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Nuclear spin dependent transport in quantum dots

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1. Introduction

Zero-dimensional electronic system can be confined in semiconductor quantum dots [1]. The electronic state in the quantum dot, including the spin configuration, can be well controlled as a function of plunger gate voltage and magnetic field [2]. Recently, spin and nuclear spin degrees of freedoms in quantum dot are subject to intensive studies from the viewpoints of applications to future spintronics and quantum computations [3]. This paper presents our recent studies on the electron transport properties of quantum dots, concerning how the spins and nuclear spins in the quantum dots can influence the electron transport.

2. Device

We use two quantum dots connected in series between source/drain contacts, which are incorporated in a gated sub-micron pillar of triple barrier resonant tunneling structure: 8.0nm (6.0nm) thick $Al_{0.22}Ga_{0.78}As$ outer (center) barriers and 12nm thick two $In_{0.05}Ga_{0.95}As$ wells (Fig. 1) [4]. A DC magnetic field is applied parallel to the wells. An AC magnetic field of frequencies up to 15MHz, which is generated by a coil near the device, is applied perpendicular to the wells.

3. Spin Pauli blockade [5]

When the electrostatic potentials for two dots are relevantly adjusted, three charge states $(N_1,N_2) = (0,1)$, (1,1) and (0,2), where N_1 (N_2) is the number of electrons in dot 1 (dot 2), are degenerate and at the same time Coulomb blockade is lifted at zero source drain voltage V_S,. The (1,1) state contains two spin-states, a singlet and a triplet, with a slight energy difference by the amount of inter-dot exchange energy (estimated to be ~100μeV or less). On the other hand the (0,2) state only takes a spin singlet because the two electrons share the same orbital of the dot 2 due to Pauli exclusion principle. By applying negative V_S (Fig. 2(a)) current is carried by the cycle of three irreversible steps as (0,1) → (0,2) singlet → (1,1) singlet → (0,1) … For positive V_S (Fig. 2(c) and (f)), however, although there is a current carrying cycle of (0,1) → (1,1) singlet → (0,2) singlet → (0,1) …, once the other transition (0,1) → (1,1) triplet takes place, further electron transfer is prohibited by Coulomb blockade and Pauli exclusion.

Figure 3 shows a current voltage characteristic at certain V_G where a large conductance peak first appeared at zero bias following the scheme of Fig. 2(b). For V_S larger than 1mV, the transport is in the nonlinear regime and the current is suppressed. This suppression is lifted for $V_S >$ 7mV, where the Fermi energy of the right reservoir is lower than N_2=1 state of the right dot.

4. Leakage current in spin blockade regime

In this spin blockade state a small leakage current of order ~ 1pA has been observed. This means the (1,1) triplet has a finite lifetime of order e/I ~ 100ns (e, elementary charge). Possible causes for the leakage current are spin scattering that changes the state from (1,1) triplet to (1,1) singlet and co-tunneling processes that can directly scatter (1,1) triplet to (0,1) [5].

The leakage current in this spin blockade region is measured as a function of DC magnetic field. When the magnetic field is increased, the current increases rapidly at 0.5T and starts to oscillate as a function of time at about 0.7T. Both of the period and amplitude of the current oscillations increase with magnetic field, and disappear at about 0.9T. Figure 4(a) shows the data taken at 0.85T. A strong reduction in the oscillation period and amplitude of the current is observed when AC magnetic field whose frequency matches to ^{71}Ga nuclear spin resonance, is applied (Fig. 4(b)). This NMR-like behavior is only observed for the spin blockade region.

The origin of the current oscillations and the NMR response are not yet understood. Here we only outline our tentative explanation below. The spin scattering from (1,1) triplet to (1,1) singlet can be possible via the hyperfine flip-flop scattering with nuclei in quantum dots when the energy differences of the two spin states (electron spins and nuclear spins) are compensated [7]. This compensation will be achieved at a certain magnetic field where one of the Zeeman-split (1,1) triplet states is degenerate with (1,1) singlet. Then the hyperfine flip-flop scattering provides the nuclei with the same spin momentum, i.e., “down” nuclear spin can be flopped to “up” but not for vice versa. Because of the long relaxation time of nuclear spin at low temperature (up to few tens of min), the flopped nuclear spins can be accumulated during many cycles (period ~100ns) of the (1,1) triplet occupation followed by scattering from (1,1) triplet to (1,1) singlet. This eventually leads to dynamical polarization of nuclei, which can acts back to the electronic state and hence the electron transport through the two-dot system via the Overhouser effect [8].

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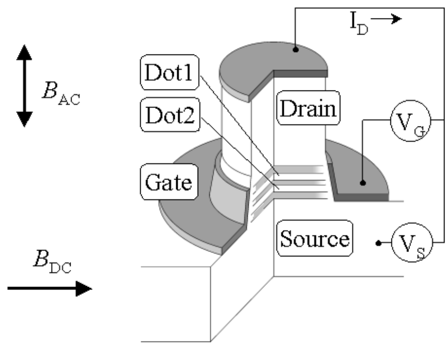

Fig. 1 Schematic of a vertical double dot sample: The triple barrier heterostructure is etched to cylindrical mesa of a diameter of 0.6µm. Ohmic contacts are formed on top of the mesa and on the substrate. The potentials of the dots are controlled by a Schottky gate electrode.

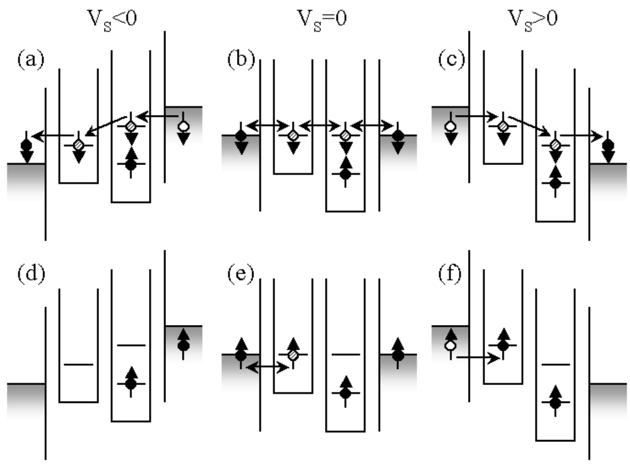

Fig. 2 Potential landscapes for two quantum dots connected in series for various source drain voltage V_S and spin configurations. Energies of two dots are tuned so that the electron number N_1=1 ground state of the left dot is aligned to N_2=2 ground state of the right dot at V_S=0 ((b) and (e)). Spin state of the N_2=2 state must be singlet (shown as antiparallel arrows) because the N_2=2 state share the same orbital state with N_2=1. (a) and (d): An electron forming triplet (parallel arrows) with trapped electron in the right dot cannot enter the double dot from the right reservoir. But electrons with an antiparallel spin can pass through the double dot thus current flows for V_S<0. (c) and (f): Once an electron with a parallel spin enter the left dot, the electron cannot go back to the reservoir because the hole in the reservoir is relaxed much faster than the mean intervals of the tunneling events. Although an electron with anti-parallel spin can pass through the double dot, parallel spin configuration is sooner or later realized and conduction is blocked for V_S>0.

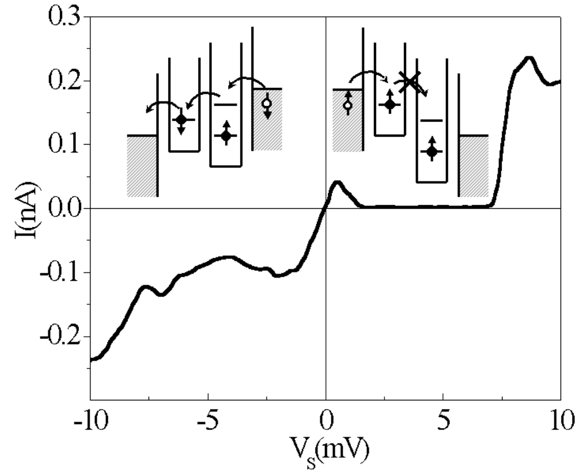

Fig. 3 Current-voltage characteristics at T=100mK, V_G=−1.854 V. The system shows current rectification described in the text.

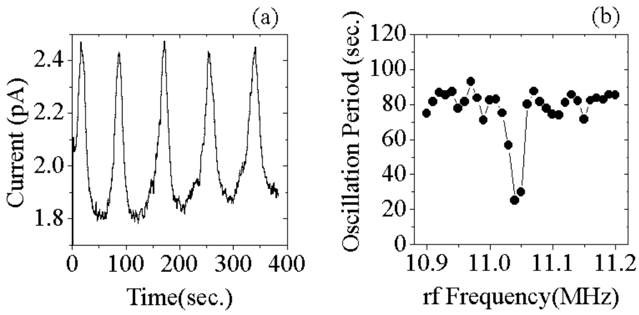

Fig.4 (a) Time evolutions of the current at fixed magnetic field .B=0.85T, V_S=3.0mV at T=1.6K. No decay of the oscillation is observed in both amplitudes and periods within our measurement time up to 15 hours except a sudden shift in the phase of the oscillation. (b) The oscillation period under rf magnetic fields. When the rf frequency matches to ^{71}Ga resonance, both the amplitude and period are reduced. A similar characteristic is observed for ^{69}Ga nuclei.