E-1-03 Extended Abstracts of the 2019 International Conference on Solid State Devices and Materials, Nagoya, 2019, pp213-214

Bipolar Pauli spin blockade in a silicon linearly coupled triple quantum dot

Shunsuke Ota[1], Soichiro Hiraoka[1],
Ryutaro Matsuoka[1], Raisei Mizokuchi[1] and Tetsuo Kodera[1]

[1] Tokyo Institute of Technology
2-12-1-S3-702 Ookayama, Meguro-ku,
Tokyo 152-8552 Japan
Phone: +81-3-5734-2508 E-mail: ota.s.ab@m.titech.ac.jp

Abstract

We have fabricated and characterized a linearly coupled triple quantum dot system with a charge sensor, which is physically-defined on a silicon-on-insulator substrate. By using the charge sensor, we monitor the charge transitions in each dot of the triple quantum dot. In addition, by measuring the current passing through the triple quantum dot, bipolar current blockade phenomenon is observed, which can be attributed to the bipolar Pauli spin blockades.

1. Introduction

In recent years, various physical systems have been studied as candidates for qubits. Among them, charge spins in silicon quantum dots (QDs) are promising because of their advantages such as a relatively long coherence time (~ 28 ms) [1], physically smallness (~ 50 nm), and compatibility with the mature CMOS technology.

Research on controllable interactions between electrons in QDs is also necessary to realize quantum information processing. These interactions are achieved by tunnel couplings although the couplings are usually effective only between adjacent QDs because the coupling strength decreases exponentially with distance. Extending the tunnel coupling beyond the nearest qubits through long-range interactions has been studied in QDs systems [2-5]. Such interactions are expected to provide direct quantum operation between remote qubits without SWAP operations and a more complex architecture that is more tolerant to failures [6].

In this study, we fabricated a physically-defined silicon linearly coupled triple quantum dot (LTQD) in order to capture the transport phenomena related to electrons in distant QDs. In particular, we focused on a phenomenon called Pauli spin blockade (PSB), in which the current is suppressed depending on the spin state. We observed a bipolar PSB, which is peculiar characteristics to LTQD. Our results have implications for the realization of the long-range interaction between electrons in distant QDs.

2. Device fabrication

The MOS-based device [7] structure of the physically formed a LTQD is shown in Fig. 1. The device consists of a LTQD and a charge sensor (CS) that detects the charge transitions in the LTQD. The electronic state within each QD in the LTQD is manipulated by a corresponding side gate ($V_{SGL}, V_{SGM}, V_{SGR}$). The device is formed by dry-etching the undoped silicon-on-insulator (SOI). The SOI is thinned to about 30 nm by thermal oxidation in advance to increase the charging energies of QDs. The MOS structure composed of a heavily doped polysilicon top gate and an oxide film is formed to generate two-dimensional inversion charges. The gate oxide film is composed of a thermal oxide film of 10 nm and an oxide film of 50 nm deposited by thermal chemical vapor deposition (CVD). The source and drain are formed by self-aligned impurity doping using the top gate as a mask. Therefore, this structure is nominally free from dopants in the QD region.

The physically-defined QDs used in this study do not require gate electrodes to form tunnel barriers. This is because tunnel barriers are formed in physically constricted shapes. As a result, the number of gate electrodes for the physically-defined QD is reduced, so that a simple structure can be achieved.

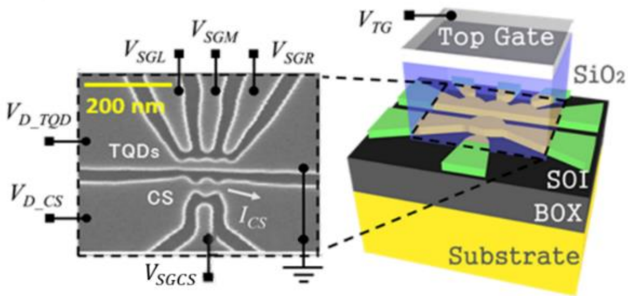

Fig. 1. Scanning electron microscope (SEM) image and schematic of an LTQD device. In the SEM image, light gray areas indicate patterned SOI, while, in dark gray areas, buried oxide (BOX) layer is uncovered.

3. Measurement results and discussion

We studied the characteristics of the n-type silicon LTQD (Fig. 1) by applying voltages to the side gates (V_{SGL}, V_{SGR}) at a temperature of 4.2 K. First, the charge stability diagram was measured by using a CS. In Fig. 2 (a), charge transition lines are observed, which are indicated by green, yellow and red dotted lines. The lines have different slopes, corresponding to electron transitions of each QD because of different capacitances between each QD and each SG. The result shows that the formation of LTQD can be confirmed by the presence of three types of slope lines. In parallel with the charge sensing, the current flowing through the LTQD was measured. The charge transport in the LTQD is limited to the case of alignment of levels in all three QDs. However, a higher-order tunneling called co-tunneling between distant QDs can cause charge transport even if all three levels do not align. In the region A surrounded by white lines in Fig. 2 (a), the center QD and the right QD are considered to behave like a double QD (DQD) after co-tunneling into the left QD. With positive bias voltage, charge transport is inhibited by Pauli's exclusion principle, leading to PSB (Fig. 2 (b)). With negative bias voltage, charge transport occurs as expected for DQD (Fig. 2 (c)). On the other hand, in the region B surrounded by white lines in Fig. 2 (a), current blockade occurs for both polarity of the bias voltage (Fig. 3 (a), (b)). This is explained as follows: with positive (negative) bias voltage, the charge of the left (right) QD enters into the center QD, and the two QDs on the right (left) become the same state of the DQD that causes PSB (Fig. 3 (c), (d)). Such bipolar PSB is a phenomenon peculiar to LTQD and has been reported in a GaAs system [5]. The present study is the first case to observe such a phenomenon in a silicon system.

4. Conclusions

We fabricated and characterized the physically-defined LTQD with the CS. We successfully detected the charge transitions of each QD by the CS. Moreover, we observed bipolar Pauli spin blockade phenomenon in a silicon system.

Acknowledgements

This study was financially supported by JST CREST (JPMJCR 1675), MEXT Q-LEAP.

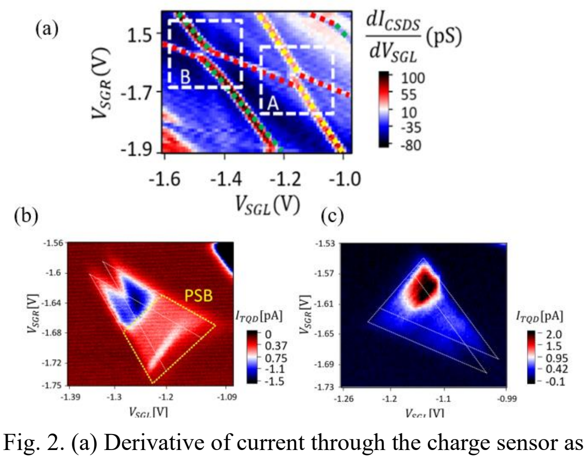

Fig. 2. (a) Derivative of current through the charge sensor as a function of V_{SGL} and V_{SGR} (V_{TG} = 1.2 V, V_{D_CS} = 8 mV, V_{D_TQD} = 5.5 mV, V_{SGCS} =-2.6 V). Charge transitions in each QD are observed (yellow, red, and green dotted lines). There are two sets of triple points between middle and right QDs (region A) and between right and left QDs (region B). (b), (c) LTQD current at region A as a function of V_{SGL} and V_{SGR} with positive (b) and negative bias voltage (c), respectively. Pauli spin blockade occurred for the positive bias condition like a DQD.

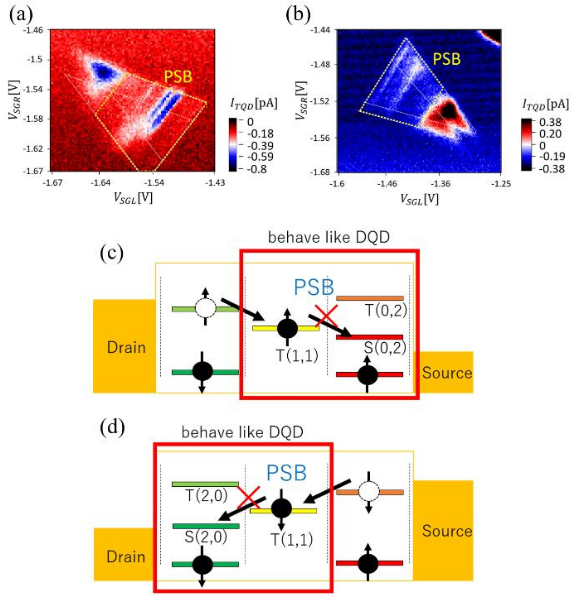

Fig. 3. (a), (b) LTQD current at region B (in Fig.2 (a)) as a function of V_{SGL} and V_{SGR} with positive (a) and negative bias voltage (b), respectively. It turned out that bipolar Pauli spin blockade occurred at this point. (c) Schematic description of spin blockade in the positive bias voltage. The electron of the left QD enters into the center QD. If the two electrons in the center and right QDs form triplet states, current is blocked due to Pauli spin blockade. (S, singlet state; T, triplet state) (d) Pauli spin blockade in the negative bias voltage. Analogically, Pauli spin blockade occurs also in this polarity.

References

[1] M. Veldhorst, et al., “An addressable quantum dot qubit with fault-tolerant control-fidelity”, Nat. Nanotech. 9, 981-985 (2014).

[2] R. Sánchez, et al., “Superexchange blockade in triple quantum dots”, Phys. Rev. B 89, 161402(R) (2014).

[3] F. Braakman, et al., “Long-distance coherent coupling in a quantum dot array”, Nat. Nanotech. 8, 432 (2013).

[4] R. Sánchez, et al., “Long-range spin transfer in triple quantum dots”, Phys. Rev. Lett. 112 176803 (2014).

[5] M. Busl, et al., “Bipolar spin blockade and coherent state superpositions in a triple quantum dot”, Nat. Nanotech. 8, 261–265 (2013).

[6] D. Reilly, “And then there were three”, Nat. Nanotech. 8, 395–396 (2013).

[7] S. Hiraoka, et al., 76th JSAP Autumn Meeting, 15a-1C-4, Nagoya, Sept 15 (2015).