# 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　Mahmoud Rasly Khoudary Eldesouky

## 学 位 論 文 題 名

Systematic investigations of transient response of nuclear spins in GaAs under the presence of polarized electron spins
（電子スピン偏極状態下における GaAs 中核スピンの過渡応答特性）

Nuclear-spin systems are ideal for the development of quantum computing systems because of their extremely long coherence time. For such computing systems, the nuclear magnetic resonance (NMR) technique enables the control and detection of the nuclear-spin-based quantum bits (qubits), a basic unit of quantum computation. Nevertheless, it is difficult originally to polarize the nuclear spins and to detect the nuclear spin states because of their tiny magnetic moment, leading to a decrease in the signal sensitivity of the NMR system. A possible solution to tackle this problem is to apply the so-called dynamic nuclear polarization (DNP), in which the nuclear spins are polarized by exchanging angular momentum with spin-polarized electrons through the hyperfine interaction. Several DNP-combined NMR systems have been developed by using optically or electrically created electron spins. Electrical spin injection from ferromagnetic electrodes into a semiconductor is the most recent proposal for an electrical DNP, and coherent manipulation of nuclear spins, or the Rabi oscillation, which is a key factor for nuclear-spin-based qubits, has been demonstrated.

Basically, the nuclear spins interact with the lattice through an extremely long time scale of $T_1$ (typically minutes to hours); called the spin-lattice relaxation time, compared to those of their internal interactions. They also interact with electron spins through the hyperfine interaction with a time scale of $T_{1e}$ (typically seconds to minutes); called the DNP time. Therefore, during the process of DNP, if the change in the external magnetic field is faster than the polarization rate ($1/T_{1e}$) and/or depolarization rate ($1/T_1$), nuclear spins behave in a complicated manner. The quantitative analyses of the DNP, thus, have mostly been limited to steady-state circumstances, where the change in the external magnetic field is relatively slow. For a precise control of nuclear spin polarization during the DNP, a complete understanding about the dynamics of nuclear spins is indispensable.

The purpose of this research is to provide a quantitative description for the electron-nuclear spin dynamics in semiconductor-based spintronics devices. To do so, we systematically investigated the dependencies of nuclear-spin polarization on the initialization time for the DNP and the sweep rates of the magnetic field through the Hanle signal and spin-valve signal measurements made in an all-electrical lateral spin injection device. In addition, we simulated all the nuclear-spin-related phenomena appearing in the Hanle/spin-valve signals using the time evolution of nuclear field, taking both the rate of polarization ($1/T_{1e}$) and the rate of depolarization ($1/T_1$) into consideration.

This dissertation consists of six chapters and the main content of each chapter is as follows:

Chapter 1 includes a research introduction, a problem statement to be solved, and research goals.

Chapter 2 covers the theoretical framework which we use to analyze our experimental results about electron-nuclear spin dynamics in semiconductor-based spintronics devices.

Chapter 3 states about our experimental techniques and simulation methods.

Chapter 4 focuses on the results and discussion of the DNP made in an all-electrical lateral spin injection device having $Co_2MnSi$/CoFe/n-GaAs Schottky tunnel junctions. At first, we demonstrated clear spin injection from a highly spin-polarized $Co_2MnSi$ source into a GaAs channel through the observation of spin-valve signal and Hanle signal, which are the strong evidences for an electrical spin injection and detection. Then, we described the DNP for Ga and As nuclei with the electron spins injected into GaAs. We experimentally observed the modulation of Hanle signals arising from the nuclear field produced in the DNP, and showed that the strength of the produced nuclear field was four orders higher than that obtained without polarized electron spins, indicating that the efficient nuclear polarization was successfully achieved by spin injection. Next we systematically investigated the dependencies of nuclear field on the initialization time for the DNP and the sweep rates of the magnetic field through the Hanle signal and spin-valve signal measurements. Moreover, we simulated all the nuclear-spin-related phenomena appearing in the Hanle/spin-valve signals using the time evolution of nuclear field, taking both $T_{1e}$ and $T_1$ into consideration. The simulation results well reproduced our experimental results, leading to enabling quantitative analysis for the transient response of nuclear spins against the fast change in the magnetic field. We also discussed the DNP in terms of nuclear spin temperature, and showed that the DNP process cooled the nuclear-spin systems. A population inversion of nuclear spins arising from the DNP was also described as a negative spin temperature.

Chapter 5 describes the influence of NMR on the nuclear spin dynamics by both experiment and simulation. Under an irradiation by rf-magnetic field with its frequency of 200 kHz, we observed clear changes in Hanle signal at resonant fields of $^{69}$Ga, $^{71}$Ga, and $^{75}$As nuclei, indicating that the nuclear field was changed by the NMR. By assuming that the nuclear field of each nuclei is vanished at the resonant field, the change of Hanle signal arising from NMR was well reproduced by the simulation, which clarifies the influence of NMR on the nuclear spin polarization. Moreover, we discussed the effect of NMR in terms of the nuclear spin temperature, and showed that the NMR can be treated as a heating of nuclear spin system in contrast to the cooling by DNP.

Chapter 6 summarizes the main results and ends up with a conclusion.

In summary, we clarified the transient response of nuclear spins against the change in the magnetic field by both experiment and simulation in an all electrical spin injection device, enabling a precise control of nuclear spin states along with a quantitative analysis under the DNP process with/without NMR. These findings provide a deep understanding of nuclear spin dynamics and offer a promise for multitude of quantum computing applications.