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Transient Current in the Spin Blockade Region of a Double Quantum Dot

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1. Introduction

Electron spins in gated quantum dots have been extensively studied for their possible use in quantum information processing [1]. Pauli spin blockade in a double quantum dot (DQD) provides a way to manipulate two-electron spin states as well as the nuclear spin environment of the host crystal [2-4]. In case of typical GaAs double quantum dots, the Overhauser field, which is the effective fluctuating magnetic field felt by the electrons due to hyperfine coupling, is of a few tesla at maximum, strong enough to alter the electronic states completely. Spin blockade can be lifted by dynamic nuclear-spin polarization (DNP) with a small leakage current, which can change the electronic states significantly [5-8]. The current is sensitive to the nuclear spin polarization, but not directly related. The current can be hysteretic during the voltage or magnetic-field sweeps, and can fluctuate quite rapidly when the DNP is efficient. Controlling the nuclear spin polarization is an important step toward spin-based quantum information technology. Recently, some theoretical treatments for studying nuclear spin dynamics have been developed to explain experimental observations [9-11].

In order to study how the nuclear spin polarization develops we investigate the slow transient buildup of current influenced by DNP in this work. Here, we focused on slightly off-resonant conditions, where the current is extremely small with initially unpolarized nuclear spins. However, leaving the system in such a situation causes the current to increase stepwise *twice*. Such transient current steps can be understood by considering that at the first step inhomogeneous nuclear spin polarization significantly increases and at the second step stable polarization is attained. This finding may help in understanding how to stabilize nuclear spin fluctuation.

2. Spin-blockade and dynamic nuclear polarization

The DQD was formed by applying appropriate gate-voltages of the device fabricated in an AlGaAs/GaAs heterostructure as shown in Fig. 1(a). The experiments were performed in a dilution refrigerator at about 30 mK. The external magnetic field, B, applied perpendicular to the wafer, is small enough just to change the Zeeman splitting of the electronic states. The exact electron numbers (N_L, N_R) respectively in the (left, right) dots were identified with a quantum-point-contact (QPC) electrometer next to the DQD. Figure 1(b) and 1(c) show the current in non-blockade and spin-blockade bias direction, respectively,

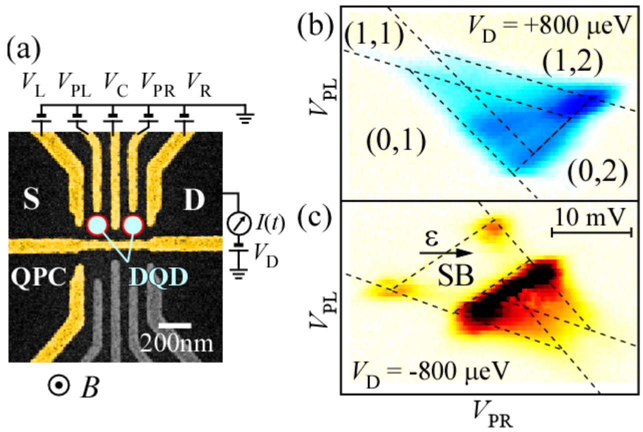

Fig. 1(a) Schematic of the experimental device, which incorporates 7 independently controlled gates. (b) and (c) Current I as a function of V_{PL} and V_{PR} for B = 0.1 T.

as a function of plunger-gate voltages, V_{PL} and V_{PR}. Two triangular transport windows at the bias voltage of 800 μV are clearly seen in Fig. 1(b), while the current is well suppressed by the spin blockade in the trapezoidal region (marked by SB) in Fig. 1(c). The shape of the current spectrum is consistent with the electrochemical potential of the system as seen in previous studies [4].

The spin blockade and DNP can be understood by considering the energy diagrams in Figs. 2(a) and (b), where one electron with either up or down spin resides permanently in the right dot. Injection of another electron from the left lead brings the system into one of the four (1,1) charge states shown, but only the spin-singlet state (1,1)S is allowed to move to (0,2) charge state (Pauli spin blockade). Current is suppressed when the electrons are in any of the long-lived three triplet states T_+, T_0, and T_- with spin z components +1, 0, and -1, respectively. T_+ and T_- states can change to (1,1)S by flipping the electron spins in the presence of Fermi's contact hyperfine interaction (the flip-flop term). Nuclear spin polarization accumulates when these flip-flop processes, corresponding to DNP in the two opposite directions, occur at unequal rates. The remaining T_0 state is uncoupled as long as the Overhauser fields at the two dots are identical ($P_L = P_R$), but becomes short-lived when nuclear spin polarization P_L and P_R in the left and right dot respectively develop differently.

Figure 2(c) shows the B dependence of the current spectrum in the spin blockade region, plotted as a function of the detuning ε converted from V_{PR}. The leakage current shows a peak (seen as a vertical line), which is assigned to

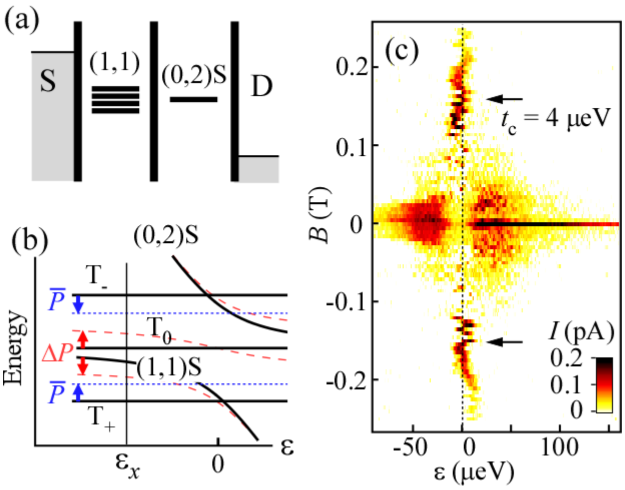

Fig. 2 (a) Schematic of electrochemical potentials in the spin blockade region. (b) Energy levels of the two-electron DQD system plotted as a function of the detuning ε These energies are perturbed by ΔP (red dashed) and $\overline{P}$ (blue solid), respectively the difference and average of the nuclear spin polarizations in the left and right dots. (b) The leakage current as a function of detuning ε and magnetic field B.

the resonant condition $\varepsilon = 0$. This resonant leakage current is maximized at $B = \pm 150$ mT, where T_+ and T_- energetically coincide with the bonding and anti-bonding states of (1,1)S and (0,2)S states. The tunnel coupling is estimated to be $t_c = 4$ μeV for this case. The peak field or the corresponding t_c changes systematically with the central gate voltage V_C. The current profile in Fig. 2(c) depends on the sweep rate and directions, implying DNP occurring in the device.

3. Transient current measurement

We investigated how the leakage current changes with time, $I(t)$. First, we nominally depolarize the nuclear spins ($P_L \sim P_R \sim 0$) by leaving the system in the Coulomb blockade regime at $\varepsilon < -260$ μeV for typically 200 sec or more. Then, V_{PR} is changed stepwise to bring the system to $\varepsilon = \varepsilon_x$, and the current $I(t)$ after the step is recorded as in Fig. 3. Current increases stepwise to a medium level after a certain interval (marked by dashed lines) in all traces, and then rises one step further up to a yet higher level after an additional developing time (solid lines) in some traces. Such a double-step structure can be explained by considering inhomogeneous DNP ($P_L \neq P_R$) as follows [10,11].

The energy diagram at unpolarized condition ($P_L = P_R = 0$) is shown in panel (i) of Fig. 3(b), where an extremely small current is understood to result from cotunneling from the long-lived T_0 state. In this case, although the DNP rate is small, P_L and P_R gradually develop but at slightly different rates. When the difference ($\Delta P = P_L - P_R$) becomes significant, the eigenstates become more like |↑↓> and |↓↑> as shown in (ii), and the increased current in the medium level is associated with DNP very efficiently in one partic-

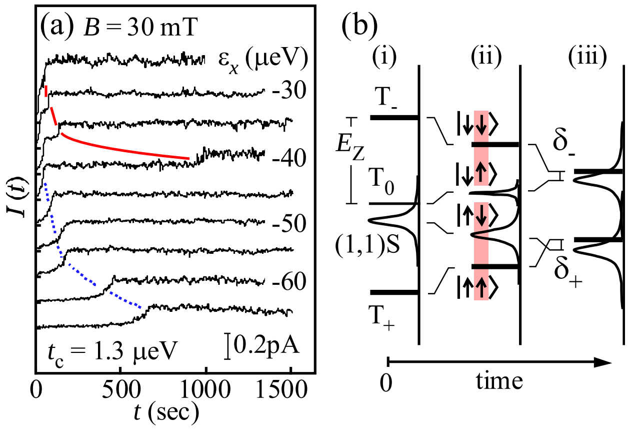

Fig. 3 (a) Transient current $I(t)$ at different detunings (b) Energy diagrams showing how the (1,1) states gradually evolve with DNP. DNP is more efficient in the right dot for the example in (ii)

ular dot (say, right dot, as in the figure). At the same time, the positive average polarization [$\overline{P} = (P_L + P_R)/2$] changes the energies of T_+ and T_- to be closer to those of |↑↓> and |↓↑>. Eventually, the system will be trapped in a stable condition as in (iii), where the energy difference δ_+ between T_+ and |↑↓>, and δ_- between T_- and |↓↑> are locked to small positive values. The high current level with moderate noise implies the DNP feedback in action.

4. Summary

The double-step structure in transient current is investigated in the spin blockade regime of a double quantum dot. We have successfully explained the first step as the onset of an efficient DNP process and the second step as indication of attaining stable nuclear spin polarization in one dot.

Acknowledgments

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