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Long Spin Relaxation Time Observed in a Lateral Quantum Dot

Satoshi Sasaki[1], Toshimasa Fujisawa[1,2], Toshiaki Hayashi[1] and Yoshiro Hirayama[1,3]

[1]NTT Basic Research Laboratories, NTT Corporation,
3-1 Morinosato- Wakamiya, Atsugi, Kanagawa 243-0198, Japan
Phone: +81-462-40-3465 E-mail: satoshi@nttbrl.jp
[2] Tokyo Institute of Technology, 2-12-1 Ookayama, Meguro-ku, Tokyo 152-8551, Japan
[3]SORST-JST, 4-1-8 Honmachi, Kawaguchi, Saitama 331-0012, Japan

1. Introduction

Dynamics of electron spins in quantum dot is attracting a great interest recently in the context of spintronics and quantum computation. In particular, spin is considered as one of the promising candidates for a quantum bit because of its long relaxation time. So far, electrical pump-and-probe method has been employed to extract a long spin relaxation time of about 200 μs from a spin triplet (S=1) excited state to a singlet (S=0) ground state in a vertical quantum dot (artificial atom) [1]. Non-essential cotunneling is found to be a dominant spin relaxation mechanism in the above case. Therefore, investigation of the spin relaxation mechanism is necessary when cotunneling is suppressed. In this work, we use a lateral quantum dot which allows us an in-situ control of the tunneling-rate, Γ. We find that the dominant spin relaxation mechanism changes from cotunneling to spin-orbit interaction as Γ is suppressed.

2. Experimental

Figure 1 shows an SEM picture of our quantum dot device. AlGaAs/GaAs two-dimensional electron gas (2DEG) is constricted by combined dry-etching and surface Shottky gates. We use only the three gates on the right hand side while leaving the other gates grounded to form a single quantum dot as shown by a white circle. We perform an electrical pump-and-probe measurement by applying two-step square pulses to the plunger gate as schematically shown in Fig. 1 [1]. All the measurements are performed in a dilution refrigerator at ~90 mK. The relaxation time, τ, can be determined from the exponential decay of $\langle n_t \rangle$, an average number of tunneling electrons per one pulse cycle, as a function of the wait time, t_h, during which an electron is allowed to relax from the excited state to the ground state. We study the spin relaxation from the triplet excited state, where electrons with parallel spin occupy different orbitals, to the singlet ground state, where electrons with anti-parallel spin occupy the same orbitals. Although it is difficult to accurately determine the number of electrons contained in our lateral quantum dot, we can identify the spin states by observing an evolution of the Coulomb blockade oscillation peaks with magnetic field applied perpendicularly to the 2DEG.

3. Results and Discussion

Figure 2 shows observed $\langle n_t \rangle$ as a function of t_h at B=0.6 T for various total tunneling-rate, $\Gamma_{tot}=\Gamma_L+\Gamma_R$, where Γ_L and Γ_R are the tunneling-rate for the left and right tunnel barriers, respectively. The solid lines are single exponential function fitted to the data, from which τ is estimated. The spin relaxation time decreases as Γ_{tot} increases.

Figure 3 shows a log-log plot of τ as a function of $\Delta \cdot \Gamma_{tot}^2$ for B=0.55 T and 0.6 T. Here, Δ is the energy difference between the triplet and singlet states, and depends on magnetic field. The data shown in Fig. 2 belong to large $\Delta \cdot \Gamma_{tot}^2$ regime (on the right hand side of the vertical dotted line in Fig. 3) where τ is inversely proportional to $\Delta \cdot \Gamma_{tot}^2$, indicating that cotunneling is a dominant spin relaxation mechanism there [1]. On the other hand, τ shows a saturation as Γ_{tot} is suppressed (on the left hand side of the vertical dotted line). The solid lines are the curves $(1/\tau_{so}+1/\tau_{cot})^{-1}$ fitted to the experimental data. Here, τ_{cot} is the relaxation time due to cotunneling which is inversely proportional to Γ_{tot}^2, and τ_{so} is the Γ_{tot} –independent relaxation time which, as we show below, is due to spin-orbit interaction [2]. The dashed line shows only the cotunneling component.

Figure 4 shows a spin relaxation characteristic observed at B=0.55 T in the small Γ_{tot} regime. We find that a single exponential curve cannot fit the measured decay characteristic of $\langle n_t \rangle$ here. Of the three triplet states whose spin z-component, S_z, is ±1 and 0, only S_z=±1 states can relax to the singlet state by spin-orbit interaction [3]. The solid line in Fig. 4 shows a double exponential function $C_1\exp(-t/\tau_{so})+C_2\exp(-t/\tau_{cot})$ fitted to the data. Here, C_1, C_2 and τ_{so} are fitting parameters, and τ_{cot} is determined as 810 μs by extrapolating the dashed line in Fig. 3 to the present value of small Γ_{tot} (=2.7x10^8). We find that the obtained ratio of C_1/C_2 is exactly 2 and τ_{so} is 60 μs. These results show that the dominant spin relaxation mechanism in the small Γ_{tot} regime is spin-orbit interaction (the allowed S_z=±1 transition) while the forbidden S_z=0 component slowly decays due to suppressed cotunneling.

4. Conclusion

We have measured spin relaxation time from a triplet state to a singlet state in a lateral quantum dot holding an even number of electrons by employing the electrical pump-and-probe method. We have found that the dominant spin relaxation mechanism changes from cotunneling to spin-orbit interaction as a tunneling-rate is suppressed.

References

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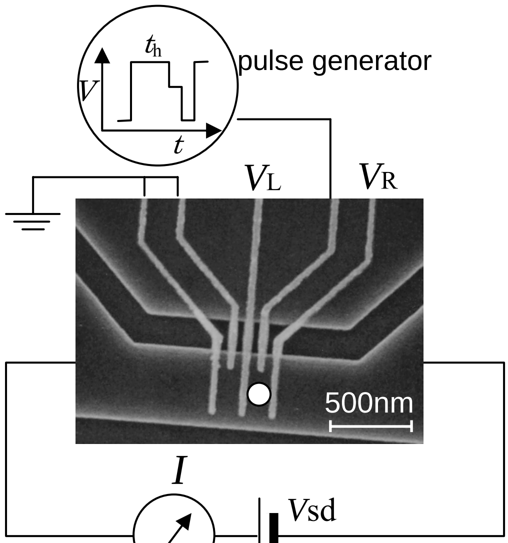

Fig. 1 SEM picture of the lateral quantum dot device. A schematic diagram of the measurement set-up is also shown. A single dot is formed as shown by a white circle. Voltage pulse is applied to the plunger gate.

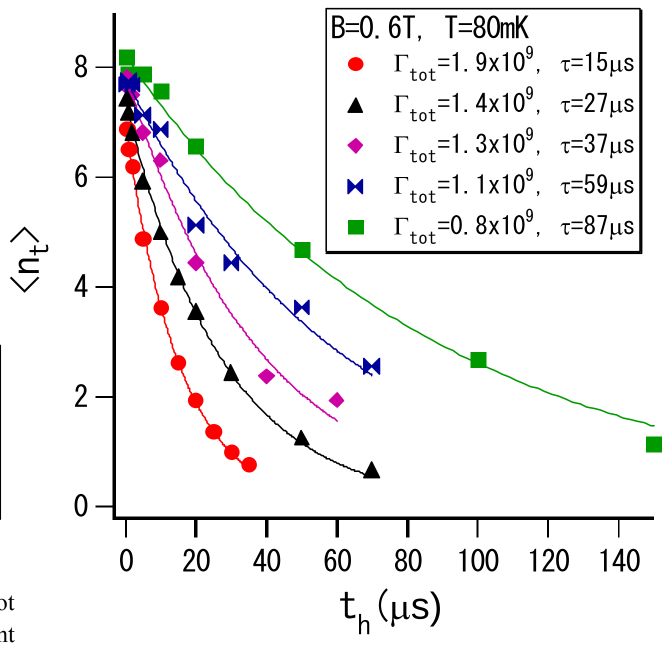

Fig. 2 Average number of tunneling electrons per one pulse cycle, $\langle n_t \rangle$, as a function of the high-pulse duration time, t_h, for various $\Gamma_{tot}=\Gamma_L+\Gamma_R$. The estimated spin relaxation time, τ, is inversely proportional to Γ_{tot}^2 indicating that cotunneling is a dominant spin relaxation mechanism in this large Γ_{tot} regime.

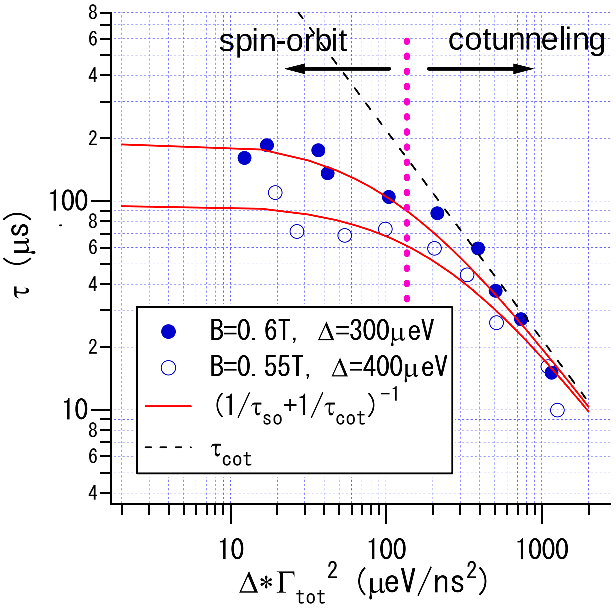

Fig. 3 The observed spin relaxation time, τ, as a function of $\Delta\cdot\Gamma_{tot}^2$ for B=0.55T and 0.6T. The solid lines are the curves $(1/\tau_{so}+1/\tau_{cot})^{-1}$ fitted to the experimental data, where τ_{so} and τ_{cot} are the relaxation time due to spin-orbit interaction and cotunneling, respectively. The dashed line shows only the cotunneling component, τ_{cot}.

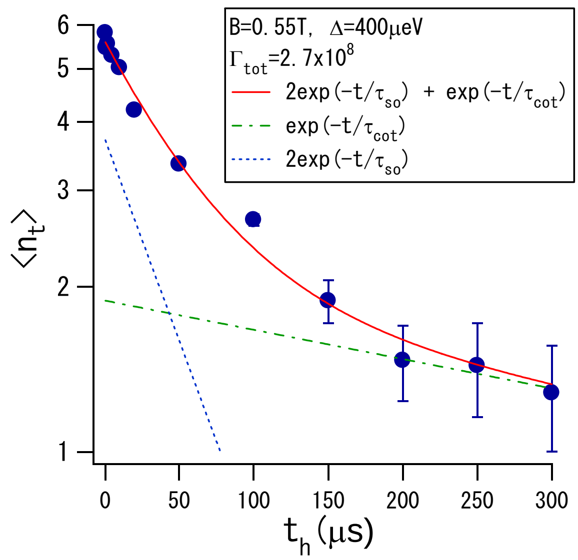

Fig. 4 Spin relaxation characteristic observed at small Γ_{tot} regime. Note that a single exponential decay is expressed as a straight line since the vertical axis is a log scale here. The experimental data is fitted well by a double-exponential decay (solid line). The dotted line shows the fast component due to spin-orbit interaction, and the dash-dotted line shows the slow component due to suppressed cotunneling.