Extended Abstracts of the 2008 International Conference on Solid State Devices and Materials, Tsukuba, 2008, pp. 938-939

D-8-3

Diameter-controlled 2-dimensional Array of Si Nanodisk using Bio-nano-process and Neutral Beam Etching for Realistic Quantum Effect Devices

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1. Introduction

Increasing miniaturization of semiconductor device toward nanometer scale will result in serious problems, such as short channel effect and high power consumption, in the near future. Quantum effect device, such as single electron transistor (SET), has been extensively studied to overcome the limitation. Most silicon-based SETs are single quantum dot (QD); however, single-QD SETs have shown stability problem in Coulomb blockade due to cotunneling effect[1]. Recently, multi-QD SETs, such as 2-dimension-QD, have been proposed to overcome the problem[2,3]. QD and tunnel junction are the key structures in a SET; however, it is very difficult to fabricate consistent performance of SET because size controllability of the key structures is very hard to achieve. On the other hand, fabrication process must prevent defect on the structures because loss of even only one electron will result in malfunction in SET.

To overcome the fabrication problem mentioned above, we have developed a novel silicon nanodisk[4] structure that was fabricated by bio-nano-process, which combines the ferritin supramolecules and neutral beam (NB)[5] etching. The nanodisk shows quantum effect by observing staircase even at room temperature. In this study, we investigated the thickness and diameter-dependence of single nanodisk on the staircase width. Moreover, we fabricated device with 2-dimensional nanodisk (2D-nanodisk), which combines the concept of multi-QD SET and our developed nanodisk.

2. Experiment

The detail of bio-nano-process of single nanodisk fabrication was described in the [ref.4,6]. The fabrication process of nanodisk started with (i) forming 1.4 nm-thick SiO_2 by rapid thermal oxidation, (ii) 2.5–5 nm-thick a-Si film was deposited and then annealed in N_2 to form poly-Si (the nanodisk thickness was controlled by changing poly-Si thickness.), (iii) making surface hydrophilic by H_2SO_4 + H_2O_2 solution, (iv) ferritin molecules were deposited, (v) ferritin protein shell was removed in heat treatment in O_2 to obtain iron core (7 nmϕ) inside the ferritin, (vi) etching was carried out by combination of the NF_3 treatment (surface oxide removing) and NB etching (poly-Si etching) with ferritin iron core mask. A dry process using NF_3 gas and hydrogen radical (NF_3 treatment) was performed to selectively remove surface native silicon oxide and control nanodisk diameter, as shown in Fig. 1(a). Details of etching process were described elsewhere.[6] After NB etching (vii) iron cores were removed by hydrochloric acid. I-V measurement of nanodisk was performed using conductive AFM at room temperature.

Additionally, 2D-nanodisk was fabricated. Figure 1(b) shows a schematic diagram of the fabrication process. The process is similar to that of single nanodisk's process written above, but 100-nm-thick thermal oxide was used instead of 1.4nm RTO in the step (i), our developed neutral beam oxidation (NBO)[7] was used in the step (iii), and 2-dimensional ferritin array was generated on the NBO film in the step (iv). A device was fabricated by depositing two Al electrodes with a space of several tens of nanometer on the 2D-nanodisk. Figure 1(c) shows the schematic diagram of the device. I-V measurement was performed for the device to investigate lateral tunneling of 2D-nanodisk.

3. Results and discussion

Figure 2 shows the thickness and diameter-dependence of single nanodisk on staircase width at room temperature. It was shown that the staircase strongly depends on the thickness while it is almost independent of diameter. On the assumption that Si nanodisk was made by single crystalline silicon because the disk diameter was smaller than grain size in the poly-Si, the results suggest that nanodisk works as a quantum well. Since the nanodisk thickness is much smaller than Bohr radius in silicon nanodisk (about 5 nm), quantum confinement occurrs in the thickness direction. On the other hand, the nanodisk diameter is larger than that and quantum confinement doesn't occur in the diameter direction.

SEM images of top-view of the 2-dimensional iron cores on NBO SiO_2 is shown in Figure 3(a). Then the sample was treated by NF_3 treatment for 30 minutes to remove surface SiO_2 and etched by NBE etching for 90 seconds to remove poly-Si. The 2D-nanodisk was successfully fabricated on the NBO SiO_2 as shown in Figure 3(b). We also prepared thermal SiO_2 as surface oxide for 2D-nanodisk fabrication by the same processing condition. However, the 2D-nanodisk was not clear in the case of using thermal SiO_2 as shown in Figure 3(c). It is suggested that NBO SiO_2 surface could strongly connect with ferritin molecules and iron cores, as compared with thermal SiO_2 surface. Figure 4 shows the dependence of NF_3 treatment time on the gap between adjacent nanodisks in 2D-nanodisk on the NBO SiO_2. When the time was 5 minutes, the 2D-nanodisk was not clear. Because the poly-Si was almost not etched by NB etching due to remained surface oxide, as shown in Figure 4(b)-(i). When the NF_3 treatment time ranges from 15 to 30 minutes, the 2D-nanodisk was very clear and regular. The gap between nanodisks ranges from 1 to 3 nm while the diameter ranges from 8 to 10 nm. However, when the time was 45 minutes, the 2-dimensional arrangement collapsed due to large side etching of surface oxide under iron core, as shown in Figure 4(b)-(iv), by NF_3 treatment. Both

results of independence of diameter on staircase width, as shown in Figure 2(a), and gap controllability between nanodisks, as shown in Figure 4, are very important characteristics when incorporating 2D-nanodisk into device. They indicate that the tunneling gap can be controlled without changing the quantum effect of each nanodisk in the 2D-nanodisk device.

Figure 5 shows optical microscope and SEM images of the Al electrodes in 2D-nanodisk device. Then, the tunnel gap between nanodisks was fixed at 3 nm and the space between Al electrodes was about 30 nm.

Figure 6 shows an I-V curve of the device by applying voltage between Al electrodes at room temperature. A fluctuating current was observed as shown by arrows in the figure. This may be because carrier flows percolation path in 2D-nanodisk structure and the potential of the path is modified by charge-discharging of adjacent nanodisks[3]. The I-V curve indicates single electron motion even at room temperature.

4. Conclusions

In summary, 2D iron cores were successfully fabricated on NBO SiO_2. By using 2D iron cores as etching mask, we obtained 2D-nanodisk by etching process, including NF_3 treatment and defect-free chlorine neutral beam. The tunneling gap could be controlled in 2D-nanodisk without changing the quantum effect of each nanodisk because of independence of diameter of single nanodisk on staircase width. The 2D-nanodisk device could obtain I-V curve which shows the current fluctuation in percolation path in the nanodisk array even at the room temperature.

Acknowledgements

The authors wish to thank Rikako Tsukamoto and Dr. Kazuaki Nishio of Matsushita Electric Industrial, Co., Ltd. for preparing the salt-free ferritin molecules. This study was supported by the Leading Project and Nanotechnology Support Network Project of the Ministry of Education, Culture, Sports, Science and Technology (MEXT), Japan.

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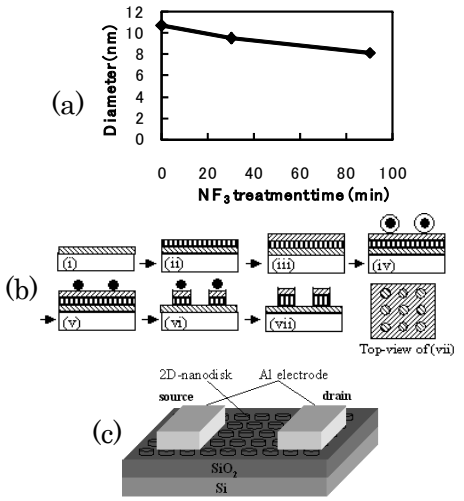


Figure 1. (a) Nanodisk diameter as a function of NF_3 treatment time, (b) fabrication flow 2D-nanodisk, and (c) schematic diagram of device with 2D-nanodisk.

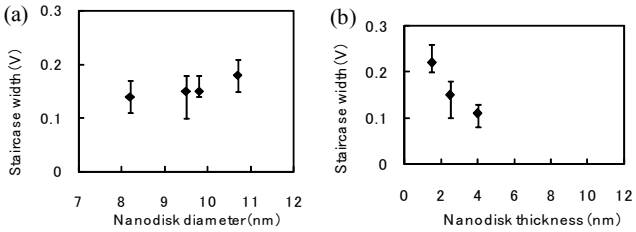


Figure 2. Staircase width as a function of diameter and thickness for single nanodisk at room temperature.

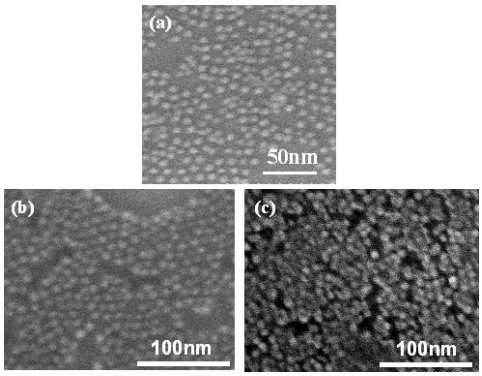
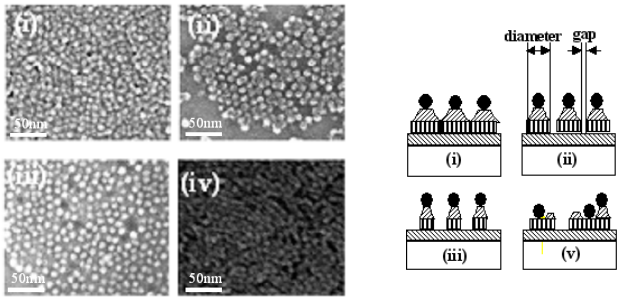


Figure 3. SEM images of top-view of (a) 2-dimensional iron cores on NBO SiO_2, 2D-nanodisk fabricated by using (b) NBO SiO_2 and (c) thermal SiO_2.



(a) (b)

Figure 4. (a) SEM images and (b) schematic diagrams of 2D-Si-nanodisk with different NF_3 treatment time of (i) 5; (ii) 15, (iii) 30 and (iv) 45 minutes for NBO SiO_2.

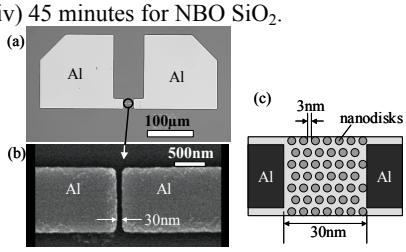


Figure 5. Optical microscope images of (a) 2D-nanodisk device and (b) its SEM image around space between Al electrodes. (c) shows a schematic diagram of the device.

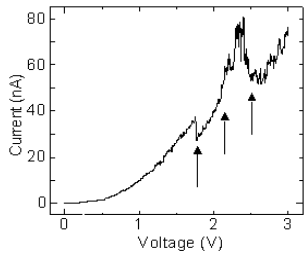


Figure 6. I-V curve of 2D-nanodisk device by applying voltage between Al electrodes at room temperature. The tunnel gap between nanodisks was fixed at 3 nm and the space between Al electrodes was about 30 nm.