic moments of the nuclear spins, which are three orders of magnitude smaller than that of the electron spins. Dynamic nuclear polarization (DNP), where nuclear spins are dynamically polarized through a hyperfine interaction between nuclear spins and electron spins, has attracted much interest, since it can dramatically increase the NMR signal. Several instances of DNP in semiconductors induced by optical means or electrical means have been reported. Furthermore, coherent manipulation of nuclear spins in semiconductors by NMR has been demonstrated electrically in GaAs/AlGaAs quantum Hall systems by observing the Rabi oscillation and optically in GaAs/AlGaAs quantum wells by observing the Rabi oscillation and spin-echo signals. Although the optical method is suitable for clarifying the fundamental physics of nuclear spins, it is restricted in its scalability because the spatial resolution is limited by the optical wavelength. The quantum Hall systems require a strong magnetic field of several Tesla and a low temperature below 1 K to create highly polarized electron spins for DNP. Considering these shortcomings, a spin injection system is a better choice since it is all electrical and a highly polarized spin source allows efficient DNP without a strong magnetic field.

For achieving nuclear-spin-based qubits, it is important to clarify the nuclear-spin phase coherence time T_2, because the lifetime of a qubit is limited by T_2. However, in a real system, the real coherence time is known as T_2^*, and it consists of an intrinsic component T_2, which results from the dipolar-dipolar interaction between the nuclear spins, and the other component T_2^{inhom}, which results from the inhomogeneity in the external magnetic field. T_2 is the intrinsic coherence time and it is determined by the material itself. T_2^{inhom} is extrinsic and determined by the measurement system. In order to know the intrinsic T_2, a spin echo measurement, which refocuses nuclear-spin magnetization by using a specific pulse sequence, has to be made to exclude the T_2^{inhom} component.

The main purpose of the present study is to clarify the intrinsic coherence time T_2 of the nuclear spins in GaAs through an electrical spin-echo measurement in a spin injection device.

This dissertation is organized as follows:

Chapter 1 introduces the background and the purpose of this study.

Chapter 2 covers the theoretical principles of NMR, spin echo, as well as electron spin injection/detection.

Chapter 3 describes the results of spin injection into bulk GaAs and AlGaAs/GaAs heterostructures

with a highly polarized spin source. In bulk GaAs, a clear spin-valve signal and a Hanle signal were observed. The highly polarized spin source of Co_2MnSi resulted in a high spin polarization, which is promising for the DNP process. Moreover, a clear transient oblique Hanle signal was observed, which was evidence of nuclear spin polarization. In the AlGaAs/GaAs heterostructure, a spin-valve signal was observed up to room temperature. The temperature dependence of the spin-valve signal shows relatively complicated behavior compared with that of the bulk device, which results from the opposite tendency of sheet resistance. Moreover, the spin-valve signal in the AlGaAs/GaAs heterostructure is less sensitive to temperature than that in bulk GaAs. This result contributes to a better understanding of spin transport in a two-dimensional channel, which is indispensable for realizing future spin transistors that can operate at room temperature.

Chapter 4 analyzes the transient behavior of nuclear spins in the presence of DNP using the concept of nuclear spin temperature for a better understanding of nuclear spin dynamics.

Chapter 5 describes the detection of nuclear spin coherence time in GaAs through a spin-echo measurement. All the measurements were done at a low magnetic field of approximately 0.1 T and a relatively high temperature of 4.2 K because the highly polarized Co_2MnSi spin source enabled efficient DNP. First, Rabi oscillation, which is an oscillation behavior of nuclear spins along an rf-magnetic field, was measured to determine the pulse durations for the spin-echo measurement. Then the spin-echo measurement was conducted. It was found that the intrinsic coherence time T_2 obtained from the spin-echo signals was slightly larger than T_2^* obtained by the Rabi oscillation, which indicates that the inhomogeneity in the external fields exists. In our device, the external fields consist of a static field, a stray field from the ferromagnet, and an electron field generated by the electron spins. Since the device has nanoscale dimensions, the inhomogeneity in the static field is probably negligible. Therefore, the inhomogeneity probably comes from the stray field or the electron field.

Finally, chapter 6 summarizes the results and makes a conclusion.

In summary, spin echoes of nuclear spins were demonstrated in a spin injection device with a highly polarized spin source. Efficient spin injection into GaAs from a half-metallic spin source of Co_2MnSi enabled efficient DNP and sensitive detection of NMR signals even at a low magnetic field of approximately 0.1 T and a relatively high temperature of 4.2 K. The intrinsic coherence time T_2 of the nuclear spins was evaluated from the spin-echo signals. The relation between T_2 and T_2^* suggests that the inhomogeneity exists in our system, which probably comes from the stray field or the electron field. This study provides an all-electrical NMR system for future nuclear-spin-based qubits.