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Electron – Nuclear Spin Interaction in Vertical Double Quantum Dot with Different g-factor Layers System

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1. Introduction

Electron spins in semiconductor couple to a large number of nuclear spins N ~10^5–10^6, via hyperfine interaction. The various effects caused by this interaction have been studied by electron transport in III-V semiconductor nano structures, such as quantum Hall system [1] and quantum dots [2].

We are studying this interaction in a vertical double quantum dot (DQD) device. In our previous studies, Pauli Spin Blockade (SB) regime [3] has been used. Under weak in-plane magnetic fields, a leakage current in SB can be a sensitive prove for hyperfine interaction because SB state is relieved by the spin flip events [4]. In this paper, we studied this effect in more detail with various parameter range such as energy offset between dots, g-factor of each dot.

2. Device structure and measurement

Fig. 1(a) shows a schematic of the DQD device. The device has two independent gate electrodes that enable us to control of two electrostatic potentials of each dot independently. This device is made of sub-micron pillar structure (~0.5 μm in diameter) of double quantum well structure. Double quantum wells consist of 10 nm GaAs and 7.5nm $In_{0.04}Ga_{0.96}As$, and triple barriers is 7.0 nm and 6.5 nm $Al_{0.3}Ga_{0.7}As$ (the thicker is center barrier). The electron g-factors of each dot in our device are estimated as –0.33 for GaAs well and –0.89 for InGaAs well [5]. The Ti/Au metal double gates are surrounding the pillar of device. We measured current I_{sd} flows through dots with applying dc source drain voltage V_{sd} and in-plane magnetic field B_{dc} at temperature ~1.5 K.

Fig. 1(b) shows an intensity color plot of stability diagram of our device as function of V_{g1} and V_{g2}. Coulomb oscillations that have peaks at so called triple points, are clearly observed. It is found that tunable range of a *potential offset* (defined as the deference of numbers of electron at V_{sd} = 0) is 0 ~ 2. SB state occurs around *offset* = 1, where the two-electron spin is almost fixed to the spin triplet and the electron transport is blocked (see Fig. 1 (d)). We measured Coulomb diamonds at *offset* ~ 0.65 as shown in Fig. 1(c). SB region appears on the left side of N = 2 diamond (dotted line). In this region, we fixed the gate voltages and V_{sd}, and measured a leakage current of order of 1pA with applying B_{dc}.

We observed two types of current steps in the B_{dc} dependence of the leakage current as various V_{sd} as in Fig. 2(a) and (b). One of the current steps (Fig. 2(a)) shifted toward lower magnetic field side with increasing V_{sd} (equivalent to increasing the energy difference between two dots). This is similar to those, which were observed in our previous study [4]. Another type of current steps is observed in lower V_{sd} region, which shift toward high magnetic field side with increasing V_{sd}. This behavior has not been observed in our previous DQD devices.

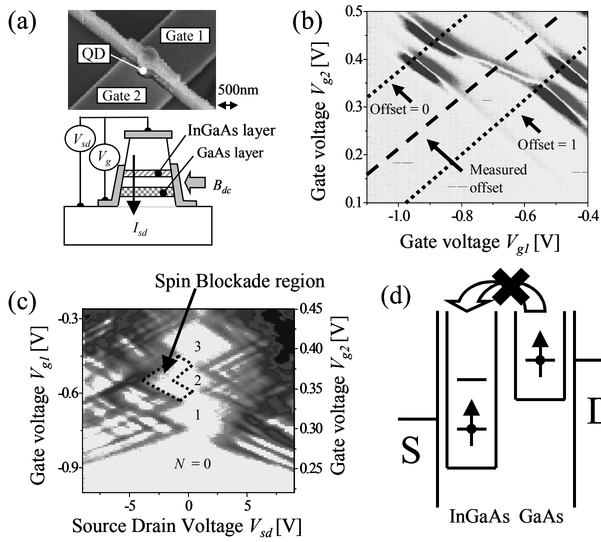

Fig. 1 (a) SEM image and Schematic of our DQD device. (b) Intensity color plot of the stability diagram. Dot lines indicate *potential offset* between dots is 0 and 1. We measured a Coulomb diamond along the dash line (*offset* ~ 0.65). (c) Measured Coulomb diamond at *offset* ~ 0.65. (d) Potential landscape and the electron spins in SB region. An electron in GaAs dot cannot tunnels to InGaAs dot by Pauli principle, the two-electron spin state is almost fixed to the triplet state in two electrons system, and the current is suppressed.

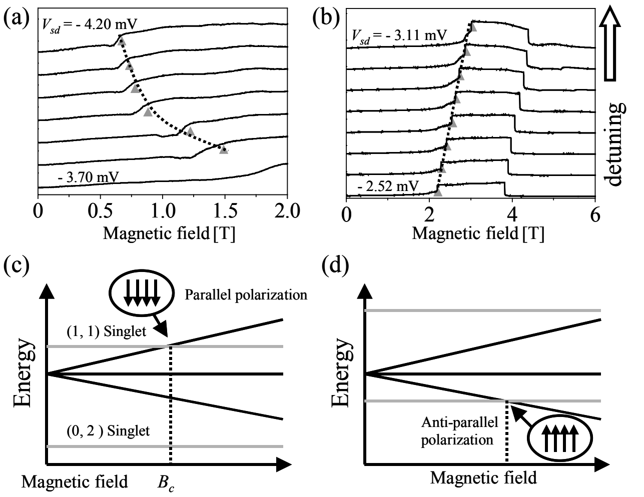

Fig. 2 (a), (b) Leakage curernt of SB region with sweeping B_{dc} up from 0 T, with fixing V_{sd} and gate voltages. Current steps (indicating as gray triangle marks) are observed. Hystereses of the current against B_{dc} sweep are also observed (not shown). With increasing V_{sd}, the current step in (a) shifts toward lower magnetic field, and the current step in (b) shifts toward lower field. (c), (d) Crossing of triplet (black lines) and singlet (gray lines). The electron spin direction is opposite in higher and lower triplet, therefore nuclear spin polarization direction may become opposite.

The current steps as in Fig. 2(a) were explained as follows [3]. Electrons state in SB is fixed to the spin triplet state, and SB state is relived by scattering from the triplet to singlet state. Fig. 2(c) shows schematic energy diagram of spin states in SB region with B_{dc}. The higher spin triplet state crosses the spin singlet state at a crossover magnetic field B_c (noted as a (1, 1) singlet, where each dot holds one electron). At this point, the spin triplet state can be scatter to the (1, 1) singlet state elastically due to the electron spin -nuclear spin flip-flops of the hyperfine interaction. As this flip-flop process are repeated, nuclear spins in the dot are polarized. (1, 1) singlet level decreases with increasing detuning, therefore B_c shifts toward lower side with V_{dc}.

In contrast, the current steps observed in Fig. 2 (b) shift towards lower B_{dc}. Thus we consider the crossing between the triplet and the lower singlet (noted as a (0, 2) singlet, where GaAs dot is empty and InGaAs dot holds two electrons) in Fig. 2(d), because the separation between the triplet and the (0, 2) singlet is increase with increasing V_{dc}, B_c shifts toward higher side. We calculated V_{dc} dependence of the B_c based on the Hubbard model [6] with parameters obtained from the Coulomb diamond analysis. Although using no fitting parameters, the calculation reproduced reentrant behavior with reasonable quantitative agreements with Fig. 3(a), showing the plot of current step positions extracted from the measurements (Fig. 2 (a) and (b)).

Thus we conclude that the observed current steps in Fig. 2 (a) ((b)) are due to the crossover between the spin triplet and (1, 1) singlet ((0, 2) singlet) respectively. This means that nuclear spin polarization with *both directions* (Parallel or anti parallel to the B_{dc}) in achieved by the only electrical control of quantum dots.

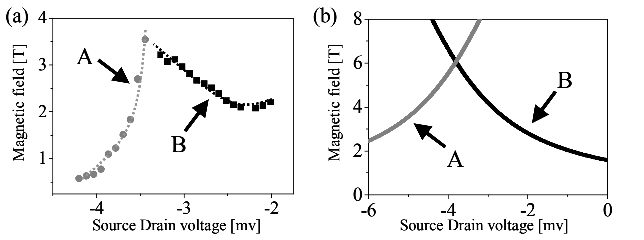

Fig. 3 (a) Extracted the Current step position in measured data. (b) Calculation based on the Hubbard model. Parameters are obtained from the Coulomb diamond analysis of the device. The estimated parameters are onsite (inter-dot) Coulomb energy = 3.78 meV (1.61 meV), potential offset at zero voltage = 1.41 meV, tunnel coupling constant = 0.134 meV and voltage drop ratio for three barriers are 0.40, 0.20 and 0.40. The line A (gray line) corresponds to the crossing the triplet and (1, 1) singlet and the line B (black line) correspond to the triplet and the (0, 2) singlet.

3. Conclusions

We investigate the electron – nuclear spin interaction in SB state with using DQD device has different g-factor layers. Two types current step that shifts toward opposite magnetic field side with increasing detuning observed. It is suggest that electrical control of nuclear spin bipolar is possible.

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References

[1] M. Dobers *et al*., Phys. Rev. Lett. **61**, 1650 (1988), A. Berg *et al*., Phys. Rev. Lett. **64**, 2653 (1990), K. R.Wald *et al*., Phys. Rev. Lett. **73**, 1011 (1994), D. C. Dixon, *et. al*., Phys. Rev. B **56**, 4743 (1997), S. Kronmüller *et al*., Phys. Rev. Lett. **81**, 2526 (1998), K. Hashimoto *et al*., Phys. Rev. Lett. **88**, 176601 (2002), J. H. Smet *et al*., Nature (London) **415**, 281 (2002), T. Machida, *et al*., Appl. Phys. Lett. **80**, 4178 (2002), W. Desrat *et al*., Phys. Rev. Lett. **88**, 256807 (2002), G Yusa *et al*., Nature (London) **434**, 1001 (2005), G. Gervais *et al*., Phys. Rev. Lett. **94**, 196803 (2005), N. Kumada et al., Science **313**, 329 (2006), M. Kawamura *et al*., Appl. Phys. Lett **90**, 022102 (2007), X. C. Zhang *et al*., Phys. Rev. Lett. **98**, 246802 (2007).

[2] F. H. L. Koppens et al., Science **309**, 1346 (2005), J. R. Petta et al., Science **309**, 2180 (2005).

[3] K. Ono *et al*., Science. **297**, 1313 (2002).

[4] K. Ono *et al*., Phys. Rev. Lett. **92**, 256803 (2004), J. Baugh *et al*., Phys. Rev. Lett. **99**, 096804 (2007).

[5] S. M. Huang *et al*., arXiv:0904.1046 (2009).

[6] T. Kodera *et al*., Phys. Rev. Lett. **102**, 146802 (2009).