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Fabrication and characterization of p-type heavily doped silicon quantum dots

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Abstract

We study hole transport properties in p-type silicon quantum dots (QDs) on a heavily doped silicon-on-insulator (SOI) substrate. Hole spin in silicon QDs is considered to be a promising candidate for quantum information processing using its spin-orbit coupling. We fabricate p-type heavily doped silicon QDs. We observe Coulomb diamonds using single QDs and estimated the charging energy. We also obtain charge stability diagram of double QDs using single QDs as a charge sensor.

1. Introduction

Silicon quantum dots (QDs) have been well studied toward spin-based quantum bits (qubits) [1-4]. Silicon QDs are attractive materials because natural ^{28}Si [5] has no nuclear spins and they can be fabricated using conventional silicon device technologies such as Metal-Oxide-Semiconductor (MOS) fabrication process [6-8]. Therefore, silicon QDs are expected to have long coherence time and suitability for large-scale integration. Especially, p-type silicon QDs attract much attentions recently [9-13], since holes in silicon QDs have a wave function with p-like orbital, it leads to small hyperfine interaction with surrounding nuclear spins. Furthermore, hole spins in silicon QDs have spin-orbit coupling (SOC), which can be used for spin manipulation.

In this work, we fabricate and characterize p-type heavily doped silicon QDs. One of the advantages of heavily doped silicon QDs is that we obtain the devices with simpler fabrication process than MOS-type devices because the fabrication of the top gate to induce carriers is not needed [14,15]. In heavily doped devices, impurity doping is performed all over the substrate to have enough carriers in QDs. This simple fabrication process gives the good reproducibility and high integration possibility of the devices. The other advantage of heavily doped silicon QDs is that we can eliminate top gate capacitance, which may lead to efficient introduction of high frequency signals to the device. Here we present the fabrication process of p-type heavily doped silicon QDs and measurement results of Coulomb diamonds obtained using single quantum dots (SQDs). We also show the charge sensing of the hole configuration in double QDs (DQDs) using a SQD as a charge sensor (CS). This is the first realization of p-type heavily doped silicon DQDs with CSs.

2. Device fabrication

We present the fabrication process of p-type heavily doped silicon DQDs. We implanted Boron at a dose of 1.0×10^{15} cm^{-2} into the 30 nm thick SOI substrate through 100 nm thick oxide. This dose condition creates an effective carrier concentration of 1.0×10^{19} cm^{-3} after annealing. This carrier concentration is sufficient to form an Ohmic contact with the source and drain. Then, we fabricated DQDs and a SQD as a CS on a heavily doped SOI substrate using electron-beam lithography (EBL) and SF_6 dry etching by reactive ion etching. Small QDs without surface defects were fabricated via precise EBL and vertical SF_6 dry etching. After the reactive ion etching, a protective SiO_2 layer was formed by thermal oxidation at 900℃ for 3 min to passivate the surface states of the SOI layer. The final thickness of the SOI layer was 20–30 nm; the layer thus provided a suitable resistance for tunnel junctions on the heavily doped SOI substrate. Finally, aluminum electrodes were formed by using photolithography and vacuum vapor deposition.

The device structure and a scanning electron microscope (SEM) image are shown in Fig. 1. The side gates (SGL, SGR, and SG) can control the potential of each QD. The CS is fabricated in the vicinity of the DQD.

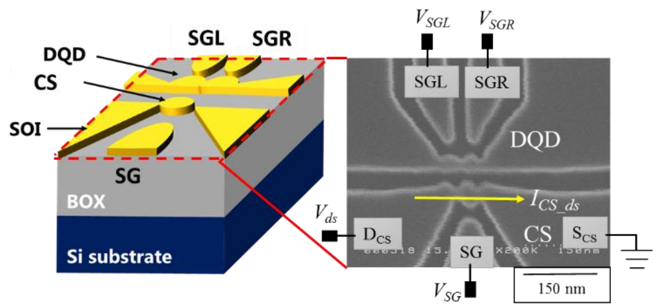

Fig. 1 Schematic device structure and a scanning electron microscope (SEM) image of p-type heavily doped device, composed of DQD and CS. The QDs are capacitively coupled with side gates. The SEM image was taken using the device on the same process chip as the device measured below.

3. Measurement results and discussions

The measurements were performed at 4.2K in liquid helium. The current flowing through the CS was measured by connecting drain contact to the source measurement unit of a semiconductor device parameter analyzer. Figure 2 shows the contour plot of the current I_{CS_ds} as a function of the source-drain voltage V_{ds} and the side gate voltage V_{SG}. Typical Coulomb diamonds of a SQD were observed. Coulomb blockade was clearly observed inside the diamonds, where the hole number is fixed. From the size of the blockaded region, we estimated the charging energy E_C (~1.6 meV). We also estimated the capacitive coupling C_{SG} between the CS and SG as 1.34 aF. The obtained E_C is smaller than expected, which is possibly because the size of the measured CS is larger due to insufficient etching.

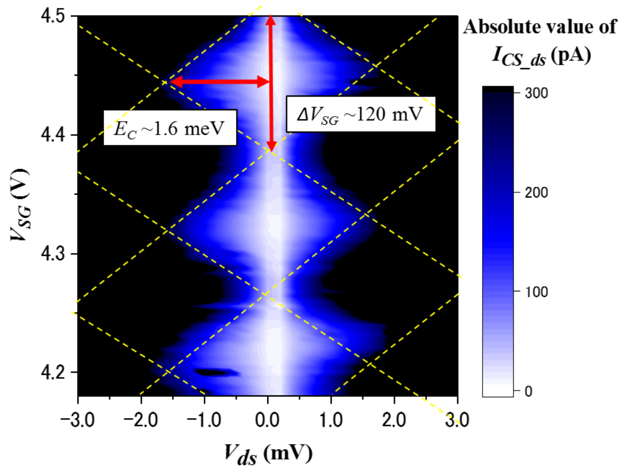

Fig. 2 Contour plot of the current I_{CS_ds} as a function of the source-drain voltage V_{ds} and the side gate voltage V_{SG}. Typical Coulomb diamonds were observed. The vertical arrows and horizontal arrows indicate the charging energy E_C and ΔV_{SG}, respectively.

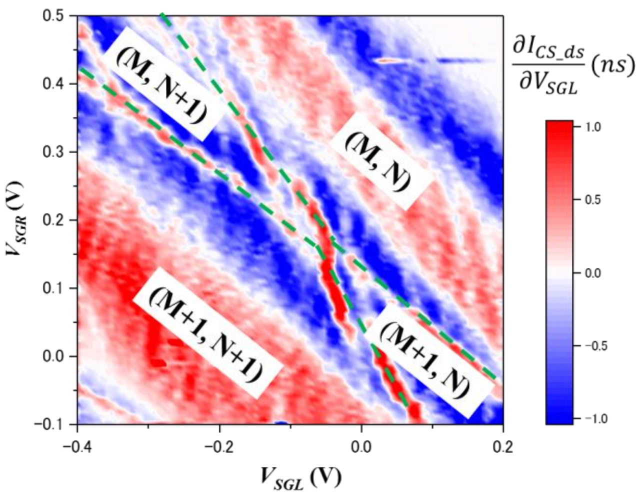

Fig. 3 Charge stability diagrams of the DQD obtained by measuring the transconductance dI_{CS_ds}/dV_{SGL} as a function of side gate voltages V_{SGL} and V_{SGR}.

Figure 3 shows the charge stability diagram of the DQDs as a function of side gate voltages V_{SGL} and V_{SGR} obtained by measuring the transconductance dI_{CS_ds}/dV_{SGL} using the CS. Abrupt changes in I_{CS_ds} correspond to the charge transitions in the DQDs. Charge configurations in each QD ((M, N), (M, N+1), (M+1, N), and (M+1, N+1)) are indicated, and at the boundaries we obtained the charge sensing signals, which are indicated by green dashed lines. This is the first demonstration of charge sensing of the DQDs on a p-type highly doped SOI substrate.

4. Conclusions

We fabricated p-type heavily doped silicon QDs and observed Coulomb diamonds. From the Coulomb diamonds, we estimated the charging energy and the gate capacitance. We also observed the charge stability diagrams of DQD using CS. This is the first demonstration of p-type heavily doped silicon QDs which is one of the suitable structure for future large scale integration of the qubits.

Acknowledgements

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References

[1] A. Morello et al., Nature (London) **467**, 687-691 (2010).
[2] B. M. Maune et al., Nature 481, 344–347 (2012)
[3] M. Veldhorst et al., Nature 526, 410–414 (2015).
[4] K. Takeda, et al., Science Advanced, 2, 8, e1600694-1-6 (2016).
[5] K. M. Itoh and H. Watanabe, Mater. Res. Soc. Commun. 4, 143–157 (2014).
[6] G. Yamahata, et al., Phys. Rev. B 86, 115322 (2012).
[7] K. Horibe, et al., Appl. Phys. Lett. 106, 083111 (2015).
[8] K. Horibe, et al., Appl. Phys. Lett. 106, 053119 (2015).
[9] B. Voisin., et al., Nano Lett., 16 (1), 88-92 (2015).
[10] Li. Ruoyu., et al., Nano Lett., 15.11 (2015).
[11] R. Maurand, et al., Nature Commun. 7 13575 (2016).
[12] K. Yamada, et al. Appl. Phys. Lett. 105, 113110 (2014).
[13] Y. Yamaoka, et al., Jpn. J. Appl. Phys. 56, 04CK07-1-4 (2017).
[14] T. Kodera et al., Jpn. J. Appl. Phys. 48 (6) 06FF15-1-6 (2009).
[15] Y. Yamaoka, et al., Appl. Phys. Lett. 109, 113109-1-4 (2016).