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Fabrication of Nanometer-Scale Vertical MIM Tunnel Junctions Using a Double-Layered Inorganic Resist

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1. Introduction

The single electron devices are considered as a powerful candidate of future devices which overcome the integration limit in conventional Si-devices.[1] Nanofabrication techniques for ultrasmall tunnel junctions are indispensable to develop single electron devices which operate at room temperature. Nanometer-scale tunnel junctions have been realized by various structures such as split-gated heterostructures,[2] tunnel junctions in a very thin poly-Si layer,[3] and metal-insulator-metal (MIM) tunnel junctions.[4,5] Recently the authors, Wada et al. have developed a SiO_2/poly-Si double-layered EB resist process for suspended mask fabrication and applied it to the $Al/Al_2O_3/Al$ tunnel junctions fabrication by using the multiple-angle deposition-oxidation-deposition method.[6] The fabricated tunnel junctions exhibited a clear Coulomb staircase at 12 K.

In this study, we have developed another MIM junctions fabrication process using top two layers of an SOI (Silicon On Insulator) substrate as a double-layered inorganic resist to fabricate nanometer-scale vertical MIM junctions with high reliability. We could successfully fabricate the mask with a contact-hole of minimum diameter about 20 nm. A vertical array of two MIM junctions fabricated by this method showed the typical current-voltage (I-V) characteristics of tunnel junctions at room temperature.

2. Experiment

The schematic sequence of the vertical MIM junctions fabrication process using an SOI substrate is shown in Fig. 1. The SOI samples with resist layers of 70 nm SiO_2 and 300 nm Si were prepared on 100 nm SiO_2/Si(100) substrates. The 300 nm Si layer is thermally P-doped n-type Si of resistivity about $3.6\times10^{-4}\,\Omega\,cm$ used as a current path. The double-layered inorganic resist was selectively irradiated with a 50 kV finely focused EB with spot doses ranging from 4 to 15 pC/dot (Fig. 1(1)). After EB irradiation, the samples were processed in a barrel-type oxygen plasma asher for 15 min to remove the contamination layer due to the EB irradiation. The oxygen pressure was about 1 Torr and the RF power was 100 W. The top SiO_2 layer was then etched with a solution of buffered HF ($HF:NH_4F:H_2O$=1:5:40) at room temperature, and the underlying Si layer was etched by a commercially available photoresist developer, NMD-3 solution, from Tokyo Ohka Kogyo Co., Ltd., Japan, at 70 ℃ (Fig.1(2)). We could easily get a good undercut contact-hole because of the high selectivity (the ratio of etch rate of Si(111) to that of SiO_2) of NMD-3, about 1000 at 50 ℃.[7] An EB-evaporated Al was vertically deposited onto a sample across the contact-hole with a deposition rate of about 0.2 nm/s (Fig. 1(3)). The thickness of deposited Al film was about 30 nm. The surface of the deposited Al film was oxidized with exposure to pure oxygen of 1 Torr for 20 min, and the saturated oxidation layer of Al_2O_3 with the thickness of about 1 nm[8] was formed. Desired number of MIM junctions can be fabricated by depositing Al and oxidizing the surface of Al alternately. Finally, Al pad patterns of thickness about 120nm were made by a PMMA lift-off process (Fig. 1(4)), and the I-V characteristics of a vertical array of MIM junctions were measured.

3. Results and Discussion

Figure 2 shows the exposed dose dependence of the diameter of contact-holes of the top SiO_2 layer. The diameter of contact-holes tends to saturate with increase in exposed dose, and the mask with a contact-hole of minimum diameter about 20 nm was successfully fabricated. Figure 3 shows the I-V characteristics at room temperature of a vertical array of two MIM junctions fabricated by using the masks with a contact-hole, made by several exposed dose conditions of 4, 5 and 6 pC/dot. All of the I-V characteristics show the typical I-V curves of tunnel junctions, however, the current-order of each curves varies widely with no dependence on the exposed dose condition, namely, the contact-hole diameter. This large dispersion of conductance of fabricated vertical MIM junctions is probably due to the granular structure of deposited Al films. After repeating 30-50 times measurements of the I-V curves, the MIM junctions suddenly showed large leakage current. Figure 4 shows the I-V characteristics at room temperature of the same MIM junctions (in Fig.3) when measurements were repeated for 30-50 times. All of the I-V curves show large leakage current of mA-order because of the breakdown of the weak part of Al_2O_3 films. It is necessary to realize the deposition of much smooth metal films and the formation of the uniform barrier layers.

4. Conclusions

We have developed a vertical MIM junctions fabrication process using top two layers of an SOI substrate as a double-layered EB resist. The diameter of contact-holes of the top SiO_2 layer tends to saturate with increase in exposed dose, and the mask with a contact-hole of minimum diameter about 20 nm was successfully fabricated. A vertical array of two MIM junctions fabricated by this method showed the typical current-voltage characteristics of tunnel junctions at room temperature. However, the MIM junctions showed large dispersion of conductance and large leakage current after repeating 30-50 times I-V measurements. Much smooth metal films and uniform barrier layers are required.

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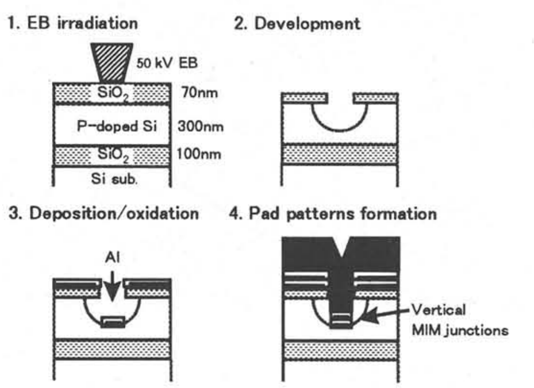

Fig.1. Schematic sequence of the vertical MIM junctions fabrication process.

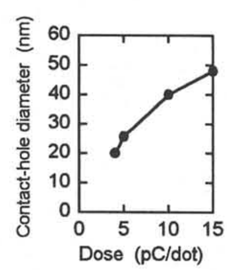

Fig.2. Contact-hole diameter depndence on exposed dose.

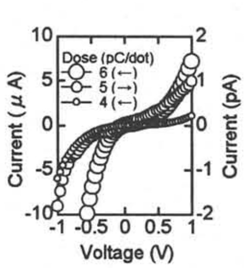

Fig.3. I-V characteristics at room temperature of a vertical array of two MIM junctions.

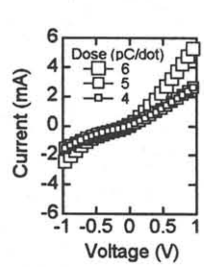

Fig.4. The change observed in I-V characteristics when measurements were repeated for 30-50 times.