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Epitaxial Si on Al_2O_3 Films Grown with O_2 Gas by UHV-CVD Method

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1. Introduction

Recently, silicon on insulator (SOI) structures are mainly fabricated by means of silicon direct bonding(SDB) and separation by implanted oxygen (SIMOX). With these method, it is difficult to obtain multi-stacked SOI structures. To realize multi-stacked SOI structures, considerable efforts have been devoted to epitaxial growth methods such as CaF_2 on Si[1,2] and $MgO \cdot Al_2O_3$ on Si[3]. We have reported epitaxially grown Al_2O_3 films on silicon for insulator materials[4,5] and SOI structures of double-heteroepitaxial Si/ γ -Al_2O_3/Si by low-pressure chemical vapor deposition(LP-CVD) and Si_2H_6 gas-source molecular beam epitaxial growth.[6] The SOI structure with Al_2O_3 was applied to a high-temperature-operated pressure sensor.[7,8] Using these materials, metal-oxide semiconductor field-effect transistors (MOSFETs) were fabricated, which were fabricated by the polycrystalline-Si gate process on double-heteroepitaxially grown Si(100)/ γ - Al_2O_3/Si(100) SOI structures. The electrical properties were found to be similar to those obtained from silicon on sapphire (SOS) wafers. There remain problems such as uniform thickness of a grown film, control of the reappearance of crystallinity and high-temperature growth. In the device application of multi-stacked SOI structures such as Si(100)/ Al_2O_3(100)/Si(100)/ Al_2O_3(100)/Si(100),[8] uniform thickness and control of the reappearance of crystallinity of each epitaxial layer are important. For the purpose of adapting these SOI structures to a multi-stacked SOI structure device such as a pressure sensor, we have reported epitaxially grown Si/ γ - Al_2O_3/Si structures by ultrahigh vacuum (UHV)-CVD method.[9] Uniformity of the films was improved by using UHV-CVD method with a hot-wall heating system. The UHV-CVD method was proven to be an effective method for Al_2O_3 and silicon growth at low growth temperatures, yielding uniform film thickness and good crystalline quality. For device applications, however it must be solved that micro-roughness exists on Si top layer originated in Al_2O_3 layer. Micro-roughness which exists on Al_2O_3 layer is caused by parasitic reactions between N_2O and Si surface in the initial growth stage of Al_2O_3. These parasitic reactions are prevented by using O_2 gas instead of N_2O which are one of source gas for Al_2O_3 growth[10,11], and the surface morphology caused by these micro-roughness are improved.

In this work, by improved Al_2O_3 growth with O_2 gas instead of N_2O gas, SOI structures were successfully fabricated by UHV-CVD system, and multi-stacked SOI structures which consist of Si/Al_2O_3/Si/Al_2O_3/Si substrate were also successfully fabricated. These SOI structures were investigated by reflection high-energy electron diffraction (RHEED) and scanning electron microscopy (SEM).

2. Experimental Procedures

Fabrication of SOI structures which consist of epitaxial Al_2O_3 and Si growth was performed by UHV-CVD method.[9-11] Substrates can be transferred between an Al_2O_3 growth chamber and a Si growth chamber *in situ*. Epitaxial Al_2O_3 films were grown on 2 inch p-type Si(100) wafers by pyrolysis of N_2-bubbled trimethyl aluminum(TMA:$Al(CH_3)_3$) and O_2 at a pressure of 6×10^{-1} Pa in a vertical electric furnace. The substrate temperature for Al_2O_3 growth was 890°C. The gas flow rates and other CVD conditions are described in Table I. Growth rate of Al_2O_3 films was about 0.3 nm/min, and 10-nm-thick Al_2O_3 films were grown. To fabricate the SOI structure, silicon epitaxial growth was carried out on the Al_2O_3(100) /Si(100) substrate by the UHV-CVD method after Al_2O_3 growth on the silicon substrate. Multi-stacked SOI structure, Si/Al_2O_3/Si/Al_2O_3/Si substrate, was fabricated by continuous epitaxial growth of Al_2O_3 and Si films. Pure Si_2H_6 was used as a source gas. The substrate temperature of 1000°C was used in this growth. The Si CVD conditions are indicated in Table II. Growth rate of Si films was about 30 nm/min, and 500-nm-thick Si films were grown. SOI films have the structures as shown in Fig. 1.

Table I. Epitaxial growth conditions for Al_2O_3.

Base pressure	2×10^{-6} Pa (at 700°C)
Pressure	1 Pa
TMA(N_2 bubbled)	35 sccm
O_2	126 sccm
Substrate temperature	890°C

Table II. Epitaxial growth conditions for Si.

Base pressure	2×10^{-6} Pa (at 700°C)
Pressure	4×10^{-1} Pa
Si_2H_6	10 sccm
Substrate temperature	1000°C

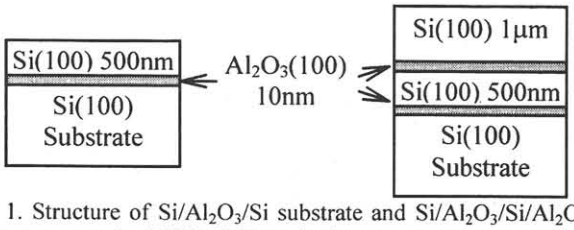

Fig. 1. Structure of Si/Al_2O_3/Si substrate and Si/Al_2O_3/Si/Al_2O_3/Si substrate grown by UHV-CVD method.

3. Results and Discussion

Figures 2(a) and 2(b) show surfaces of Si(100)/Al_2O_3(100)/Si(100) and Si(100)/Al_2O_3(100)/Si(100)/Al_2O_3(100)/Si(100), respectively. Epitaxial 10-nm-thick Al_2O_3 film on Si (100) and epitaxial Si film on Al_2O_3(100)/Si(100) showed a mirrorlike surface. Also multi-stacked SOI structure has mirrorlike surface. Figures 3 (a) and (b) show the surface morphology of the Si top layers with Al_2O_3 layers grown by O_2 and N_2O, respectively. Si surface of the SOI sample which has 10-nm-thick Al_2O_3 layer grown with O_2 shows smooth surface. RHEED patterns from this sample showed bulk-like Si patterns. This result indicates that crystallinity of this Si top layer is the same level of that of bulk Si. The SOI sample which has 40-nm-thick Al_2O_3 layer grown with N_2O shows rough surface as shown in Fig. 3(b). RHEED pattern of this sample showed faceted 2×1 pattern, which reflects the surface roughness. The surface morphology of Si top layer of the SOI structure with Al_2O_3 grown by O_2 is better than that of silicon on sapphire (SOS) structure grown by UHV-CVD system. Figures 4 (a) and (b) show the surface morphology of the Al_2O_3 films which are grown with O_2 and N_2O, respectively. Al_2O_3 film grown with O_2 show smooth surface, but Al_2O_3 film grown with N_2O show very rough surface with many small pits. The difference of morphology between two samples indicates that roughness of Al_2O_3 layer influence morphology of Si top layer, and progress of surface flatness of Al_2O_3 layer results in the improved flatness of Si top layer and successful realization of multi-stacked SOI structure.

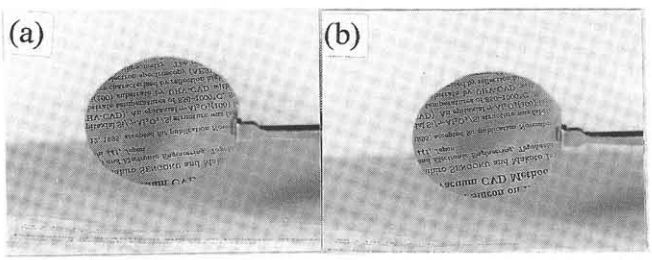

Fig. 2. Photograph of Si top layer on Al_2O_3/Si substrate. Mirrorlike surface of (a) epitaxial Si grown on 10-nm-thick epitaxial Al_2O_3 and (b) multi-stacked SOI(Si/Al_2O_3/Si/Al_2O_3/Si substrate).

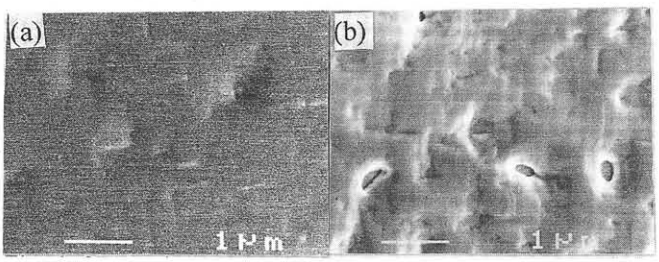

Fig. 3 SEM micrograph of Si top layer on Al_2O_3/Si substrate. Thickness of Si top layer is about 450nm. Al_2O_3 films are grown with (a) O_2 and (b) N_2O.

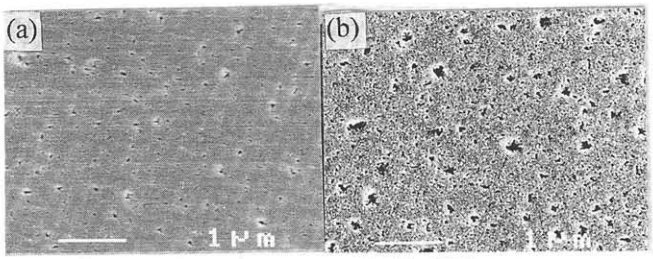

Fig. 4 SEM micrograph of Al_2O_3 layers on Si substrate. Al_2O_3 films are grown with (a) O_2 and (b) N_2O.

4. Conclusions

By improved Al_2O_3 growth with O_2 gas, multi-stacked SOI structures were successfully fabricated by UHV-CVD method. The surface morphology of Si top layer of the fabricated SOI structure is better than that grown by Al_2O_3 with N_2O gas and silicon on sapphire (SOS) structure grown by UHV-CVD method. This progress of surface flatness of SOI structure was due to the development of Al_2O_3 layer grown with O_2 gas, which reduces the small pits on Al_2O_3 films. By this improvement, multi-stacked SOI structures were realized.

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