Coherent control of two individual electron spins and influence of hyperfine coupling in a double quantum dot

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Abstract. Electric dipole spin resonance of two individual electrons and the influence of hyperfine coupling on the spin resonance are studied for a double quantum dot equipped with a micro-magnet. The spin resonance occurs by oscillating the electron in each dot at microwave (MW) frequencies in the presence of a micro-magnet induced stray field. The observed continuous wave (CW) and time-resolved spin resonances are consistent with calculations in which the MW induced AC electric field and micro-magnet induced stray field are taken into account. The influence of hyperfine coupling causes an increase and broadening of the respective CW spin resonance peaks through dynamical nuclear polarization when sweeping up the magnetic field. This behaviour appears stronger for the larger of the two spin resonance peaks and in general becomes more pronounced as the MW power increases, both reflecting that the electron-nuclei interaction is more efficient for the stronger spin resonance. In addition the hyperfine coupling effect only becomes pronounced when the MW induced AC magnetic field exceeds the fluctuating nuclear field.

1. Introduction
Following the Loss and DiVincenzo's proposal on spin-based quantum computing with quantum dots (QDs) \cite{loss1}, and motivated by the realization of single and double QDs holding just one or two electrons \cite{koppens1,ming1,ding1} and the observation of a robust spin degree of freedom \cite{hanson1,liu1}, considerable effort has been devoted to make electron spin qubits. Consequently spin qubits utilising the spin up and down state in single QDs have been demonstrated using electron spin resonance (ESR) \cite{baibich1,baibich2,baibich3} and qubits utilising the spin singlet and triplet state have been demonstrated by manipulating the inter-dot exchange
coupling in a double QD [12,13]. ESR is a well-known technique but its application to spin qubits is still a challenge, because a sufficiently strong AC magnetic field has to be operated on single electrons in single QDs. Such an AC field has been prepared using a micro-coil placed on top of a QD with an AC current flowing through it [8] and an electric dipole spin resonance (EDSR) technique. In the latter a local AC magnetic field for a QD is generated by application of a MW electric field to the QD through a spin-orbit interaction [9,14,15] and an inhomogeneous magnetic field [16]. We have recently used a micro-magnet to generate the inhomogeneous magnetic field [10,17] and demonstrated two qubits for the first time [11], and in addition proposed a scheme for implementing a multiple qubit system. The micro-magnet when externally laterally magnetized, produces an out-of-plane stray field across a QD with a gradient of ~ T/\mu m. Spatial oscillation of an electron inside the dot driven by the MW field can generate an AC magnetic field local to the dot (see Fig. 1a). In addition, the micro-magnet induced stray field has an in-plane component along the magnetization direction, which is added to the external magnetic field to provide a total Zeeman field to the dot. Spin resonance localized to the dot occurs when the MW frequency is consistent with the total Zeeman energy.

Here we present CW and time-resolved EDSR experiments for two individual electrons in a double QD using the micro-magnet technique and then we discuss the influence of the hyperfine interaction observed in the CW EDSR. This influence occurs through dynamical nuclear polarization (DNP) [18,19] and statistical fluctuation of the Overhauser field [20], and has been argued as an emerging problem in spin-based quantum computing. We find that the DNP appears stronger for the stronger of the two spin resonances.

2. Electron spin resonance

Figure 1b shows a scanning electron micrograph of the GaAs double QD used in the experiment. Two dots, Dot 1 and 2, are made in a two-dimensional electron gas by applying relevant voltages to the gate electrodes (Fig. 1c). A current $I_{dot}$ flowing through the double dot is initially measured as a function of two side gate voltages to define the charge state with the electron number $N_1$ and $N_2$, for Dot 1 and 2, respectively of $(N_1,N_2)=$(1,1) and (2,0) under an external in-plane magnetic field $B_0$. When the Co micro-magnet on top of the gated structure is externally magnetized in-plane (along $z$), a stray magnetic field is generated at the double dot with a slanted out-of-plane field $B_{\perp}(z)$ ($dB_{\perp}/dz \sim 0.8$ T/\mu m) and an inhomogeneous in-plane field $B_\perp(x)$ providing a Zeeman field offset, $\Delta B_0 \approx B_{0L}-B_{0R}$ ($\approx$ 20 to 30 mT) between the two dots.

![Figure 1.](image_url)

Figure 1. (a) Oscillating electron in a micro-magnet induced stray field. (b) Scanning electron micrograph of the device. The Co micro-magnet is intentionally displaced but usually placed between the dotted lines. (c) Schematic device cross-section, indicating formation of a double dot.
EDSR occurs for each QD by spatially displacing the electron in the presence of B. (z) by applying high frequency AC voltage to the MW gate electrode to satisfy the condition \( f_{\text{a.c.}} = g\mu_B B_{0,\pm1,2} \), where \( f_{\text{a.c.}} \) denotes the MW frequency, \( \mu_B \) is the Bohr’s magneton, \( B_{0,\pm1,2} \) corresponds to the total in-plane magnetic fields at the left and right dot, respectively (see Fig. 1b). To observe the EDSR for each QD we operate a double dot in the Pauli spin blockade (PSB) [21] established by the formation of a spin triplet state \((T_+ = |\uparrow\rangle|\uparrow\rangle\) or \(T_- = |\downarrow\rangle|\downarrow\rangle\)) for \((N_1,N_2) = (1,1)\) (Fig. 2a). Figure 2b shows the current \(I_{\text{dot}}\) through the double dot vs. the external magnetic field \(B_0\) measured for \(f_{\text{a.c.}} = 25.6\) GHz. A sufficiently large source-drain bias of 1.0 to 1.5 mV is applied to avoid the influence of photon assisted tunneling (PAT) through the outer barriers. In this figure, we see two peaks separated by 30 mT, reflecting the EDSR for the individual electrons in the two dots. The current through the double dot is initially blocked by Pauli exclusion once a spin triplet state has been formed in the double dot. Spin-flip induced by EDSR in either dot lifts the blockade, giving rise to a finite leakage current. The EDSR peak height, \(I_{\text{EDSR}}\), is proportional to the square of the MW induced magnetic field, \(B_{\text{MW}}\), and therefore \(I_{\text{EDSR}} \propto E_{\text{MW}}^2 (dB_{\perp}/dz)^2\), where \(E_{\text{MW}}\) is the amplitude of the MW electric field at each dot [11]. From calculation of \(E_{\text{MW}}\) and \(dB_{\perp}/dz\) we assign the larger peak (smaller peak) at the lower (higher) \(f_{\text{a.c.}}\) to EDSR for Dot 1 (2).

![Figure 2](image)

**Figure 2.** (a) Measurement scheme of EDSR current. (b) CW EDSR current measured for two individual electrons in the two dots (Dot 1 and 2).

After the CW EDSR experiment, we readjusted the device conditions and performed a pump and probe experiment to observe time-resolved EDSR (Fig. 3). We varied the detuning \(\varepsilon\) with gate voltage pulses to switch the operation stage between A (initialization to either \(T_1(1,1)\) or \(T_2(1,1)\) in the Pauli spin blockade regime with \(\varepsilon = 0\) and \(J \sim t\), inter-dot tunnel coupling) and B (spin rotation in either dot with \(\varepsilon \gg 0\), \(J \sim 0\)). The EDSR is only pumped in stage B for various MW burst time \(\tau_b\) and then probed in stage A. The result of the pump and probe experiment performed for the right dot is shown in Fig. 4 as a function of MW burst time \(\tau_b\). The oscillatory current with \(\tau_b\) indicates Rabi oscillations with a frequency \(v_{\text{Rabi}}\) of 8.9 MHz in the sinusoidal curve fit. The Rabi frequency \(v_{\text{Rabi}}\) is proportional to \(B_{\text{MW}}\), i.e. \(v_{\text{Rabi}} = g\mu_B B_{\text{MW}}/2h = g\mu_B/2h \times (dB_{\perp}/dz) E_{\text{MW}} L_{\text{orb}}^2/\Delta\) [17]. Here, the orbital spread, \(L_{\text{orb}}\), and the QD confinement energy, \(\Delta\), are 48 nm, and 0.5 meV, respectively obtained from experiments performed separately. Using a calculated value of \(E_{\text{MW}}\) we derive \(v_{\text{Rabi}}\) of 11 MHz, fairly consistent with the experiment.
3. Influence of hyperfine coupling

Coupling between electron spin and nuclear spin is represented by a hyperfine interaction Hamiltonian:

\[ H_{\text{hf}} = A |\psi(x)|^2 \left( \frac{I_z S_z + I_x S_x}{2} + I_z S_z \right) \]

where \( A \) is the hyperfine constant, \( \psi(x) \) is the electron wavefunction and \( S (I) \) is the electron (nuclear) spin operator. The first term in the bracket indicates a flip-flop interaction, while the second term accounts for the Overhauser effect. Nuclear spins are dynamically polarized through the flip-flop interaction to build up a Zeeman field on the electron spin (DNP). This causes an Overhauser shift of the EDSR and at the same time works to sustain the EDSR condition through a positive feedback in the case of up-sweep of external field \( B_0 \) or down-sweep of MW frequency \( f_{\text{ac}} \). We studied the DNP effect for a device similar to that in Fig.1a but using a technique of charge sensing instead of transport measurement. The transconductance \( G = dI_{\text{QPC}}/dV_p \) of a quantum point contact (QPC) placed just outside the double dot is measured for the charge sensing. Here, \( I_{\text{QPC}} \) is the current through the QPC.
and $V_p$ is the voltage applied to the plunger gate of Dot 1, which is one of the gate electrodes attached to Dot 1 (not shown).

Figure 5 shows the QPC transconductance measured for sweeping up $B_0$ from 0.98 to 1.08 T with MW power $P_{MW}$ as a parameter and $f_{ac}$ fixed at 5.6 GHz. Two peaks in dark blue or red representing EDSR for two dots are initially observed at 1.0, and 0.99 T, respectively, for the lowest $P_{MW}$. Both peaks become broader and larger, suffering from DNP as the $P_{MW}$ increases. The peak height starts to increase for $P_{MW}$ exceeding -30 dBm, and more or less simultaneously the influence of DNP appears pronounced. The peak increase directly reflects the increase of $B_{MW}$ or Rabi frequency compared to the dephasing rate due to statistical fluctuation of nuclear spin. From the threshold of the MW power we calculate the corresponding $B_{MW}$ of a few mT comparable to the fluctuating nuclear field [10, 23]. This is reasonable because the influence of DNP should be visible when $B_{MW}$ is larger than the fluctuating nuclear field. The peak broadening, and peak shift with increasing $P_{MW}$ is due to the feedback effect, and the Overhauser effect, respectively, as described before. On the other hand, as the $P_{MW}$ is further increased exceeding -25 dBm, the peak height starts to decrease. This is probably because of multiple-photon assisted tunneling through the outer tunnel barriers or electron heating to degrade the EDSR signal. Note when sweeping down $B_0$, no significant DNP effect is observed.

![Figure 5. Two EDSR peaks measured for various microwave powers.](image)

### 4. Conclusion

We have used a micro-magnet technique to realize CW and time-resolved electric dipole spin resonance of two individual electrons in a double quantum dot and study the influence of hyperfine coupling on the spin resonance. The spin resonance occurs when an electron oscillates inside the dot driven by the microwaves in the presence of a micro-magnet induced stray field across the dot with the microwave frequency equivalent to the Zeeman energy. We have observed two spin resonance peaks separated by the inhomogeneous Zeeman energy between the two dots which is also imposed by the micro-magnet. We have applied a pump and probe technique for the spin resonance to observe Rabi oscillations for one of the two dots. The Rabi oscillation frequency is proportional to the microwave field, consistent with theory. We have observed the influence of hyperfine coupling on the two CW spin resonance peaks through the dynamical nuclear polarization, which is stronger for the larger of the two spin resonance peaks and in general becomes more pronounced as the microwave power increases, both reflecting that the electron-nuclei interaction is more efficient for the stronger spin resonance.
Acknowledgments
This work was supported financially by Grants-in-Aid for Scientific Research S (No.19104007), B (No. 18340081), and Special Coordination Funds for Promoting Science and Technology. S. T. acknowledges support from the QuEST grant (HR0011-09-1-0007). S. T. and Y. T. acknowledge support from MEXT Grant-in-Aid for Scientific Research on Innovative Areas, Contract No. 21102003, Funding Program for World-Leading Innovative R&D on Science and Technology (FIRST) and ERATO-JST (08030000477). M.P.-L. acknowledges supports from the Japan Society for the Promotion of Science and the Canadian Institute for Advanced Research.

References
[1] Loss D and DiVincenzo D P 1998 Phys. Rev. A 57 120
[2] Tarucha S, Austing D G, Honda T, van der Hage R J and Kouwenhoven L P 1996 Phys. Rev. Lett. 77 3613
[3] Ciorga M, Sachrajda A S, Hawrylak P, Gould C, Zawadzki P, Jullian S, Feng Y and Wasilewski Z 2000 Phys. Rev. B 61 R16315
[4] For review see, for example van der Wiel, De Francesch S, Elzerman J M, Fujisawa T, Tarucha S and Kouwenhoven L P 2003 Reviews of Modern Physics 75, 1-22
[5] Fujisawa T, Austing D G, Tokura Y, Hirayama Y and Tarucha S 2002 Nature 419 278
[6] Elzerman J M, Hanson R, Willems van Beveren L H, Witkamp B, Vandersypen L M K and Kouwenhovenet L P 2004 Nature 430, 431
[7] Amasha S, MacLean K, Radu I P, Zumbühl D M, Kastner M A, Hanson M P and Gossard A C 2008 Phys. Rev. Lett. 100, 046803
[8] Koppens F H L, Buizert C, Tielrooij K J, Vink I T, Nowack K C, Meunier T, Kouwenhoven L P and Vandersypen L M K. 2006 Nature 442 766
[9] Nowack K C, Koppens F H L, Nazarov Yu V and L.M.K. Vandersypen L M K 2007 Science 318 1430
[10] Pioro-Ladriere M, Obata T, Tokura Y, Shin Y -S, Kubo T, Yoshida K, Taniyama T and Tarucha S 2008 Nature Physics 4 776
[11] Obata T, Pioro-Ladrière M, Tokura Y, Shin Y -S, Kubo T, Yoshida K, Taniyama T and Tarucha S 2010 Phys. Rev. B 81 085317
[12] Petta J R, Johnson A C, Taylor J M, Laird E A, Yacoby A, Lukin M D, Marcus C M, Hanson M P and Gossard A C 2005 Science 309 2180
[13] Foletti S, Bluhm H, M. Aharonov V, and Amir Yacoby A, 2009 Nature Physics 5 903.
[14] Golovach V N, Borhani M, and Loss D 2006 Phys. Rev. B 74 165319
[15] Rashba E I and Efros A L 2003 Phys. Rev. Lett. 91 126405
[16] Laird E, Barthel A C, Rashba E I, Marcus C M, Hanson M P and Gossard A C 2007 Phys. Rev. Lett. 99 246601
[17] Tokura Y, van der Wiel W G, Obata T and Tarucha S 2006 Phys. Rev. Lett. 96 047202
[18] Ono K and Tarucha S 2004 Phys. Rev. Lett. 92 256803
[19] Kodera T, Ono K, Kitamura Y, Tokura Y, Arakawa Y and Tarucha S 2009 Phys. Rev. Lett. 102 146802
[20] Koppens F H L, Folk J A, Elzerman J M, Hanson R, Willems van Beveren L H. Vink I T, Tranitz H P, Wegscheider W, Kouwenhoven L P and Vandersypen L M K 2005 Science 309 1346
[21] Ono K D.G. Austing, Y. Tokura, and S. Tarucha 2002 Science 297 1313.
[22] Obata T, Pioro-Ladriere M, Tokura Y, Brunner R, Shin Y -S, Kubo T, Yoshida K, Taniyama T, and Tarucha S 2009 J. Phys.: Conf. Ser. 193, 012046 1-3
[23] Rashba E I 2008 Phys. Rev. B 78, 195302