Dynamical polarization effect of nuclear spin bath dragged by electron spin resonance in double quantum dot integrated with micro-magnet.

T. Obata1, M. Pioro-Ladrière1,2, Y. Tokura1,3, R. Brunner1, Y.-S. Shin1, T. Kubo1, K. Yoshida1, T. Taniyama1, and S. Tarucha1,5,6
1Quantum Spin Information Project, ICORP, Japan Science and Technology Agency, Atsugi-shi, Kanagawa, Japan
2Department de Physique, Université de Sherbrooke, Sherbrooke, Quebec, J1K-2R1, Canada
3NTT Basic Research Laboratories, NTT Corporation, Atsugi-shi, Kanagawa, Japan
4Materials and processes for innovative next-generation devices project, PRESTO, Japan Science and Technology Agency; Materials and Structures Laboratory, Tokyo Institute of Technology 4259 Nagatsuta, Yokohama, Japan
5QPEC & Department of Applied Physics, University of Tokyo, Hongo, Bunkyo-ku, Tokyo, Japan
6Institute for Nano Quantum Information Electronics, the University of Tokyo, Komaba, Meguro-ku, Tokyo, Japan
E-mail: obata@tarucha.jst.go.jp

Abstract. We studied on Overhauser shift of electron dipole spin resonance (EDSR) peaks by using a double quantum dot integrated with a micro-magnet. Two EDSR peaks are well resolved, reflecting electron spin flip events at different resonance conditions between two dots, which depend on the in-plane field at the two dots produced by a micro magnet. One of the two peaks is significantly higher than the other and shows a larger Overhauser shift, indicating that an electron spin flip process local to the dot causes dynamical polarization of local nuclear spins to the same dot. After the nuclear spin polarization is saturated, we observed the decay of the Overhauser shift by repeatedly measuring the EDSR peak with a minimum microwave power. The decay time constant is much longer than by other groups. We discuss the possible reason for this difference.

1. Introduction
Quantum information processing by use of quantum dots in GaAs semiconductor is now on the most exciting stage towards the realization of spin QUBIT. In this context, dephasing due to nuclear spin fluctuations is an emerging problem to be sorted out, and intensive studies have been performed to understand and to suppress it [1, 2, 3, 4, 6]. Larmor precession of electron spins becomes inhomogeneous reflecting the statistically fluctuating nuclear field, and this is observed as dephasing. It is possible to partially eliminate the effect of the nuclear spin fluctuation using a spin echo technique [7] but it is more valuable to squeeze the fluctuations and to understand the role of the hyperfine interaction [4]. In order to examine the nuclear spin effect, we measured the Overhauser shift of electric dipole spin resonance (EDSR) for a lateral double quantum dot made in an AlGaAs/GaAs hetero structure and integrated with micro-magnet (Sec 2).
2. Experiment of Dynamical Nuclear Spin polarization

We micro-fabricated a lateral double quantum dot (DQD) structure defined in a two-dimensional electron gas (2DEG) at a AlGaAs/GaAs interface by Schottky gates in Fig. 1(a). The 2DEG is located 100 nm below the surface. Two micro-magnets were placed on the surface with an insulating layer in between. We apply an in-plane magnetic field $B_0$ and then the magnets are magnetized in-plane as well. These magnets generate a static out-of-plane stray slanting field and a static in-plane stray field, both of which are slightly different between the two dots. EDSR is generated by applying a MW electric field to the right magnet to laterally accelerate an electron in each dot with MW frequency $\nu$ equivalent to the Zeeman energy. The Zeeman energy is given by the sum of an external magnetic field and a strong in-plane field, so that addressability to an electron in each dot is due to the in-plane stray field local to the dot [8, 9]. We measured the trans-conductance signal of current $I_{QPC}$ flowing through a nearby quantum point contact (QPC). Figure 2 shows the EDSR results for sweeping up and down MW frequency, repeatedly, at various $B_0$ fields from 0.9 to 1.1T. Two EDSR peaks are well resolved, and we label the peak at the lower $B_0$ as peak 1 and the other as peak 2, respectively. Both peaks fall on the straight lines with the same slope, from which we derived the Landé g-factor of $0.39 \pm 0.1$.

When comparing the two panels in Fig. 2, we find that the peak is much wider in the right, i.e. for the down sweep of MW frequency. This hysteretic behavior is assigned to DNP [13, 15, 6], which accompanies Overhauser shift. The local field $B_{local}$ indeed by the polarization of nuclear spins is given as $B_{local} = B_0 - A_n P$, where $P = N_\uparrow/(N_\uparrow + N_\downarrow) - 1/2$ is the polarization of nuclear spin bath and $A_n = 5T$ is the coupling contact of hyperfine interaction. The EDSR condition is finally given by $g_\mu_e B_{local} = h \nu$.

When sweeping down $\nu$ or sweeping up $B_0$ in Fig. 3(a), the polarization $P$ or DNP increases so as to sustain the EDSR condition. We measured the MW power dependence of DNP. By sweeping up $B_0$ the effect of DNP on EDSR becomes stronger with increasing MW power as shown in Fig. 3(a). Each $B_0$ field sweep from 0.98 to 1.08T took 10 minutes and it was repeated as increasing the MW power in a step of 0.2 dB. The MW frequency was set at 5.6 GHz.

Overhauser shift is attributed to a dynamic nuclear spin polarization (DNP) effect [5]. We swept down microwave (MW) frequency and up magnetic field to measure the EDSR signals. This way of measurement is efficient to generate DNP [6]. Then we examined the decay of the Overhauser field as a function of wait time (Sec 3). The decay time constant is different. We compared the values with those by other groups (Sec 4).
Figure 3. The power dependence of DNP. (a) The power dependence of Overhauser shift. (b) The power dependence of peak heights. As increasing the MW power, the peak height is getting higher saturates (b). Once the peak saturates, it starts to drag the peak (a). An interesting contrast between the Overhauser shift and the peak height is clearly measured. The base line is adjusted to 0 to avoid the effects by heating and photon assisted tunneling.

Figure 4. The time evolution of the reduced peak position from the saturation field $B_{sat}$ of 1.009 T. The peak position shows exponential decay [2, 6]. An exponential fitting function is adopted to the data points from 40 mT to 4 mT by taking account of an experimental error.

Two peaks were initially observed at 1.0, and 0.99 T, respectively, and suffered from DNP more strongly as the MW power was increased (note that peak 2 shows small amplitude of DNP). The DNP effect is significantly larger for peak 1 than for peak 2. We plot the maximum height of the two peaks in Fig. 3(b). Both peaks become gradually large, saturated, and finally small. In Fig. 3(b) the peak height starts to increase with increasing MW power exceeding -30 dBm, and more or less simultaneously DNP starts to increase to apparently induces the Overhauser shift as seen in Fig. 3(a). From the critical MW power of -30 dBm we calculate the MW magnetic field of a few mT at the dot. This field is comparable to the amplitude of nuclear field fluctuation [8, 12]. This sounds reasonable because DNP can only be visible if the MW magnetic field overcomes the fluctuating Overhauser field. On the other hand, as the MW power is further increased exceeding -25 dBm, the EDSR peak height starts to decrease. This is probably because photon assisted tunneling between quantum dots and reservoirs or heating degrades the EDSR signal.

3. Decay of Overhauser shift and possible mechanism.

After observation of the largest Overhauser shift, we repeatedly measured EDSR in the down sweep of $B_0$ with the lowest MW power of -33 dBm. This power is weak enough to neglect the DNP effect. Each $B_0$ sweep took 6 minutes. Because the Overhauser field should decay during the $B_0$ sweep, we calibrated the elapse time before the EDSR peak was observed by taking into account the sweep rate and the peak position. The elapse time is counted from the time when
the last peak of the polarization was measured in Fig. 3(a). We plotted the time evolution of the peak 1 position, $B_{peak}$ in Fig. 4 (The other peak has no resolution for the time evolution ). The origin of the measurement is taken at the time when the last peak point on the top right corner in Fig. 3 (a). $B_{peak}$ decays with a time constant of 530 sec, which reflects nuclear spin dynamics or the relaxation time of nuclear spin polarization [11]. Decay time of Overhauser field previously reported is $\sim$ 10 seconds [2, 6], much shorter than the present value. In addition, typical Overhauser shifts in the reports [2, 6] are from 10 to 20 mT and a few times smaller than our results.

There are several reports about the decay time of nuclear spin polarization in GaAs systems, but the values are sometimes different. A short decay time of order of 10 seconds is reported in Ref. [2] and [6], while a decay time longer than a minute and the other is reported in Refs. [13] and [14]. There is also a report on observation of a fast decay followed by a slow decay. We consider that we only observed the slow decay, although the reason is not very clear.

The possible reason of the difference is due to the fact that nuclear spins are only polarized in one of the two dots, whereas nuclear spins in both dots are polarized in previous reports [2, 6]. For example in Ref. [2], nuclear spins are polarized through a flip-flop process between electron and nuclear spins when electrons transit the double dot thereby affecting nuclear spins over the two dots. In Ref [6] an Overhauser shift measured in ESR is explained by considering that both electron spins are sometimes flipped in two dots. Then the nuclear spin bath should be polarized differently between two dots, and it can accelerate the decay of nuclear spin polarization. In order to examine the decay mechanism in detail it is necessary to tune symmetry or asymmetry of nuclear spin polarization between two dots. For this purpose we have to modulate the magnetic field quickly over the range of EDSR for both dots. So we are developing a faster magnetic field handling system to polarize nuclear spins in both dots almost simultaneously.

4. Conclusion
We measured the Overhauser shift of EDSR in QD. The higher peak exhibit larger Overhauser shift than the other. The relaxation time of Overhauser field is so long as $\sim$ min but recently is reported much shorter. We compare our result with those previously reported. It is important to study carefully in detail to understand the DNP mechanism and the origin of the difference of relaxation time constant. Further studies are needed.

Acknowledgments
The authors thank L.M. Vandersypen for fruitful discussions.

References
[1] D. Klauser, W. A. Coish, and D. Loss, Phys. Rev. B 73, 205302 (2006).
[2] D. J. Reilly et al., Science 321, 781 (2008).
[3] J. Danon and Y. V. Nazarov, Phys. Rev. Lett. 100, 056603 (2008).
[4] M.S. Rudner and L.S. Levitov, Phys. Rev. Lett. 99 036602 (2007).
[5] A. Abragam, Principles of Nuclear Magnetism, (Oxford University Press, 1961).
[6] I. T. Vink et al., Nature phys on-line 16 August 2009, nphys1366.
[7] F.H.Koppens, K.J. Nowack, and L.M. Vandersypen, Phys. Rev. Lett. 100 (2008) 236802.
[8] M. Pioro-Ladriere et al., Nature Physics 4 776 (2008).
[9] Y. Tokura et al., Phys. Rev. Lett. 96 047202 (2006), M. Pioro-Ladriere et al., App. Phys. Lett. 90 024105 (2007).
[10] M. Pioro-Ladriere et al., in preparation.
[11] N. Kumada et al., Phys. Rev. Lett 94, 096802 (2005).
[12] E.I. Rashba, Phys. Rev. B 78, 195302 (2008).
[13] K. Ono and S. Tarucha, Phys. Rev. Lett. 92, 256803 (2004).
[14] S. Teraoka et al., Physica E 21, 928 (2004).
[15] J. Baugh et al., Phys. Rev. Lett. 99, 096804 (2007).