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Pauli spin blockade in a silicon triangular triple quantum dot

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Abstract

We measure current flowing through a silicon triangular triple quantum dot (QD) at a temperature of 300 mK. The triangular triple QD is advantageous for integration because it is a unit structure in a triangular grid that can arrange the QDs with high density. We observe Pauli spin blockade in two QDs of the triple QDs, where the current is suppressed depending on the spin state in the QDs. By utilizing this phenomenon, it is possible to initialize and read spin states, which is useful for future realization of qubits and study of spin-related physics.

Introduction

A qubit is a bit used in quantum computing, which can have a quantum superposition of 0 and 1. Massively parallel computing is considered possible in quantum computing, and applications to various fields such as artificial intelligence, big data analysis, drug discovery, etc. are expected. So far, qubits using various systems have been proposed [1]-[5]. Among them, spin qubits using electron spins in semiconductors have attracted attention. Semiconductor qubits can be manufactured utilizing existing microfabrication techniques and thus are advantageous for integration which is necessary for future quantum computer implementation.

Here, we present the characteristics of a triangular triple quantum dot (TTQD) fabricated on silicon-on-insulator substrate [6]. TTQD is a structure in which three QDs (TQDs) are arranged in a triangle. The triangular array is an array having the highest density of QDs per unit area, which is an advantageous structure for qubit integration.

In addition, since TQDs have exchange interaction with each other, the possibility of use as an exchange-only qubit is also expected [7]. The exchange-only qubit is an application of the exchange interaction between QDs to the qubit operation. Exchange-only qubit do not require the application of oscillating magnetic fields for spin resonance, and can be operated with electric field pulses only. Since TTQD has three sets of two QD pairs, qubit operation in three axes may be possible. Therefore, improvement in operability is expected.

Device structure

Figure 1 shows a scanning electron microscope (SEM) image of the device. QDs are physically defined on silicon-on-insulator (SOI) substrate by using electron beam lithography and SF_6 dry etching. The fabrication techniques are mostly compatible with CMOS fabrication technology. Each

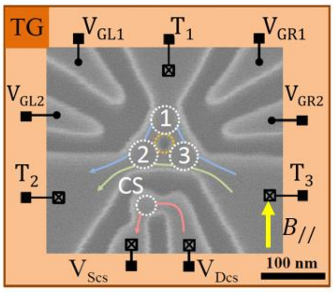

Fig. 1 SEM image of the device. Dark black area corresponds to buried oxide (BOX), and light black area corresponds to SOI. Yellow arrow indicates the direction of magnetic field.

QD is connected to a reservoir, and a two-dimensional electron gas is accumulated at the interface between the SOI and gate oxide by positive voltage applied to a top gate (TG) deposited on the top of the device. Four side gates (SGs) are formed around the TTQD, and the potential of each QD can be controlled. In addition, a charge sensor (CS), which is a single QD, is integrated adjacent to the TTQD. The CS is electrostatically coupled to the TTQD, and when the number of charges in the TTQD changes, a kink is observed in the current of the CS. This makes it possible to observe changes in the number of charges in the TTQD.

Measurement results

In the measurement, the magnetic field dependence of the current through QD1 and QD3 in the TTQD at the triple point was studied. The triple point is a current characteristic observed in a region where the number of charges in the QD changes. The triple point at zero magnetic field is shown in Fig. 2(a), and the triple point is shown in Fig. 2(b) for in-plane magnetic field $B_{//}$ = 1 T. All the measurements were performed at a temperature of 300 mK. It was found that the magnitude of the current at the triple point decreased when the in-plane magnetic field was applied, especially in the rectangular region surrounded by the yellow dashed lines. This current suppression is attributed to the phenomenon called Pauli spin blockade (PSB) [8]. PSB is a phenomenon in which the tunneling between QDs is suppressed by Pauli exclusion principle. This phenomenon is important for initialization and readout of spin states [9].

We also studied the magnetic field dependence of the current in the PSB region. TTQD current as a function of in-plane magnetic field was measured while the QD potential was changed along the detuning ε (blue arrow in Fig. 2(a)),

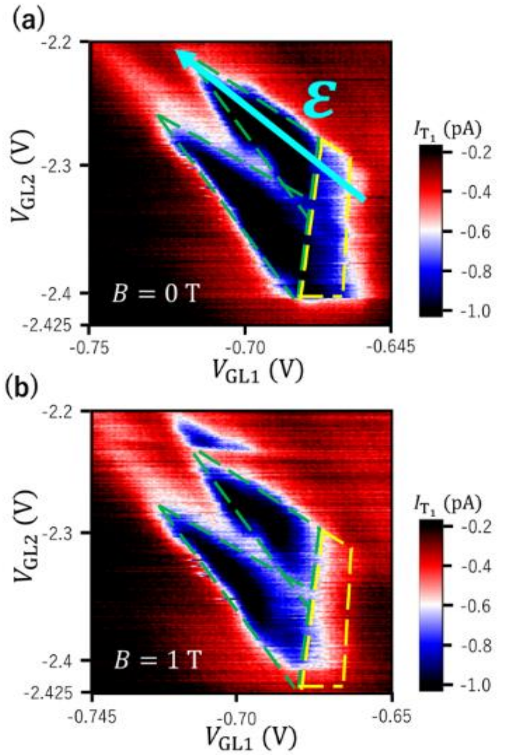

Fig. 2 Triple points (a) without magnetic field and (b) with magnetic field $B = 1$ T. In green dashed triangles, current flows through TQD while the current is suppressed in yellow dashed polygon. The triangle pairs and the polygons of (a) and (b) are the same. By comparing (a) and (b), it turns out that the magnetic field enhances the suppression. The light blue arrow in (a) shows a detuning ε of the triple point.

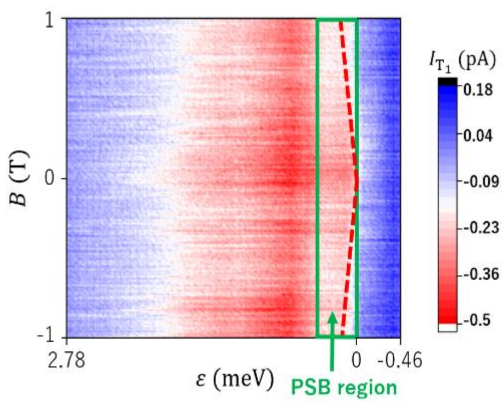

Fig. 3 Magnetic field dependence of the PSB region. The green square shows PSB region. PSB is suppressed near the zero magnetic field. This is caused by spin-flip co-tunneling, which is the phenomenon of exchange spin states between a QD and a reservoir. A red dotted line indicates the transition between triplet level and singlet level.

where ε corresponds to energy difference between QD1 and QD3. The result of the measurement is shown in Fig. 3. The green square is the PSB region. It can be seen that PSB is partially lifted near the zero magnetic field. This is due to spin-flip co-tunneling with the reservoir. Spin-flip co-tunneling is a phenomenon in which the electron having different spin states are exchanged between a QD and a reservoir. Near the zero magnetic field, this phenomenon is likely to occur, and current reduction is not so obvious since the co-tunneling changes blocked triplet states with unblocked singlet state [10]. Also, the transition between triplet level and singlet level is observed as indicated red dotted line. Since the triplet level is lowered by Zeeman energy, the carrier transportation to singlet level is suppressed. For current flowing, it is needed to apply larger detuning corresponded to the separated Zeeman energy [11].

Conclusions

We measured the characteristics of TTQD in silicon. At a triple point between QD1 and QD3 under a magnetic field, PSB was observed. From the magnetic field dependence, it turns out that PSB is suppressed near the zero magnetic field due to spin-flip co-tunneling and the transition between triplet level and singlet level is occurred. Since occurrence of PSB is decided by spin states, this result is important for spin readout, which is essential for future qubit realization.

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References

[1] Kok, P. *et al.* Linear optical quantum computing with photonic qubits. *Rev. Mod. Phys.* **79,** 135‐174 (2007).

[2] Brown, K. R. *et al.* Single-qubit-gate error below 1024 in a trapped ion. *Phys. Rev. A* **84,** 030303 (2011).

[3] Barends, R. *et al.* Superconducting quantum circuits at the surface code threshold for fault tolerance. *Nature* **508,** 500‐503 (2014).

[4] Waldherr, G. *et al.* Quantum error correction in a solid-state hybrid spin register. *Nature* **506,** 204‐207 (2014).

[5] Muhonen, J. T. *et al.* Storing quantum information for 30 seconds in a nanoelectronic device. *Nature Nanotechnol.* **9,** 986‐991 (2014).

[6] Mizokuchi, R. *et al.* Physically defined triple quantum dot systems in silicon on insulator. *Appl. Phys. Lett.* **114,** 073104 (2019).

[7] Laird, Edward A. *et al.* Coherent spin manipulation in an exchange-only qubit. *Phys. Rev. B* **82,** 075403 (2010).

[8] Ono, K. *et al.* Current rectification by Pauli exclusion in a weakly coupled double quantum dot system. *Science* **297,** 1313-1317 (2002).

[9] Koppens, Frank HL. *et al.* Driven coherent oscillations of a single electron spin in a quantum dot. *Nature* **442,** 766-771 (2006).

[10] Lai, N. S. *et al.* Pauli spin blockade in a highly tunable silicon double quantum dot. *Scientific reports* **1,** 110 (2011).

[11] Zarassi, A. *et al.* Magnetic field evolution of spin blockade in Ge/Si nanowire double quantum dots. *Phys, Rev. B* **95,** 155416 (2017).