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Electron number dependence of spin triplet–singlet relaxation time

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HIGHLIGHTS

- The relaxation time of spin singlet–triplet states for the last few even electron numbers has been studied.
- The singlet–triplet energy separation E_{ST} is tuned for the comparison of T_1 between different electron numbers.
- T_1 steadily decreases with increasing electron numbers from 2-electrons to 6-electrons.
- T_1 was found to substantially decrease due to the enhanced spin–orbit coupling strength.

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ABSTRACT

In a GaAs single quantum dot, the relaxation time T_1 between spin triplet and singlet states has been measured for the last few even electron numbers. The singlet–triplet energy separation E_{ST} is tuned as a control parameter for the comparison of T_1 between different electron numbers. T_1 steadily decreases with increasing electron numbers from 2-electrons to 6-electrons. This implies an enhancement of the spin–orbit coupling strength due to multi-electron interaction in a quantum dot.

1. Introduction

The spin singlet–triplet states of an electron pair in a quantum dot have been demonstrated as potential solid-state qubits [1–5]. Principally, any even number of electrons would form singlet–triplet configuration. Experimentally, spin blockade effect for a variety of even numbers of electrons has been observed [6] and the singlet–triplet-based qubits in the multi-particle regime has been recently studied [7]. A question that naturally arises is whether the multi-electron interaction interferes with the singlet–triplet coherence, such as enhancing relaxing or dephasing.

Here we study the singlet–triplet relaxation time T_1 in a single quantum dot for different even electron numbers. Since T_1 strongly depends on the singlet–triplet energy separation E_{ST}, we control E_{ST} by tuning the quantum dot shape with confinement gates. For a given electron number, T_1 is measured with the pump-and-probe technique [8]. At a fixed value of E_{ST}, T_1 undergoes a large decrease (roughly 3 times) when the electron number increases from 2 to 6. An increase in the spin–orbit coupling strength with larger electron number is found to explain the observed decrease in T_1.

2. Experiment

Fig. 1(a) shows a scanning electron microscopy (SEM) image of the gate-defined single GaAs quantum dot. The experiment was performed in a helium-3 refrigerator with a base temperature of 240 mK. The left barrier of the dot is closed and thus the electrons can only tunnel through the right barrier. The current through the quantum point contact (QPC) is recorded to count the charge number in the dot. A gap between the QPC and the dot is created to maximize the charge counting sensitivity. In this experiment the gap is closed tightly and the QPC dc bias voltage V_{QPC}^{dc} is small to minimize the back-action effect [9,10]. Fig. 1(b) shows the charge stability diagram measured by the QPC differential current while gate P and RB are biased at dc voltages. We will measure T_1 of the spin singlet–triplet states for 2e, 4e, and 6e, respectively.

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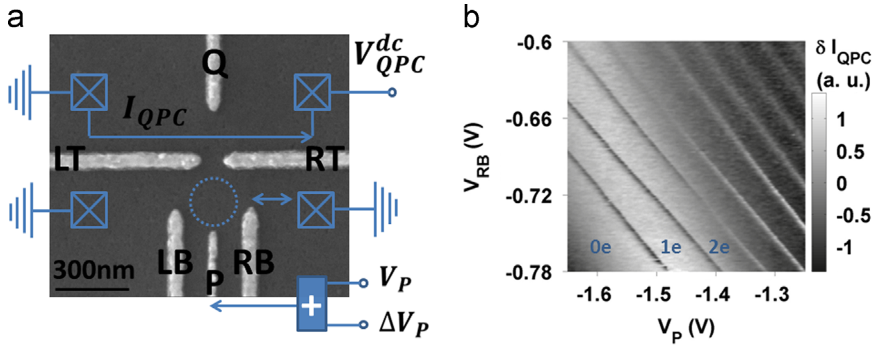

Fig. 1. (a) A SEM image showing the geometry of our sample. The dotted circle is the location of the quantum dot. Gate P is used to control the QD electron energy with respect to the Fermi level of the electron reservoir. Sometimes voltage pulse ΔV_P will be applied on gate P to dynamically probe the quantum dot energy spectrum. (b) Gray-scale plot of the QPC differential current as functions of voltages V_P and V_{RB}. Voltages on other gates are: $V_{LB}=-1.40$ V, $V_{LT}=V_{RT}=-1.50$ V, $V_Q=-0.90$ V, and $V_{QPC}^{dc}=0.3$ mV.

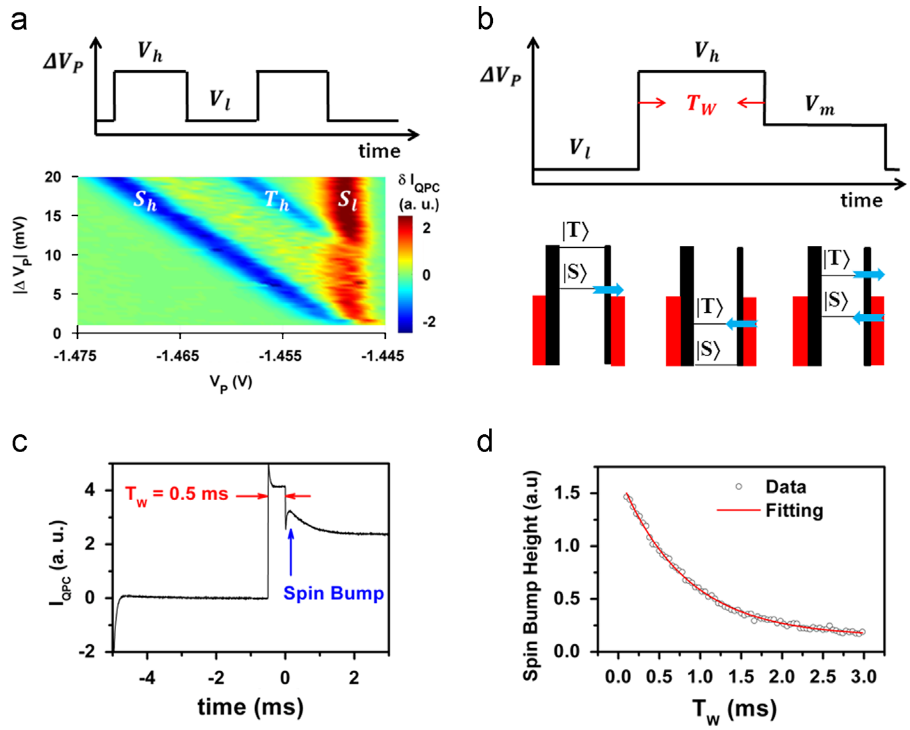

Fig. 2. (a) A sequence of square-waves is applied on gate P. The pulse frequency is typically 600 Hz. The gray-scale plot shows the numerically differentiated QPC current measured by a lock-in amplifier with time constant 300 ms. This graph is taken around the 1e↔2e transition region. $V_{RB}=-0.76$ V and all other gate voltages are the same as in Fig. 1(b). (b) The mechanism of the pump-and-probe measurement for the spin relaxation time when a sequence of three-step pulses is applied on gate P. (c) The gate-averaged QPC current over a sequence of 4000 pump-and-probe pulses. It begins with the low-level pulse, followed by a high-level pulse (T_W=0.5 ms in this example). Finally from 0 ms to 3 ms, the spin bump is read in the medium-level pulse step. (d) The spin bump height as a function of T_W. Open dots are the experimental data. Solid curve is the fitting with a first-order exponential decay.

As shown in Fig. 2(a), a sequence of square-wave voltage pulses is applied on the plunger gate P to probe the energy spectroscopy of the quantum dot by pumping the electrons to excited states [11]. The gray-scale plot shows the QPC response averaged over many duty cycles with a lock-in amplifier, in the 1e↔2e transition region. During each duty cycle, the low-level pulse V_l and high-level pulse V_h bring the QD electrons into the spin ground state $|S>$ twice, and correspondingly produce two charge transition lines, denoted as S_l and S_h. When the pulse amplitude is large enough, the high-level pulse V_h pumps the electrons into the spin excited state $|T>$ a well. In fact, we see an additional line desnoted as T_h between S_h and S_l when $|\Delta V_P| \equiv |V_h - V_l| \geq 12.3$ mV. Using the energy–voltage conversion factor 0.07 meV/mV, we determined E_{ST} as 0.86 meV in this Sample.

In order to detect the relaxation process from $|T>$ to $|S>$, we applied a sequence of three-step pulses [8,12], as illustrated in Fig. 2(b). The low voltage level V_l lifts the energy of both $|T>$ and $|S>$ states above the Fermi level E_F of the electron reservoir. This resets the quantum dot by emptying out either the $|T>$ or $|S>$ state. Then the high voltage level V_h drops the energy of both $|T>$ and $|S>$ below E_F. Therefore one electron is (may be) pumped into the dot to form a $|T>$ state with a certain probability. V_h sustains for a waiting time T_W, during which period the $|T>$ state can relax to $|S>$. Finally the medium voltage level V_m brings the energy of $|T>$ above E_F and keeps the energy of $|S>$ below E_F. If the $|T>$ state has already relaxed into $|S>$ after the waiting time T_W, no electron jumping occurs because the energy of $|S>$ is lower than E_F. If the relaxation has not completed yet, one electron on