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A New Structure of nanodisk (Stacked Nanodisk) fabricated by bio-nano-process and defect-free neutral beam etching

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1. Introduction

It is indispensable to increase the miniaturization of conventional MOSFET as year goes by. However, the miniaturization would suffer serious problems, such as leakage current and power consumption, in the near future. Quantum effect devices are highly expected to overcome these problems[1]. In many application, such as electron pump[2], and memory cell[3], primary theometry[4], electron tunneling happens through several junctions in series, i.e. one-dimensional array of tunnel junctions, which would enhance the Coulomb blockade for charge transport through the array.[5] Quantum dot (QD) is a key structure in the array. Stranski-Krastanov (SK)[6] growth mode have been widely studied to fabricate QDs. However, it couldn't avoid to induce crystalline defects[7]. Although nanocrystalline silicon (nc-Si) has also been widely studied, the size controllability is very hard to achieve as well. On the other hand, top-down approaches such as optical lithography and plasma etching can be also used for the fabrication of QDs. However, it would be also very difficult to form sub-10-nm patterns by using conventional optical lithography or plasma etching[8].

To overcome these problems mentioned above, we have developed a new structure of nanodisk[9] that was fabricated by bio-nano-process and defect-free neutral beam (NB)[10] etching. In this study, we proposed a structure of stacked-nanodisk consisting of two nanodisks connected in a series by coupling of three tunnel junctions and its fabrication. The structure combines the concept of one-dimensional array of tunnel junctions and our developed nanodisk. One of the tunnel junctions was fabricated by our developed neutral beam oxidation (NBO)[11]. Tunnel junction thickness, which was controlled by NBO, dependence and stacked nanodisk diameter dependence of Coulomb staircase were also investigated.

2. Experiment

The details of the bio-nano-process for the fabrication of stacked nanodisk were based on previous literature[9]. Here we briefly describe the sample preparation procedure. Multilayered films were fabricated sequentially as followings: a 1.4-nm-thick $SiO_2(1^{st})$ was grown by rapid thermal oxidation on a p-type Si(100) wafer; amorphous silicon (a-Si) layer was deposited on the $SiO_2(1^{st})$ using electron beam deposition and crystallized to form 3-nm-thick poly-Si(1^{st}) by heat treatment in nitrogen atmosphere; a 1~2-nm-thick $SiO_2(2^{nd})$ was grown on the poly-Si(1^{st}) by NBO; a 3-nm-thick poly-Si(2^{nd}) was deposited by the same process as poly-Si(1^{st}); finally, the surface of the sample was naturally covered by surface oxide ($SiO_2(3^{rd})$). After film deposition, the etching mask was deposited onto the sample by using recombinant ferritin molecules. The ferritin protein shell was removed by heat treatment in oxygen atmosphere to extract the 7-nm-diameter iron oxide core as etching mask. Alternative etching of NF_3 gas/hydrogen radical (NF_3 treatment) and defect-free neutral beam (NB) etching was performed to precisely remove SiO_2 and poly-Si layers, respectively. The diameter of stacked nanodisk was controlled by the NF_3 treatment time in the first etching step. We also investigated the diameter control by high energy NB etching. In order to optimize the etching condition, Si 2p regions of XPS spectra were measured after each etching step.

3. Results and discussion

Figure 1 shows the XPS spectrum of each optimized etching step. Initially, as shown in Figure 1-(a), the chemical shift was about 4eV before etching, which implies that the $SiO_2(3^{rd})$ was similar to the thermal oxide due to the heat treatment for removing protein shell. After 1^{st} NF_3 treatment with 30 minutes, as shown in Figure 1-(b), the surface of the sample was the poly-Si(2^{nd}) due to smaller chemical shift with about 3.6eV and much weaker intensity of oxide peak. Figure 1-(c) shows the larger chemical shift and stronger intensity of oxide peak after 1^{st} NB etching, which indicates that the surface of the sample was the $SiO_2(2^{nd})$. After 2^{nd} NF_3 treatment with 20 minutes, the chemical shift and intensity of oxide peak, as shown in Figure 1-(d), were similar to the one after 1^{st} NF_3 treatment due to the sample surface of poly-Si(1^{st}). Finally, as shown in Figure 1-(e), the chemical shift and intensity of oxide peak became larger again, which indicates that the $SiO_2(1^{st})$ was preserved after 2^{nd} NB etching. The SEM images, as shown in Figure 2, show the evolution of each etching step corresponding to the XPS spectra. After 1^{st} NF_3 treatment, as shown in Figure 2(a)-(i), the image shows rough surface and the disk shape is not clear. After 1^{st} NB etching, the disk shape, as shown in Figure 2(a)-(ii), could be recognized. Then, the disk shape is more obvious after 2^{nd}

NF_3 treatment, as shown in Figure 2(a)-(iii). At the end, the stacked-nanodisk was clear shown in Figure 2(a)-(iv) and the surface of remained $SiO_2(1^{st})$ was very smooth. Figure 2(b) shows the cross-sectional scanning transmission microscopy (STEM) image of stacked-nanodisk. The stacked-nanodisk with alternative layers of nanodisks and tunnel junctions was clearly observed.

Diameter of stacked nanodisk was controlled by the 1^{st} NF_3 treatment (the following etching conditions were the same). We also performed higher energy of NB etching to investigate the controllability of diameter. Figure 3 shows the result of diameter control. By changing the NF_3 treatment time, the diameter could be controlled. As the NF_3 treatment time increases, the diameter of stacked nanodisk decreases. The controllable range is from about 14 to 12nm. By using the high energy NBE, the controllable range could be extended to about 11 nm.

I-V characteristics of stacked nanodisk were taken using JEOL JSPM-4500A scanning probe microscope and an AFM probe coated with doped diamond at room temperature. Figure 4 shows an example of the I-V for a stacked nanodisk. Coulomb staircase was observed. Figure 5(a) and (b) show the diameter dependence and $SiO_2(2^{nd})$ thickness dependence of Coulomb staircase. The staircase width highly depends on the $SiO_2(2^{nd})$ thickness due to the change of tunnel probability. On the other hand, the staircase was almost independent of diameter because the nanodisk works like a quantum well[12].

4. Conclusions

In summary, a stacked-nanodisk with two nanodisks connected in a series by coupling of three tunnel junctions was successfully fabricated by bio-nano-process. By utilizing XPS spectra, the etching depth could be precisely detected and the etching condition could be optimized as well. The SEM and TEM images clearly show the evolution of the shape of the stacked-nanodisk after each etching step and the alternative structure of stacked-nanodisk, respectively. The diameter of stacked nanodisk could be controlled by different etching condition. The Coulomb staircase was observed in I-V measurement at room temperature. The staircase width was almost independent of diameter. By varying the thickness of tunnel junction of $SiO_2(2^{nd})$ by our developed NBO, the characteristic of Coulomb staircase could be controlled.

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References

[1] C. S. Wu et al., Appl. Phys. Lett., 81, 4595 (2002).
[2] H. Pothier et al., P. Lafarge, C. Urbina, D. Esteve, and M. H. Devoret, Europhys. Lett., 17, 249 (1992).
[3] M. Shin et al., Nanotechnology, 12, 178 (2001).
[4] K. P. Hirvi et al., J. Appl. Phys., 80, 256 (1996).
[5] J. Johansson et al., Phys. Rev. B, 63, 014201 (2001).
[6] D. Leonard et al., Appl. Phys. Lett., 63, 3203 (1993).
[7] D. Leonard et al., J. Vac. Sci. Technol., B12, 2516 (1994).
[8] W. H. Chang et al., Appl. Phys. Lett., 64, 2154 (1994)
[9] T. Kubota et al, Appl. Phys. Lett., 89, 233127 (2006).
[10] S. Samukawa et al., J. Vac. Sci. Technol., A 20, 1566 (2002).
[11] T. Ikoma et al., Extended Abstracts of 2006 International Symposium on Solid State Devices and Materials, p.448 (2006).
[12] S. Samukawa et al., Appl. Phys. Exp., 1, 074002 (2008).

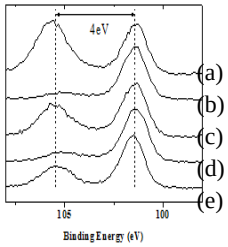
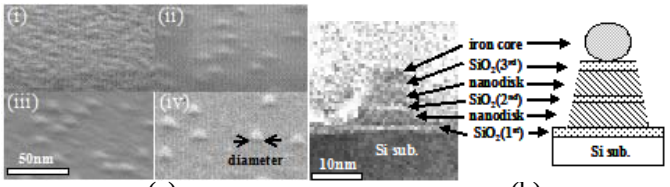


Figure 1 XPS spectra of each optimized etching step. (a) before etching; (b) after 1^{st} NF_3 treatment; (c) after 1^{st} NB etching; (d) after 2^{nd} NF_3 treatment; (e) after 2^{nd} NB etching.



(a) (b)

Figure 2 (a) SEM images of each etching step. (b)STEM image of stacked nanodisk

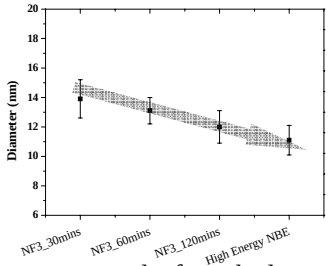


Figure 3 Diameter control of stacked nanodisk by different etching condition.

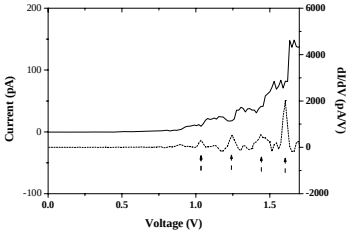


Figure 4 I–V curve (solid) of stacked nanodisk and its differential (dashed)

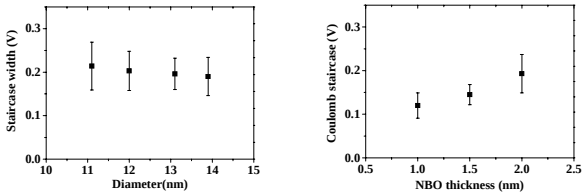


Figure 5 (a) Diameter dependence; (b) NBO thickness dependence of Coulomb staircase of stacked nanodisk.