

Study of single-electron transport via suspended double silicon quantum dots

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Recent advance on fabricating silicon nano electromechanical systems (NEMS) has enabled us to study single-electron tunnelling through nanometer-scale suspended structures with restrained coupling to the environment [1]. In particular, a suspended quantum dot cavity structure built on a suspended Si nanowire provides an ideal system to explore the interaction of single electrons with phonons with tailored spectra in the cavity which is acoustically isolated from the Si substrate. Such a system has recently become of great interest in order to study physics of decoherence mechanisms for quantum bits and also to reveal ultimate energy dissipation process in Si nanostructures. Theoretical [2,3] and experimental [4,5,6] investigations have been performed by using GaAs quantum dots. We have reported single electron transport in suspended Si quantum dots fabricated by using either bottom-up or top-down method [1]. In this paper we report on fabrication of suspended double quantum dots (SDQDs) on the Si nanowire channel by using top-down method and evaluation of single electron transport via the SDQDs.

We fabricated the SDQDs on a suspended nanowire by combining EB-lithography and thermal oxidation in the same manner as used to fabricate a single QD in [1]. We first patterned nanowire structures on a SOI wafer and etched the nanowire in the wedged shape by using EB-lithography and ECR-RIE. SiO₂ under the nanowire was etched out by using liquid HF and a suspended nanowire channel was formed. Finally, we thermally oxidized the suspended nanowire to passivate the device surface and to reduce the QD size. Figure 1 shows DQDs embedded in a suspended nanowire. We patterned three wedged regions on the suspended nanowire channel, which are expected to act as a tunnel barrier and thus to define coupled DQDs. Double side gates are located near the DQDs to control their potential individually.

First we studied electron transport through the SDQDs of approximately 100 nm in diameter on the SOI with phosphorous doping of $9 \times 10^{18} \text{ cm}^{-3}$. If the SDQDs are ideally formed as intended, double crossing current peak lines should be observed [7], but current peaks in the measurement results look quite complex. Apparently there are many unintentional QDs or some charge traps in the nanowire channel. These problems are often seen for doped QDs [8]. In order to overcome this issue, we then prepared the SDQDs with larger diameter formed on the SOI with higher doping concentration. In the Fig. 2, the source drain current I_{ds} is plotted versus each two gates, V_{g1} and V_{g2} , with the source-to-drain voltage, V_{ds} of 400 μV at temperature of 4.2 K. The double crossing current peak lines appeared as indicated by supporting thin lines. We increased the size of the QDs to 150 nm to reduce the effect of the line edge roughness and to avoid unintended extra QDs which may

be formed in the wedged regions [8,9]. Doping concentration was increased to $5 \times 10^{19} \text{ cm}^{-3}$ to improve the overall conductance and to reduce the effects of random dopant potential barriers. The higher-doped and thicker nanowire exhibited the enhanced conductance compared to the lower-doped and thinner nanowire as shown in Fig. 3. The conductance was found virtually independent of temperature, proving that the random potential effects were successfully reduced.

One of the double crossing peak lines in Fig. 2 is not as clear as the other presumably because the QD is not small enough to study the coulomb blockade at 4.2 K. We therefore conducted ultra-low temperature measurements to observe clear Coulomb blockade. Figure 4 shows the characteristics for the SDQDs measured at 120 mK. The anti-crossing natures of the current peaks were clearly observed, and the currents were maximum at the crossing points as expected for the series-connected DQDs.

Figure 5 shows a blow-up of the squared region in Fig. 4. Double triangular shaped regions are clearly identified as a fingerprint of coupled DQDs. However, the crossing region in Fig. 5 also exhibited fine structures superposed on the conventional DQD patterns. Figure 6 shows the details of the current peaks plotted along the solid line in Fig. 5. After deconvolution, three current subpeaks were revealed in addition to the two main peaks. There exist various possible physical origins for such current subpeaks. Two small subpeaks have been reported for tunnel-coupled parallel DQDs [10, 11], and the origin was discussed in terms of tunnelling via higher anti-bonding states of the DQDs. However, three subpeaks observed for our SDQDs cannot obviously be understood in the same manner. Another possible origin of the subpeaks is phonon-assisted tunnelling [12], which may be enhanced in our SDQD structure because of the existence of the localized phonons in the SDQD cavity [4]. However, we cannot exclude the possibility of the unintentional extra QDs effects and still need further investigations to conclude the mechanism.

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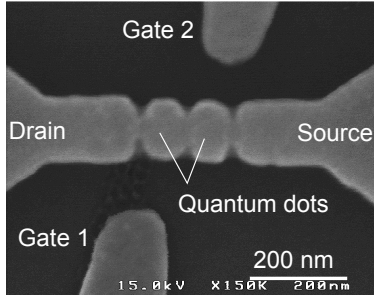


Fig. 1: SEM image of fabricated SDQDs.

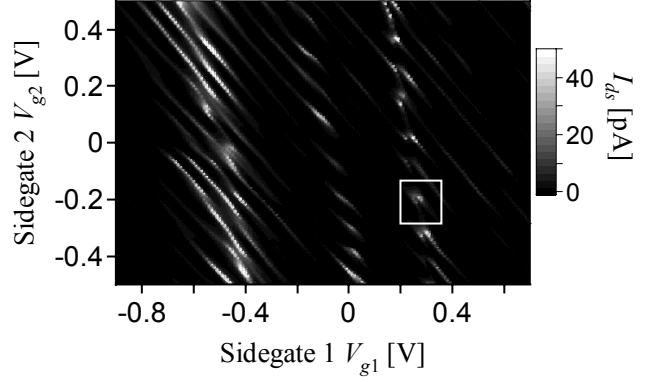


Fig. 4: Single electron transport at 120 mK. $V_{ds} = 200 \mu\text{V}$.

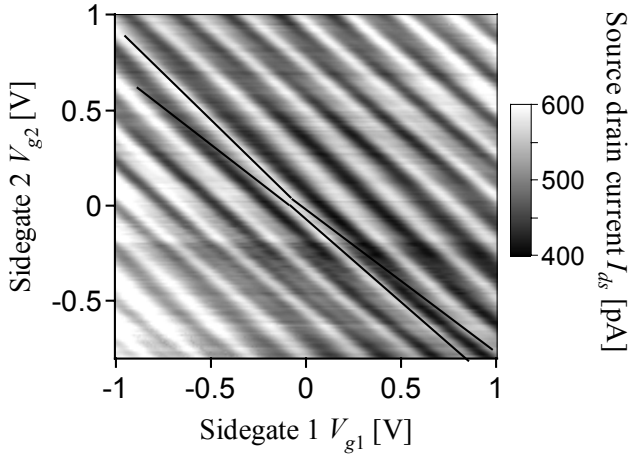


Fig. 2: Single electron transport through SDQDs at 4.2 K. $V_{ds} = 400 \mu\text{V}$. The black solid lines indicate the double crossing current peak lines.

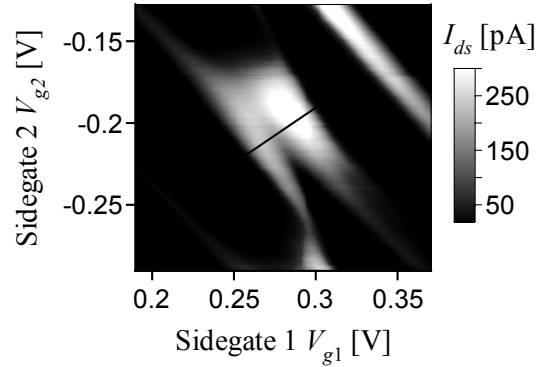


Fig. 5: A blow up of the squared region indicated by solid line in Fig. 4. $V_{ds} = 500 \mu\text{V}$.

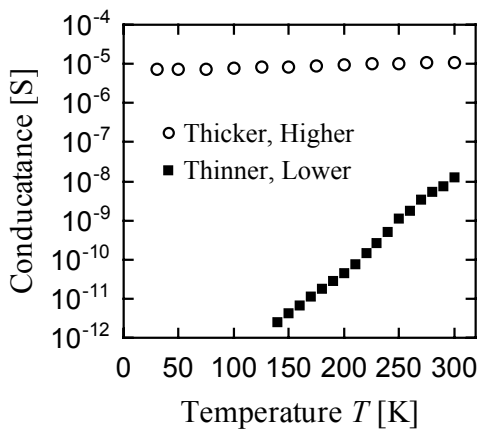


Fig. 3: Comparison of conductance for a suspended nanowire with thicker and higher dopant concentration with one for a thinner and lower dopant concentration nanowire. Width is 100 nm and dopant concentration is $5 \times 10^{19} \text{ cm}^{-3}$ for the circles, and width is 50 nm and dopant concentration is $9 \times 10^{18} \text{ cm}^{-3}$ for the squares.

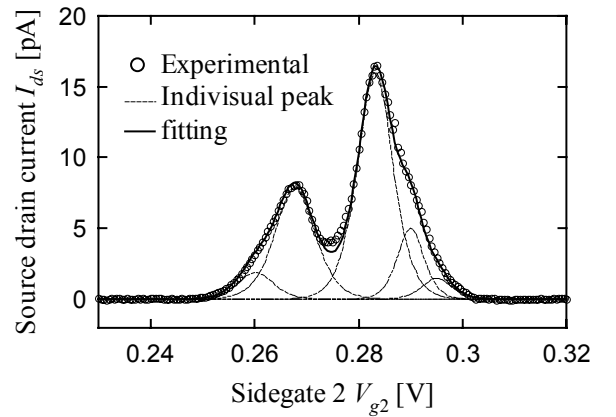


Fig. 6: Current peaks along the solid line in fig. 5 at $V_{ds} = 100 \mu\text{V}$. The circles are experimental results and five peaks are assumed as the dashed lines. The solid line is summed up the five peaks and fitted to the experimental results. We assume peak function as $A \cosh^{-2}(\log(3 + 2\sqrt{2})(V_{g2} - x_c)/w)$. A , x_c and w are peak height, centre of the peak and FWHM, respectively.