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Coherent Manipulation and Bi-Directional Polarization of Nuclear Spins in a Quantum Dot Device

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1. Introduction

Nuclear spins in solids are attracted to condensed matter physics or an application as a quantum bit or memory with quantum information technologies. Recently, electrically controlled dynamic nuclear polarization (DNP) has been demonstrated in quantum Hall regime [1] or quantum dot [2] using spin-flip-flops in the hyperfine interaction. However, a direction of DNP in previous works was limited only one, because a change of spin angular momentum of electron spins is limited to +1.

In vertical double quantum dots (DQDs), this DNP appears by lifting of the Pauli spin-blockade (SB) state [3] that corresponds to the (1, 1) spin triplet state in two-electron system where (n, m) means number of electrons in a left and a right dot. This lifting is caused by a transferring from the triplet to the singlet by flip-flop spin scatterings with nuclei of host material, and detected by an increase of the leakage current value of order 1 pA. In previous works [2], the only spin scatterings from T_- to the singlet (a T_-–singlet scatterings, see Fig. 1), thus the change of electron spin angular momentum is always +1, and the change of nuclear spin is always –1. By repeating this process, DNP with downward direction appears as showed in the upper panel of Fig. 1.

We introduce an electrically pumped bi-directional DNP combining with T_+–singlet scatterings as well as the T_-–singlet scatterings. It is considered that in previous works DNP with T_-–singlet scatterings appears only in the SB state, we found that new DNP with T_+–singlet scatterings can be appeared close to the SB region. Above new DNP due to T_+–singlet scatterings leads to opposite polarization direction, *i.e.* upward (see the lower panel of Fig. 1). Thus it means bi-directional DNP can be realized. With using pulsed RF measurement, we confirmed that bi-directional DNP can be realized, and these directions can be switched only source-drain voltage values.

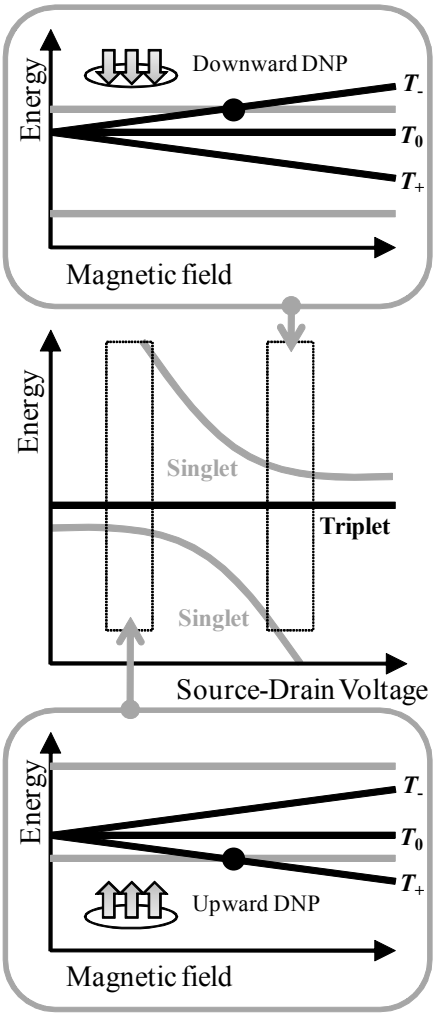

Figure 1 (Center) two-electron and two-site energy diagram with changing source-drain voltage. (Upper) Intersecting of T_-–singlet under a finite magnetic field. Appeared DNP direction is downward. (Lower) Intersecting of T_+–singlet, thus DNP direction is upward. These directions can be switched by only source-drain voltage.

2. Device and Measurement

Figure 2 (a) shows a schematic of our vertical DQD device. This device is made of sub-micron pillar structure (~ 0.5 μm of diameter) of double quantum wells. These wells consist of both 10-nm-thick GaAs and 7.5-nm-tchick $In_{0.04}Ga_{0.96}As$, and triple barriers consist of layers of $Al_{0.3}Ga_{0.7}As$ with thickness of 7.0 nm and 6.5 nm (the thicker layer is the center barrier) [4].

This devise has two independent gate electrodes that enable us to control of two electrostatic potentials of each dot. The stability diagram showing in Fig. 2 (b) indicates Coulomb oscillation and electron configurations in dots plotted as functions of these gate voltages,

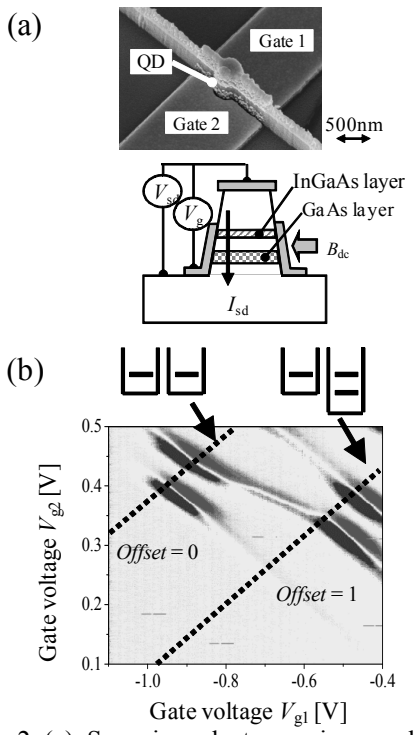

Figure 2 (a) Scanning electron micrograph image and schematic of our vertical DQD device. (b) Intensity color plot of the stability diagram. Dashed line indicates that energy level state of dots corresponds to *offset* = 0 or 1 showing in upper figure.

V_{g1} and V_{g2} at temperature ~ 1.5 K. Potentials can be tuned, for example, all levels align on the line indicating as *offset* = 0, or only one lowest level mismatches on the line indicating *offset* = 1. The SB state arises around the two-electron state on the *offset* = 1 line, and the previous DNP were measured in this region. We investigated in the region with 0 < *offset* < 1 that corresponds to the region between *offset* = 0 and 1 line in Fig. 2 (b).

Figure 3 shows Coulomb diamond at from *offset* ~ 0 to 1. In (b), the SB region also appears on the negative source-drain voltage, V_{sd}, side next to the Coulomb blockade region of $N = 2$ where N is total electron number in dots. In this region, we measured a magnetic field dependence of the leakage current with applying static magnetic field, B_{dc}, to in-plane direction showing in Fig. 2 (a). We observed two kinds of current steps that behave different each other against changing V_{sd}. One is the same to current steps in previous works, which shifts toward lower magnetic field side with changing V_{sd} because energy level difference between the triplet and higher singlet becomes smaller (see the center of Fig. 1). On the other hand, another shifts toward higher filed side that corresponds to the change of energy difference between the triplet and lower singlet as shown in the middle panel of Fig. 1.

At both steps, continuous wave with radio frequency (RF) approximately resonant frequency of nuclear spices, ^{75}As, ^{69}Ga and ^{71}Ga, respectively, applied with using a coil

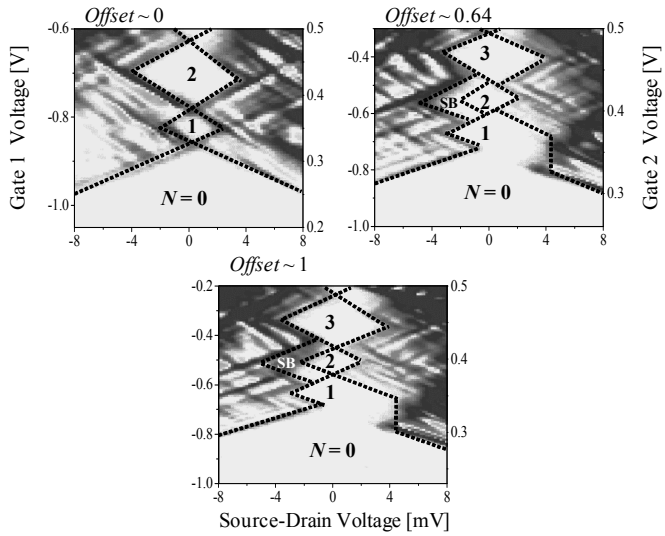

Figure 3 Coulomb diamond at *offset* ~ 0, 0.64, 1, respectively. Spin-blockade region appears at both 0.64 and 1 indicating as the SB.

[5]. In the result, NMR signal was observed, thus it is confirmed that there is a relation between current step and nuclear spin.

In order to confirm that bi-directional DNP can be realized, we measured the change of leakage current combining with voltage switching sequence [5] and pulsed RF. As the result, we found out as follows; (1) bi-directional DNP can be realized with using DC voltage and magnetic field, (2) directions of DNP can be switched by only values of V_{sd} and manipulated by pulsed RF coherently.

3. Conclusions

We confirmed that the realization of bi-directional DNP can be switched only V_{sd}. Although we used RF and several setups for these measurements, our method does not require these, in addition, not depending on device structures and materials.

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References

[1] S. Kronmüller *et al*., Phys. Rev. Lett. **81** (1998) 2526, S. Kronmüller *et al*., Phys. Rev. Lett. **82** (1999) 4070, G. Yusa *et al*., Nature **434** (2005) 1001.

[2] K. Ono *et al*., Phys. Rev. Lett. **92** (2004) 256803, S. Tarucha *et al*., Phys. Stat. Sol. B **243** (2006) 3673, J. Baugh *et al*., Phys. Rev. Lett. **99** (2007) 096804, J. R. Petta *et al*., **100** (2008) 067601, T. Kodera *et al*., Phys. Rev. Lett. **102** (2009) 146802, S. Foletti *et al*., Nature Phys. **5** (2010) 903.

[3] K. Ono *et al*., Science **297** (2005) 1346.

[4] S. M. Huang *et al*., Phys. Rev. Lett. **104** (2010) 136801, R. Takahashi *et al*., Physica E **42** (2010) 833.

[5] R. Takahashi *et al*., Jpn. J. Appl. Phys. **49** (2010) 04DJ07.