G-4-3

Extended Abstracts of the 2012 International Conference on Solid State Devices and Materials, Kyoto, 2012, pp963-964

The observation of rectangle shape geometric current blockade in vertical double quantum dots

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1. Introduction

With the development of the high technology, one can construct more and more modern structures or materials to study and realize the concept of people's dream both on the fundamental science and advanced technology application. Quantum dot is one of the famous structures which one realizes an artificial atom or molecular [1], and many interesting phenomenon, such as Spin-blockade [2] and hyperfine interaction between electron spins and nuclear spins [3] are discovered in quantum dots. Now, the study of these effects is very popular, because of the possible application on quantum memory [4, 5] and quantum information [6]. By adjusting the external electric and magnetic fields, one can tune an electron states and affect many behaviors of electrons, which is a potential application for spintronics [7]. Recently, it was reported a discovery of quantum mechanism called "geometric blockade" at a coulomb diamond edge [8]. The intrinsic physical mechanism is the difference tunneling rates of different electron wavefunctions in a single quantum dot which is coupling with one two dimensional electron gas and one three dimensional electron gas.

Here, a similar rectangle shape geometric blockade is experimental observed in standard double quantum dots. We systematically analyze the detail tunneling processes and conclude that the structure and the intrinsic physical mechanism is entirely different from the previous reported geometric blockade. The rectangle shape geometric blockade is a combination of several different traditional blockade effects, such as spin-blockade and coulomb blockade, in different regimes. According to the experimental observation, the size of the rectangle shape geometric blockade also depends on the magnetic field. As magnetic field increasing, the size of the geometric blockade regime becomes larger. This behavior consists with the prediction of our model.

2. Experiment

We measure the I-V characteristic curve of a typical $In_{0.05}Ga_{0.95}As/Al_{0.22}Ga_{0.78}As$ double quantum dots as a function of source-drain voltage, V_{SD}, and side-gate voltage, V_g. All of the experiments are performed in standard dilution refrigerator at base temperature about 40 mK. According to the full-width at half-height of the resonance tunneling peak at low source-drain voltage [1], the estimated effective electron temperature is about 0.6 K.

3. Results and Discussion

As shown in Fig. 1, coulomb diamonds are observed as a function of source-drain voltage and side-gate voltage. Different from the typical behavior of coulomb diamond, it shows a geometric blockade in the bottom edge of coulomb diamond where the total electron number is three. As shown in the inset of the Fig. 1, the geometric blockade can roughly be seperated by four resonance tunneling lines, A to D.

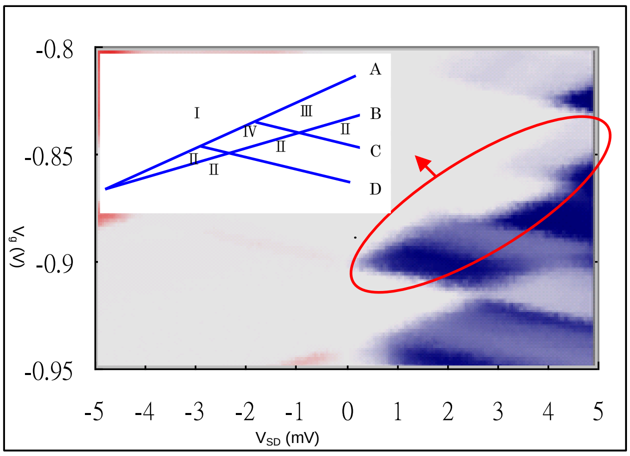

Fig. 1 The rectangle shape geometric current blockade at 1 T. The left-top inset figure indicates the schematic behavior of the current blockade.

The line A is the tunneling process that the s orbital state with down-spin of Dot 1 always line up with Fermi-level of Drain reservoir. The line B is the tunneling process that the s orbital state with up-spin of Dot 2 always lines with Fermi-level of Drain reservoir. The line C is the tunneling process that the s orbital state with down-spin of Dot 2 always lines with Fermi-level of Source reservoir. The line D is the tunneling process that the p orbital state with up-spin state of Dot 1 always lines with Fermi-level of Source reservoir.

Following the model of alignment of the energy diagram of the double quantum dots, it is deduced that the tunneling processes can be roughly divided into four regimes which is indicated as Ⅰ, Ⅱ, Ⅲ, Ⅳ. It is 3-electron coulomb blockade and typical tunneling processes in the regime Ⅰ and regime Ⅱ respectively. In the regime Ⅲ, an electron with either up-spin or down-spin can tunnel into s-state with down-spin or p-state with up-spin of Dot 1. However, the only vacancy state of Dot 2 is for s-state with up-spin so in case of that electrons with up-spin come into the Dot 1, it can not tunnel to Dot 2 and the current blockade because the tunneling process would break the Pauli Exclusion Principle. On the other, electrons with down-spin can tunnel through the double quantum dot. This effect is the well known spin-blockade effect [2].

In the regime Ⅳ, no energy levels of Dot 2 stay within the transport window, so the tunneling process is mainly from the co-tunneling process from Dot 1 to Drain reservoir. It is a very slow process because the potential barrier between Drain and Dot 2 is thicker than others thus the coupling between Drain and Dot 1 is very weak. The current is extremely low, current blockage.

Our experimental results also exhibit that the size of the rectangle shape geometric blockade becomes larger as the magnetic field increasing. This phenomenon is systematically analyzed and found that the behavior can be perfectly explained by the above model.

4. Conclusion

We measure the electron tunneling process through vertical double quantum dots at low temperature and observe a rectangle shape geometric current blockade. The size of the current becomes larger as magnetic field increasing. The phenomenon can be explained by the combination of coulomb blockade and spin blockade in different regimes. The physical mechanism of our experimental observation is entirely different from the previous reported geometric blockade which is mainly from the different coupling strength of different wavefunctions.

Acknowledgements

Huang and Sun thank the equipment and financial support from Dr. Kono in RIKEN. The experiment is processing in RIKEN, Japan. Huang thanks the financial support from the National Science council through Grants No. NSC 101-2112-M-110 -001

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