Extended Abstracts of the 2019 International Conference on Solid State Devices and Materials, Nagoya, 2019, pp223-224

Gating function of p-channel silicon quantum dots by offset bias

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Abstract

P-channel silicon quantum dot (QD) is one of the promising devices for dense integration of qubits because electrical spin manipulation can be realized by its strong spin-orbit coupling. We fabricate physically-defined p-channel silicon double QDs on a silicon-on-insulator substrate. We demonstrate a function of a QD as a gate to provide a way to further simplification of device structure which is more advantageous to large-scale integration in the future.

1. Introduction

Silicon quantum dots (QDs) have been well studied toward spin-based quantum bits (qubits), which is motivated by long coherence time, smallness of a single qubit, and compatibility with CMOS technology [1-4]. Especially p-channel silicon QDs is promising for the development of spin-based qubit system because hole spins have smaller hyperfine interaction than electron spins and can be controlled only with electric field through strong spin-orbit coupling (SOC) [5-9]. We have studied using physically-defined silicon QD devices leading to reduction of the complexity of device structure because there is no need for gates to form QDs [10]. For the large-scale integration of qubits in the future, it is desirable that the number of its gates is reduced furthermore.

In this study, we apply not only voltage difference between drain and source but also offset bias in order to modulate potential of double QD (DQD) and single QD (SQD) without any extra gate, respectively. We also demonstrate that we can control the potential of DQD by using only SQD.

2. Device fabrication and measurement setups

Scanning electron microscope (SEM) image and cross-sectional schematic image of our device are shown in Fig. 1(a) and (b), respectively. We fabricated physically-defined p-channel DQD and SQD on undoped silicon-on-insulator (SOI) substrate by electron beam lithography and dry etching. The device consists of SQD, DQD, and several side gates (G_{SQD}, G_l, G_m, G_r). 10-μm square around the QDs is covered with poly-Si used as top gate. Channels out of the square is doped with boron for the dose of 1.0×10^{20} cm^{-3}. By applying negative voltage to top gate, V_{TG}, holes are induced in the QDs like metal-oxide-semiconductor field effect transistor (MOSFET).

Figure 2(a) and (b) are schematics of measurement setup to control potential of SQD and DQD, respectively. Each voltage difference between drain and source is defined as V_{DS1} in (a) and V_{DS2} in (b), respectively. Generally, only side gates are used to control the potential of each QD [11,12]. However, in this study, we applied offset bias voltages, V_{O1} and V_{O2} to tune the potential of the QDs. This may lead to reduction of the number of gates and simplification of the device structure. All measurements were performed at a temperature of 4.2 K.

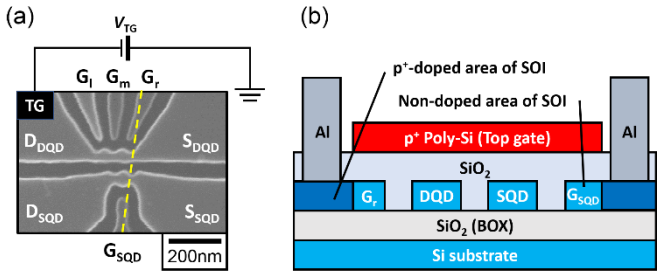

Fig. 1 (a) SEM image of our p-channel QD device. (b) Cross-sectional schematic device structure along the yellow dashed line in (a). The QDs are formed in a SOI layer and capacitively coupled with side gates formed in the same layer.

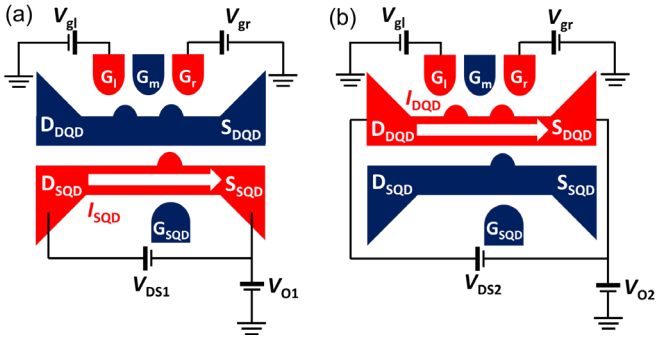

Fig. 2 Schematic of experimental setup to control potential of (a) SQD and (b) DQD, respectively. The parts used for the measurement are shown in red and the others are shown in dark blue. The results obtained using the setup (a) and (b) correspond to Fig. 3 (a) and (b), respectively.

3. Measurement results and discussion

Figure 3(a) and (b) show the current traces as a function of gate voltages of DQD when we applied offset bias voltages V_{O1} to SQD, and V_{O2} to DQD, respectively. At $V_{O1\,(O2)} = 0$ mV,

typical Coulomb peaks corresponding to discrete energy levels in the bias window, were observed. When $V_{O1\ (O2)}$ increases, shifts of Coulomb peaks were observed. These results indicate that each offset bias has a function to control the potential of SQD and DQD, respectively. We also observed changes in the height of Coulomb peaks. This is because the potential barriers between the QDs and the leads are changed according to the difference between $V_{O1\ (O2)}$ and V_{TG} [13].

Next, we used both SQD and DQD to examine whether SQD works as a gate to control the potential of DQD as shown in the inset to Fig. 4. Coulomb peaks in the current I_{DQD} through DQD as a function of the offset bias V_{O1} of SQD were observed as shown in Fig. 4. Since the channel of SQD is capacitively coupled with DQD as is the case with side gates, the potential of DQD changes according to the change of that of SQD. Furthermore, SQD can be used not only as a gate but also as a charge sensor to detect charge transition in DQD. Figure 5 shows a stability diagram of DQD with the applied V_{O1} = 4.0 mV obtained by measuring the current I_{SQD} through SQD. These results indicate that the SQD has two functions as a gate and a charge sensor. This multifunction of QDs reduces the complexity of the device structure and provides a way to large scale integration of qubits in the future.

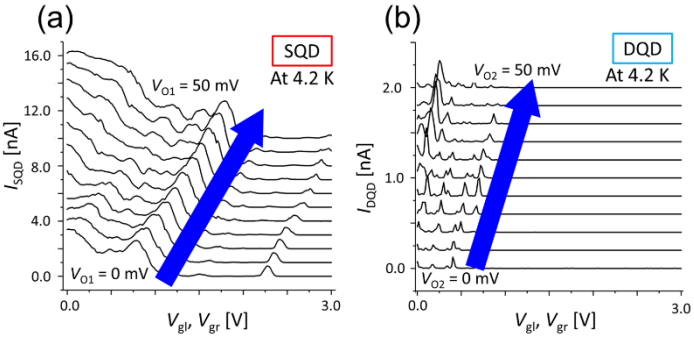

Fig. 3 Potential modulations of (a) SQD and (b) DQD by each offset bias. V_{TG} = -1.7 V in both cases, V_{DS1} = 4.0 mV and V_{DS2} = 1.0 mV. Blue arrow in each figure shows shift of Coulomb peaks.

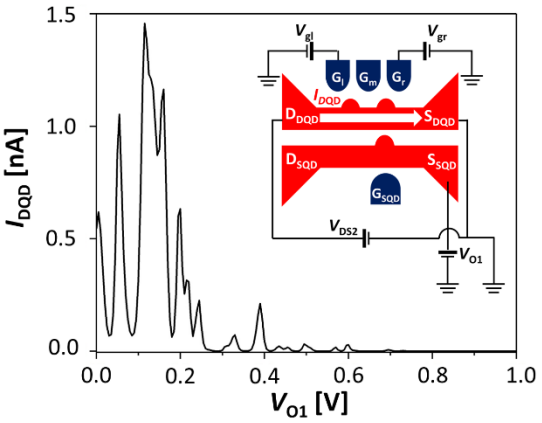

Fig. 4 Potential modulation of DQD by sweeping offset bias voltage V_{O1} of SQD. V_{TG} = -1.7 V、V_{DS2} = 1.0 mV. Inset: Schematic of this measurement setup. The parts used for this measurement are shown in red and the others are shown in dark blue. Coulomb oscillation of DQD, induced by offset bias of SQD, was observed.

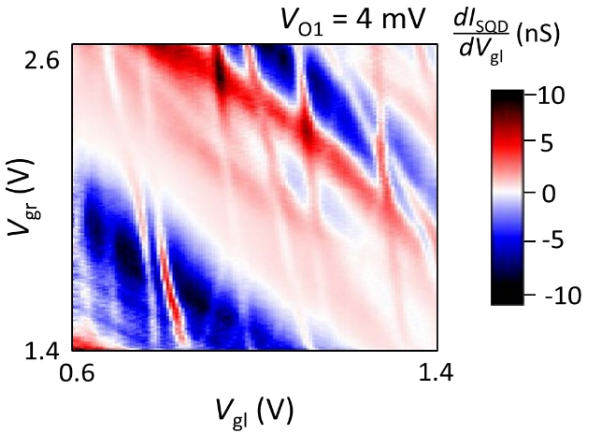

Fig.5 Numerical derivative of current through the SQD with respect to Vgl as a function of Vgr and Vgl for V_{O1} = 4.0 mV, V_{TG} = -1.7 V, and V_{DS2} = 1.0 mV. Charge sensing lines which show the hole tunneling on the DQD were observed clearly.

4. Conclusions

We fabricated physically-defined p-channel silicon QDs and observed shift of Coulomb peaks of DQD and SQD, by applying offset bias between drain and source, respectively. In addition, we measured the current through DQD and SQD as a function of bias voltage of SQD and side gate voltages. From the results, we found that SQD has two roles of the charge sensor detecting the charge transition of DQD and the gate modulating potential of DQD. The obtained results demonstrate a way to simplify the device structure for the large-scale integration of qubits.

Acknowledgements

Part of this work is financially supported by CREST-JST (JPMJCR1675), and the Quantum Leap Flagship Research Program (Q-LEAP) of Developing Innovation Systems of the Ministry of Education, Culture, Sports, Science and Technology (MEXT) of Japan.

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