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Level Broadening Effect in Electron Tunneling through Double Quantum Dots with Different *g* Factors

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The spin bottleneck effect was first observed in vertical double quantum dots with different *g* factors in high magnetic fields. We further investigate the spin-dependent resonance tunneling through the same quantum dot system in low magnetic fields. There are no resonance tunneling peak lines, even though one of the Zeeman levels is aligned, because the mismatch of the other Zeeman sublevels blocks the resonance tunneling. However, the level broadening effect partially releases the spin-dependent blockade. As a compromise between two effects, one resonance tunneling peak line splits into two peak lines and forms a kink structure. The split of the two current peak lines is half of Zeeman energy difference between two dots.

1. Introduction

The application of spin base quantum information is attracting considerable attention, resulting in a drastic increase in the amount of study on the topic.[1)] To realize a quantum information, coherent manipulation of electron spin is necessary.[2)] The semiconductor quantum dot is known to be a system in which the electron number as well as the electron spin can be well controlled and defined.[3)] It is proposed that electron spins, which are located in a quantum array, can play a role in quantum information processing.[4,5)] Two neighboring electron spins couple to each other and lead to the rotation of electron spins.[6)] The rotation period is determined by the coupling strength, which is controlled by the voltage barrier height. One of the requirements in such mechanics is that two neighboring electron spins have to be in different magnetic fields.

A direct means of satisfying the requirement is to apply a non uniform magnetic field through two quantum dots with the same *g* factor. It has been proposed that a ferromagnetic film is deposited on top or nearby double quantum dots.[7,8)] This film can act as a micromagnet and create a 10 mT magnetic field difference between two neighboring quantum dots. Another similar method is to apply a uniform external magnetic field through a vertical double quantum dot with different *g* factors. There are several advantages to this strategy. Firstly, the magnetic field difference between two dots is linearly related to the external magnetic field. Secondly, the magnetic field difference is very large. For instance, assuming the *g* factors of two dots are two times difference under a 1 T external magnetic field, the effective magnetic field difference is 0.5 T. The first study on electron spin transport through double quantum dots with different *g* factors has been reported recently, and a spin bottleneck effect was observed in high magnetic fields.[9)] The spin-dependent one-electron bottleneck effect is similar to the spin blockade in the two-electron configuration. In this work, we further study the spin bottleneck effect in low magnetic fields. The spin bottleneck was observed and found to follow the theoretical prediction in low magnetic fields. The results show that the level broadening effect releases the blockade of spin resonance tunneling. A compromise between the level broadening effect and spin bottleneck effect causes the resonance tunneling peak line to split into two lines. The spin transport processes are different in these two peak lines. This phenomenon is expected to act as a spin filter or initial state of quantum information.

2. Experiment

Because of the geometric condition, it is difficult to create a non uniform *g* factor system in a lateral quantum dot. Instead of a lateral quantum dot, vertical double quantum dots are a good system for easily creating double quantum dots with different *g* factors. We merely need to grow two quantum wells with different *g* factors. The electron *g* factor in a quantum well is sensitive to the type of material, energy gap, and thickness of the quantum well. The vertical double quantum dots with different *g* factors are formed in a submicro scale pillar with three barriers. The double quantum dots of 7.5 nm $In_{0.04}Ga_{0.96}As$ and 10 nm GaAs are interspersed between three $Al_{0.3}Ga_{0.7}As$ layers, which are 7 and 6.5-nm thick outer barrier and center barrier layers respectively. The quantum dots and barriers are surrounded by two Ti/Au Schottky gates. The absolute value of the *g* factor of $In_{0.04}Ga_{0.96}As$ is larger than that of GaAs.

The fabrication procedure is the same as that in the previous work.[10,11)] Firstly, we formed source and drain electrodes on the wafer surface by standard electron beam lithography. Secondly, we formed a pillar structure by dry etching using BCl_3 gas. Thirdly, we dipped the device into solution made of H_2SO_4, H_2O_2, and H_2O. This wet etching will undercut the side of the pillar to prevent the connection between the side gate and source gate. Finally, we deposited a Ti/Au electrode onto the pillar side as a side gate.

The sample is mounted on a dilution refrigerator with a base temperature of 10 mK. All measurements are performed in a well-considered measuring circuit with low-pass filters and noise of about 30 fA. The external magnetic field is applied perpendicular to the well. On the basis of the full width at half height of the resonance tunneling peak at low

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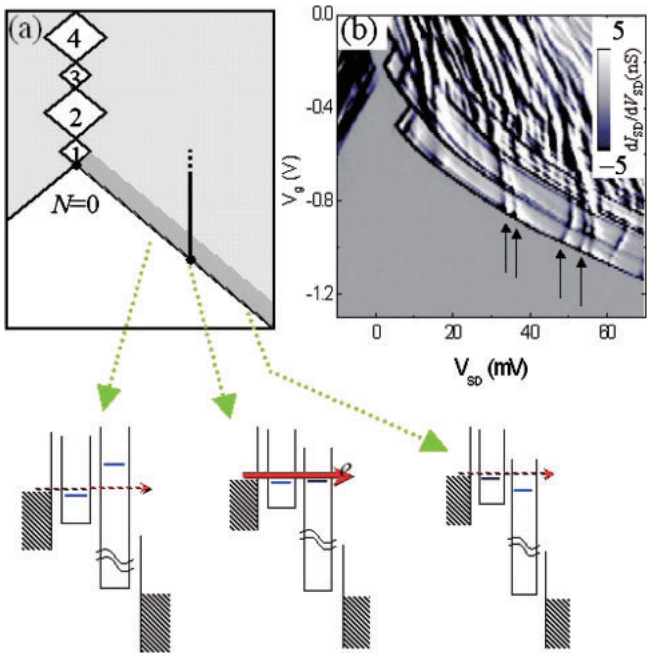

Fig. 1. (Color online) (a) Schematic diagram of electron tunneling through two quantum dots. The ground state of the left dot is fixed at the Fermi level of the source reservoir. The relative level shift is tuned by adjusting source–drain voltage and side-gate voltage. The resonance tunneling peak appears only when the state of the right dot lines up with the ground state of the left dot. (b) The differential conductance peaks as a function of source–drain voltage and side-gate voltage in magnetic field of 4 T. The peaks are indicated by dark blue lines. Several peaks, which correspond to resonance tunneling from the ground state of the left dot to the excited states of the right dot, are marked by black arrows.

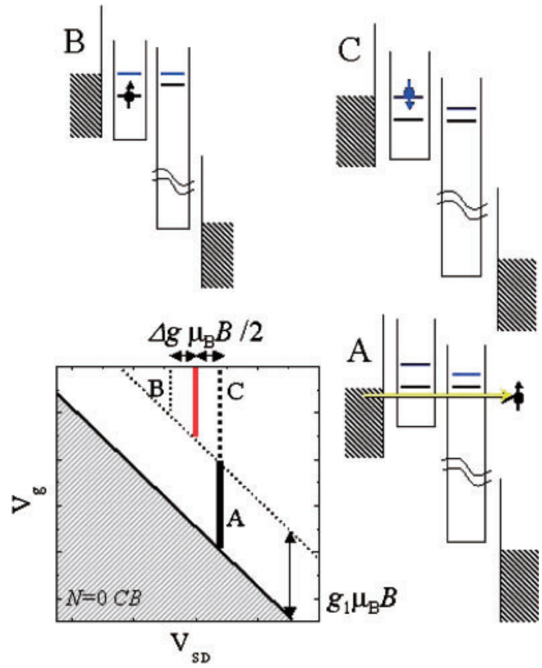

Fig. 2. (Color online) Schematic diagram of several tunneling processes in double quantum dots with different g factors. Corresponding peak positions are shown as a function of source–drain voltage and side-gate voltage. The red line is the resonance tunneling peak of the level broadening effect, which is located at the middle of peak line B and peak line C.

bias, we estimate that the effective electron temperature is about 0.1 K.[12)]

3. Results and Discussion

In order to simplify the conditions, the ground state of the left dot is set at the Fermi level of the source reservoir and the source–drain voltage is high. The tunneling configuration is $(N_1, N_2) = (0,0)$, $(1,0)$, and $(0,1)$, where N_i $(i = 1, 2)$ is the number of electrons in dot i. In this configuration, the excited states can be investigated, and we can avoid the electron-electron interaction in the dots. As shown in Fig. 1(a), the relative energy level shift of the two dots is tuned by adjusting both source voltage and side-gate voltage. The peak occurs only when the state of the right dot lines up with the ground state of the left dot.[13)] Figure 1(b) shows the differential conductance as a function of source–drain and side-gate voltages in a magnetic field of 4 T. Current peaks are indicated by dark blue lines. There are several current peaks, which are marked by black arrows, near the threshold line. These peak lines indicate the resonance tunneling in which electrons tunnel through the ground state of the left dot and the excited states of the right dot. In this experiment, we focus our discussion on these tunneling peaks.

In a system of double quantum dots with the same g factor, regardless of whether the external magnetic field is zero or not, the Zeeman sublevels always line up simultaneously so only one resonance tunneling peak appears. However, in a system of double quantum dots with different g factors, the Zeeman sublevels never line up simultaneously in magnetic field. As shown in Fig. 2, the tunneling peaks of different Zeeman sublevels can be grouped into three cases as a function of source–drain voltage and side-gate voltage. In case A, only two up-spin Zeeman sublevels stay within the transport window. In this situation, resonance tunneling occurs only when the two up-spin states align. With increasing side-gate voltage, the chemical potential of the Zeeman sublevels in quantum dots decreases and the situation will change from case A to case C. In case C, both up-spin and down-spin Zeeman sublevels stay within the transport window and up-spin states align. Up-spin electrons can tunnel through two quantum dots and a resonance tunneling peak line appears. On the other hand, once a down-spin electron enters and occupies the energy state of the left dot, the resonance tunneling stops. The resonance tunneling will continue only if the down-spin electron releases energy and tunnels to the down-spin state of the right dot. A similar situation also occurs in case B; the resonance tunneling only takes place on down-spin electrons. Once the up-spin electron occupies the up-spin state of the left dot, it blocks the resonance tunneling. This one-electron spin-dependent blockade is called the spin bottleneck effect, and is similar to the well-known spin blockade under the two-electron condition.[14–16)] Up-spin and down-spin electrons randomly enter the state of the left quantum dot so the condition is a competition between resonance tunneling and the spin bottleneck in a Zeeman-sublevel-mismatch system. As shown in Fig. 2, the peak line shift between case B and case C is equal to the Zeeman energy difference between two dots, and the peak line length in case A is equal to the Zeeman splitting of the left dot. There is no steady current in case B or case C, and the current is governed by the electron spin relaxation time.

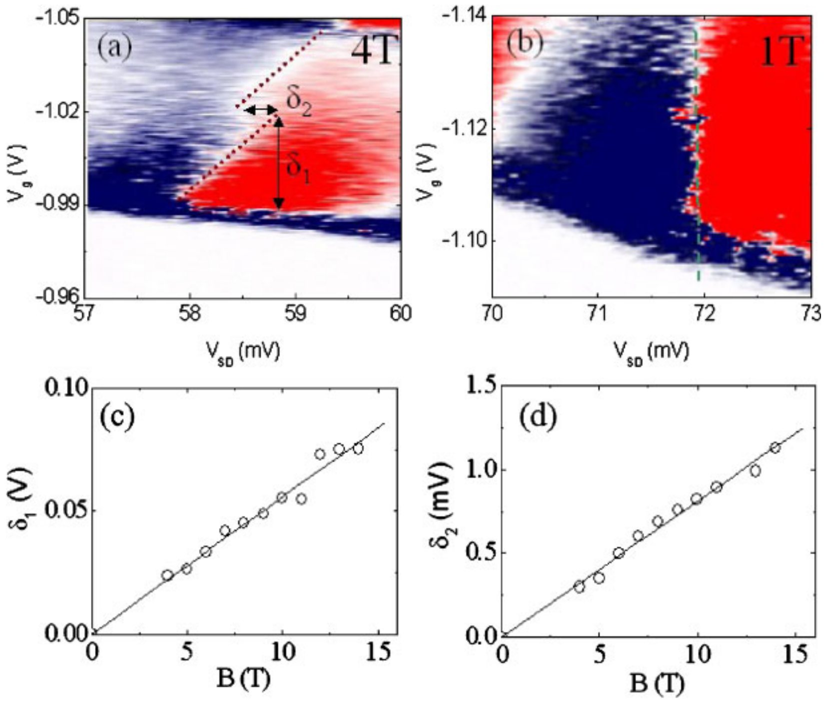

Fig. 3. (Color online) (a) The resonance tunneling peak in magnetic field of 4 T. The brown dot lines show a clear kink structure. The kink is marked by δ_1 and δ_2, and both of which are linearly proportional to external magnetic field, as shown in (c) and (d). (b) Resonance tunneling peak in 1 T. It shows a bent curve instead of a kink structure.

Figures 3(a) and 3(b) show the differential conductance of the tunneling peak lines in mganetic fields of 4 and 1 T, respectively. The peak lines are colored blue and red. The tunneling process is from the source reservoir through the InGaAs and GaAs dots to the drain reservoir. Following the brown dotted lines in Fig. 3(a), clear two splitting lines, a kink structure, can be seen in Fig. 3(a). The kink structure is marked by δ_1 and δ_2. As respectively shown in Figs. 3(c) and 3(d), both δ_1 and δ_2 have a linear relationship with the external magnetic field. The current in cases B and C is weaker than the current in case A when the phonon scattering is weak because of the spin bottleneck effect. However, the current at the upper kink is as high as that at the lower kink in the experimental result. The simple resonance tunneling behavior cannot explain the experimental results. The kink structure can be explained as a result of the level broadening effect.

A theoretical calculation predicts a level broadening effect in the double quantum dot system.[17)] The calculation yields the resonance tunneling current through two quantum dots with different g factors, g_1 and g_2, by the Bloch equation method.[18,19)] In the calculation, the temperature is assumed to be zero and only the first-order tunneling process without phonon absorption or emission is taken into account. We focus on the condition that the quantum dot with a higher Zeeman splitting energy is located closer to the source reservoir, which is consistent with our experimental condition. There are two particular conditions, case 1 and case 2. Only the up-spin level stays within the transport window in case 1 and both Zeeman sublevels stay within the transport window in case 2. According to the calculation, in case 1, the resonance tunneling occurs when the interdot detuning is zero, the same as the analysis in case A. In case 2, the condition comprises case B and case C, and the theory predicts that the current is too weak to be observed, even though one of the Zeeman sublevels lines up because mismatch of the other Zeeman sublevel blocks the resonance tunneling process. The larger detuning promotes the faster relaxation of the spin bottleneck effect. The theoretical calculation reveals that the resonance tunneling current is still high with a small detuning, even though the resonance tunneling current decreases with further increases detunig. This level broadening effect can partially release the transport blockade in a Zeeman mismatch system. As a result of combining the two effects, the theoretical calculation predicts that the current maximum occurs in case 2 when detuning corresponds to half the Zeeman energy difference between two quantum dots, $|g_1 - g_2|\mu B/2$, which is indicated by the red line in Fig. 2. The current of the level broadening effect depends on the interdot coupling. In the limit of weak interdot coupling, the current is still very low. The current increases as interdot coupling increases. In strong interdot coupling, the current of level broadening is the same as the resonance tunneling current in case 1. This is highly consistent with the experimental results that the currents are the same at the upper and lower kink structures.

In order to compare the peak line shift in Fig. 3(a) with the results of theoretical calculation, $|g_1 - g_2|\mu B/2$, the source–drain voltage drop ratio through three barriers is necessary. The method is the same as in the previous work.[9)] We analyze the peak line slope of the first- and second-order tunneling processes near zero bias in both positive and negative voltage and the phonon-assisted interdot tunneling process. Finally, we obtain 0.1, 0.19, and 0.71 voltage drop ratios for the three barriers. Comparing the experimental results and theoretical calculation, we obtain $|g_1| = 0.89$ and

$|g_2| = 0.33$. These values are in good agreement with previous results.[20,21] On the other hand, the experimental results do not follow the theoretical prediction in very low magnetic fields. As shown by the green dash line in Fig. 3(b), the resonance tunneling peak line shows a bent curve in a magnetic field of 1 T instead of a clear kink structure or a straight peak line. One of the possible reason for this is that the broadening level is greater than the small Zeeman splitting in very low magnetic fields. The details of the mechanics are not yet clear and must be further studied.

4. Conclusions

We investigate the electron spin transport properties of $In_{0.04}Ga_{0.96}As/GaAs$ vertical double quantum dots in low magnetic fields. Instead of one resonance tunneling peak line, two splitting peak lines, a kink structure, are observed. Theoretical calculation supports this result. The Zeeman sublevels of two dots do not line up at the same time. The mismatch of Zeeman sublevels suppresses the resonance tunneling process, even when one of the Zeeman sublevels lines up, because of the mismatch of the other Zeeman sublevels. However, this spin-dependent blockade is partially released by the level broadening effect. As a compromise between two effects, a current peak line appears when detuning corresponds to half the Zeeman energy difference between the two dots, and it shows two splitting resonance tunneling peak lines, a kink structure.

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1) *Semiconductor Spintronics and Quantum Computation*, ed. D. D. Awschalom, N. Samarth, and D. Loss (Springer, Berlin, 2002).
2) G. Salis, Y. Kato, K. Ensslin, D. C. Driscoll, A. C. Gossard, and D. D. Awschalom: Nature **414** (2001) 619.
3) R. Hanson, L. P. Kouwenhoven, J. R. Petta, S. Tarucha, and L. M. K. Vandersypen: Rev. Mod. Phys. **79** (2007) 1217.
4) D. Loss and D. P. DiVincenzo: Phys. Rev. A **57** (1998) 120.
5) D. P. DiVincenzo and D. Loss: J. Magn. Magn. Mater. **200** (1999) 202.
6) W. A. Coish and D. Loss: Phys. Rev. B **75** (2007) 161302(R).
7) E. A. Laird, C. Barthel, E. I. Rashba, C. M. Marcus, M. P. Hanson, and A. C. Gossard: Phys. Rev. Lett. **99** (2007) 246601.
8) M. Pioro-Ladriere, T. Obata, Y. Tokura, Y. S. Shin, T. Kubo, K. Yoshida, T. Taniyama, and S. Tarucha: Nat. Phys. **4** (2008) 776.
9) S. M. Huang, Y. Tokura, H. Akimoto, K. Kono, J. J. Lin, S. Tarucha, and K. Ono: Phys. Rev. Lett. **104** (2010) 136801.
10) R. Takahashi, K. Kono, S. Tarucha, and K. Ono: Physica E **42** (2010) 833.
11) D. G. Austing, T. Honda, K. Muraki, Y. Tokura, and S. Tarucha: Physica B **249** (1998) 206.
12) L. L. Sohn, L. P. Kouwenhoven, and G. Schon, Eds.: *Mesoscopic Electron Transport* (Kluwer, Dordrecht, 1997).
13) K. Ono, D. G. Austing, Y. Tokura, and S. Tarucha: Physica B **314** (2002) 450.
14) K. Ono, D. G. Austing, Y. Tokura, and S. Tarucha: Science **297** (2002) 1313.
15) K. Ono and S. Tarucha: Phys. Rev. Lett. **92** (2004) 256803.
16) J. Baugh, Y. Kitamura, K. Ono, and S. Tarucha: Phys. Rev. Lett. **99** (2007) 096804.
17) Y. Tokura, K. Ono, and S. Tarucha: Phys. Stat. Solidi B **246** (2009) 740.
18) S. A. Gurvitz and Ya. S. Prager: Phys. Rev. B **53** (1996) 15932.
19) T. H. Stoof and Yu. V. Nazarov: Phys. Rev. B **53** (1996) 1050.
20) T. Kodera, W. G. van der Wiel, K. Ono, S. Sasaki, T. Fujisawa, and S. Tarucha: Physica E **22** (2004) 518.
21) C. Weisbuch and C. Hermann: Phys. Rev. B **15** (1977) 816.