Spin Resonant Tunneling through Quantum Dots with Engineered g-factors

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1. Introduction

To realize the spin based quantum information device, which is one of the most ambitious applications of semiconductor spintronics, the coherent manipulation in a single spin level is necessary. Quantum dot is well known as the electron number as well as electron spin can be well defined and controlled. An application of electron spins in quantum dot array has been proposed that electron spins can perform a controlled-NOT logic operation via Heisenberg interaction if an inhomogeneous magnetic field is applied through two neighbor spins. [1] It is demonstrated a 10 mT magnetic field difference between two neighbor quantum dots which is made of the same g-factor with an additional micro-ferromagnetic lead. [2, 3] A double quantum dots with different g-factors can offer much larger magnetic field difference in a smaller external magnetic field and smaller spatial separation.

2. Experiment and Results

The vertical double quantum dots with different *g*-factors are formed in a submicro-scale pillar with a surrounding Ti/Au Schottky gate. The structure of the vertical double quantum dots consists of three barriers and two quantum wells. From top to bottom, they are $Al_{0.3}Ga_{0.7}As$ (7 nm), $In_{0.04}Ga_{0.96}As$ (7.5 nm), $Al_{0.3}Ga_{0.7}As$ (6.5 nm), GaAs (10 nm), $Al_{0.3}Ga_{0.7}As$ (7 nm). [4] The fabrication process is the same as the work. [5] The measurements were performed in a dilution refrigerator with a base temperature 30 mK and the effective electron temperature is around 0.1 K. A magnetic field up to 15 T was applied perpendicular to the wells.

Figure 1 shows the differential conductance as a function of source-drain voltage and gate voltage in zero magnetic fields. There are several current peaks, which are marked by black arrows, near the current threshold region. These peaks are due to resonance tunneling through the ground state of the left dot and excited states of right dot, as shown in the right inset.

Figure 2 shows the current peaks near current threshold region in several different magnetic fields. All of the peaks show a clear kick structure. The kick structure is characterized by δ_1 and δ_2 , as shown in Fig. 2(b). Both of δ_1 and δ_2 are linear with magnetic field, as shown in Fig. 2(c)





Fig. 1 The differential conductance of resonance tunneling current at zero magnetic fields. The arrows make current peaks due to resonance tunneling peak from ground state of left dot to excited states of right dot. The right inset shows the schematic of potential energy landscape for the resonance tunneling.

In quantum dots with the same g-factor, the current peaks always show a straight line and the kick structure resonance tunneling peak is never observed, because the Zeeman sublevels are aligned at the same time in all magnetic fields. However, the Zeeman sublevels are never aligned in double quantum dots with the different g-factors in magnetic fields.

Figure 3 shows the schematic diagrams and the alignment of Zeeman sublevels can be labeled in three particular conditions, A to C. Under the condition A, The aligned up spin states for both two quantum dots are within the transport window, and the resonance tunneling takes place. By increasing the gate voltage, lowering the energy levels of both dots, the down spin states for both dots come into the transport window. For the up spin electrons, the resonance tunneling still takes place, but once a down spin electron comes into the left dot, the resonance tunneling blockades. This suppression process is called as spin bottleneck. Similarly, under condition C, the down spin electron occupy the left dot, the resonance tunneling blockade. Under condition B and C, the mismatch of

Zeeman sublevels prohibits the subsequent tunneling even though one of the other Zeeman sublevels is aligned. The bottleneck suppresses the resonance tunneling. Therefore, there is no steady current in the condition B and C.



Fig. 2 (a)-(b) The differential conductance of resonance tunneling peaks in several different magnetic fields. All of the results show kick structure, which is characterized by δ_1 and δ_2 . Magnetic field dependence of (c) δ_1 and (d) δ_2 . Both of δ_1 and δ_2 are linear with the magnetic fields.



Fig. 3 The schematic diagram of resonance tunneling peak lines in quantum dots with different *g*-factors and the respective energy landscapes.

The bottleneck can be lifted by level broadening effect,

which is induced by finite tunneling couplings among the dots and the electrodes. The broadening couplings the misaligned Zeeman sublevels and provides an escape path for the electron in the bottleneck and relieves the bottleneck effect. The electron transport is carried out within the competition between the bottleneck and the escape effects. As a result of competition of these two effects, the maximum current peak is expected under the condition that interdot detuning is half of Zeeman energy difference.

We evaluated the resonance tunneling through two dots with different Zeeman splittings by Bloch equation method. Based on this theoretical analysis, in the strong interdot coupling region, the level broadening effect is notable and the current is maximum when the interdot detuning is half of Zeeman energy difference. [6] In order to convert the δ_1 and δ_2 to theoretical analysis, we analysis the resonance tunneling, co-tunneling effect and interdot microwave assisted tunneling. Finally, we get the absolute value of *g*-factors of two quantum dots are 0.33 and 0.89 for GaAs and In_{0.04}Ga_{0.96}As respectively. These values consist with the previous works. [7]

3. Conclusions

We investigate the resonance tunneling through vertical double quantum dots with different *g*-factors. We found that the resonance tunneling is suppressed even though one of the Zeeman sublevels is aligned. The level broadening effect partially releases the suppression of Zeeman mismatch effect and the current is maximum when the interdot detuning is half of the Zeeman energy difference.

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