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Magnetic Field Dependence of Quadrupoar Splitting and Nuclear Spin Coherence in a (110) GaAs/AlGaAs Quantum Well

J. Ishihara, M. Ono, G. Sato, S. Matsuzaka, Y. Ohno and H. Ohno

Laboratory for Nanoelectronics and Spintronics, Research Institute of Electrical Communication, Tohoku University
2-1-1 Katahira, Aoba-ku, Sendai 980-8577, Japan
Phone: +81-22-217-5555 E-mail: jun1204@riec.tohoku.ac.jp

1. Introduction

Nuclear spins in semiconductor nanostructures have recently attracted great interest because of their long coherence time which is suitable for application to quantum memories. Optical [1-4] and electrical [5-7] nuclear magnetic resonance (NMR) techniques have been developed on the basis of the hyperfine interaction between nuclear spins and electron spins, and several groups have demonstrated manipulation and detection of nuclear spin coherent dynamics. In our previous work, we investigated the relationship between the Fermi contact hyperfine interaction and nuclear spin relaxation time [8]. In addition the quadrupole interaction is also important because all the constituent nuclei of GaAs have spin $I = 3/2$ and an electric quadrupole moment. When a static magnetic field B_0 is applied, the nuclear spin states separate into four levels. In the presence of strain-induced electric field gradient, the quadrupole interaction makes the energy separation between two neighboring levels, $|m\rangle$ and $|m+1\rangle$ (m = –3/2, –1/2 and 1/2), different from each other [6]. In this work, we investigated magnetic field dependence of quadrupolar splitting and the nuclear decoherence time T_2 and the dephasing time involving the inhomogeneous broadening T_2^* in a (110) GaAs quantum well (QW) by optical time-resolved Faraday rotation technique.

2. Experimental setup

The sample we studied here was 8.5 nm-thick GaAs/AlGaAs QW with Si donor doping concentration of 5×10^{17} cm^{-3}, which was grown on a (110)-oriented semi-insulating GaAs substrate by molecular beam epitaxy. The sample was set in a cryostat with a superconducting magnet in the Voigt geometry, and the static magnetic field B_0 was applied along the [001] direction. From that geometry, we tilted the sample slightly by an angle 5º from the direction of B_0 in order to enhance dynamic nuclear polarization (DNP) [2]. The degree of nuclear spin polarization is detected by the time-resolved Faraday rotation (TRFR) technique combined with cw-NMR [1]. In the TRFR measurement, we used a mode-locked Ti:Sapphire laser with a pulse duration of ~3 ps and repetition rate of 76 MHz. The photon energy was tuned to the resonant excitation of the lowest electron-heavy-hole exciton. The intensities of the circularly polarized pump and linearly polarized probe beams were set at 8 and 0.4 mW, respectively. They are focused on the sample with a diameter of 30 μm. Cw-NMR spectra were obtained by measuring the change of the Faraday rotation angle θ_F at a fixed time delay between pump and probe pulses, with changing the frequency of the rf magnetic field B_{rf}. We performed pulsed NMR [3,4] measurements to evaluate T_2 and T_2^*.

3. Results and discussion

In this experiment, we focused on ^{75}As as a target nucleus. Figure 1 shows cw-NMR spectra for ^{75}As measured at $T = 3$ K and different magnetic field, which are drawn by fixing the position of the left resonance peak at the origin of the horizontal axis (resonance frequency difference). We observed three resonance peaks in NMR spectra by quadrupole interaction. At $B_0 = 2$ T, the NMR spectrum is symmetric. However, as the magnetic field lowers, resonance peaks shift and the NMR spectrum becomes asymmetric. To explain the observed peak shift, we have to consider the second-order perturbation term of the quadrupole interaction because the quadrupole interaction at the low magnetic field is not small compared to the Zeeman energy. In this situation, resonance peaks shift, and the spectrum becomes asymmetric. Therefore, these suggest that the second-order quadrupole interaction becomes significant at lower magnetic fields.

We also studied the decoherence time T_2 and dephasing time T_2^* of ^{75}As nuclear spins at the three resonance lines by TRFR detection of pulse NMR. We applied a sequence of π/2-π-π/2 rf pulses for measuring T_2 and π/2-3π/2 rf pulses for T_2^*. In Figs. 2(c) and (d) are plotted T_2 and T_2^*

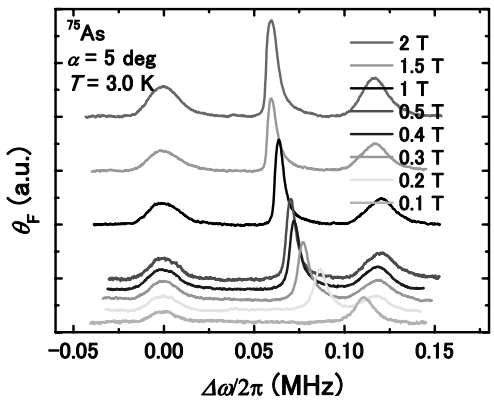

Fig. 1 Magnetic field dependence of NMR spectra for ^{75}As obtained using optically detected NMR at $T = 3$ K. At lower magnetic field, the NMR spectrum is asymmetric.

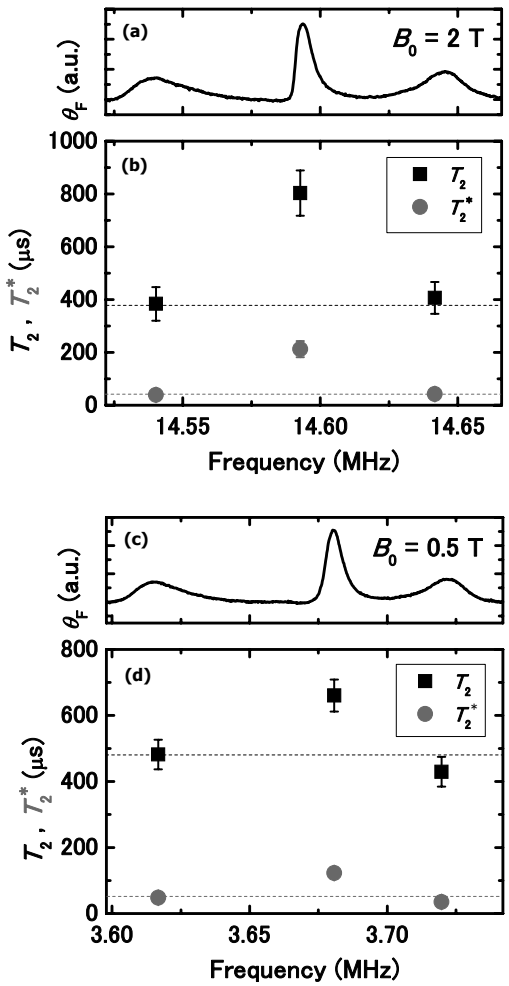

Fig. 2 (a) the cw-NMR spectrum of ^{75}As nuclei at $T = 4.5$ K and $B_0 = 2$ T. (b) Nuclear decoherence time T_2 and dephasing time T_2^* obtained by pulse NMR at three resonance lines each at $B_0 = 2$ T. (c) the cw-NMR spectrum at $B_0 = 0.5$ T. (d) T_2 and T_2^* at $B_0 = 0.5$ T. Coherence time of nuclear spins at right and left peaks have a difference.

for three resonance frequencies at $B_0 = 2$ T and 0.5 T, respectively. At $B_0 = 0.5$ T, T_2 and T_2^* measured at the central resonance peak was 660 μs and 120 μs, respectively, which are shorter than those measured at $B_0 = 2$ T (800 μs and 210 μs). In addition, at $B_0 = 0.5$ T a difference is found in decoherence times for the right and left NMR peaks: T_2 and T_2^* for the left peak are 481 μs and 48 μs, while those for the right peak are 430 μs and 35 μs, respectively. These suggest that the phase decoherence of nuclear spins is enhanced as the resonant transition energies for the central ($|-1/2\rangle \Leftrightarrow |+1/2\rangle$) and the right side ($|-1/2\rangle \Leftrightarrow |-3/2\rangle$) peaks gets close to each other. Another findings is that T_2^* is 4 times shorter than T_2 at the central peak, which might be due to some inhomogeneous effect. On the other hand, T_2^* at the side peaks are 10 times shorter than T_2. This result indicates that inhomogeneous broadening of the quadrupole interaction is also source of dephasing of nuclear spins, and strain-induced electric field gradient are not homogeneous.

4. Conclusions

In conclusion, we investigated magnetic field dependences of quadrupoar splitting in the NMR spectrum, the nuclear decoherence time T_2, and the dephasing time involving the inhomogeneous broadening T_2^* in a (110) GaAs quantum well (QW). We have shown that the NMR spectrum becomes asymmetric at the lower magnetic field. And we found that a difference of the decoherence time T_2 for the right and left peaks reflect the asymmetric NMR spectrum.

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