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Strain Measurements of Si at SiO_2/Si Interface by Ion Beam Channeling

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Strain of the underlying Si crystal at SiO_2/Si interface formed by thermal oxidation of Si has been investigated by ion beam channeling. The ion beam channeling is sensitive to the strain of the underlying Si crystal. The strain decreases with increasing oxidation temperature and increases with oxide thickness. The strain alteration of the Si crystal at Si/SiO_2 interface is attributed to the stress in the SiO_2 layer.

1. INTRODUCTION

Even though thermally grown silicon dioxide has been used as a gate dielectric material for more than 30 years, there are a number of questions related to the properties of the oxide material and the SiO_2/Si interface that are as yet unsolved. A number of studies have reported that observation of an intrinsic film stress resulting from the thermal oxidation of Si.[1-3] The origin of this stress has been attributed to the 120% molar volume expansion which results from the conversion of Si to SiO_2. The observations of the stress in the SiO_2 film have been studied by infrared (IR) transmission, ellipsometry and a laser-beam reflection technique,[1-3] and the stress in the underlying Si crystal has been studied by photoreflectance and Raman scattering.[2] Correlations between midgap interface state density and thickness-averaged stress in thermally grown SiO_2 have also been reported, and linear relationships between the midgap interface state density and the thickness-averaged stress and strain in the oxide have been established.[3] The information from the strain measurements of Si at SiO_2/Si interface is considered to be important to its characterization. It seems that the strain becomes to affect the device performance with scaling down of VLSIs.

In this paper, we report new measurements on the strain of the underlying Si crystal at SiO_2/Si interface by ion beam channeling. Ion beam channeling is an useful technique for the characterization of crystalline materials. The ion channeling effect is sensitive to the strain in heteroepitaxial layer.[4-6] This ion channeling technique for the characterization of heteroepitaxial strained-layer structure can be also applied to study the strain of crystalline surface covered with a thin amorphous layer. If the amorphous layer is thin enough so that a sufficient number of the incident ion particles maintain the original beam direction when they traverse the amorphous layer, the channeling angular scan at the near surface region (<100nm) is possible. Recently, we have reported strain measurements in heteroepitaxial yttria-stabilized zirconia (YSZ) on Si by ion beam channeling.[7] It has been found that the tensile strain in YSZ film is increased by annealing in dry O_2, due to the SiO_2 layer formed at the YSZ/Si interface. In addition, it has been found that the tensile strain is also introduced in the near-interface region of Si substrate covered with the SiO_2 layer.

2. EXPERIMENTAL PROCEDURES

All samples were p-type, (100)-oriented Si wafers. The wafers were cleaned in dilute HF solutions to remove the native oxide prior to the oxidation. SiO_2 films were grown in dry oxygen at temperatures of 800, 900, and 1000°C.

In order to measure the strain of the underlying Si crystal at SiO_2/Si interface, the channeling angular scans were carried out about <100> and <110> axes along the (001) plane perpendicular to the surface. The incident energy of $^4He^+$ ion beam (1mm diameter) was 2MeV. Figure 1 shows an RBS/channeling spectrum of a 35nm thick SiO_2 film on Si(100) along <110> direction with the scattering angle $\theta = 100°$. The window of the channeling angular scan is set at the near-interface region (100nm) of the underlying Si crystal. The ion dose at each channeling angular scan about crystalline axis was 4μC with a beam diameter of 1mm.

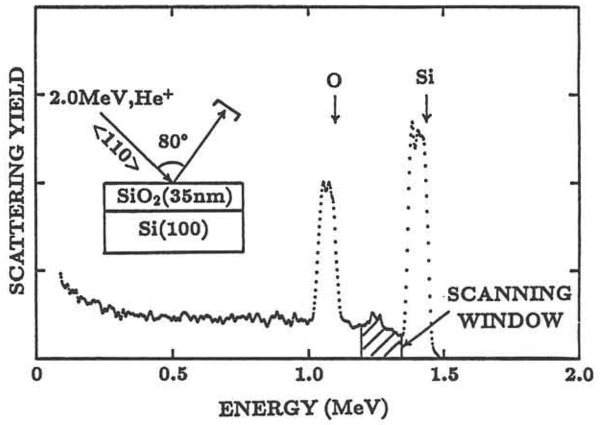

Fig.1 : RBS/channeling spectrum of a 35nm thick SiO_2 film on Si(100) along <110> direction with the scattering angle $\theta = 100°$.

3. RESULTS AND DISCUSSION

Typical channeling angular yield profile for Si(100) substrate covered with the thermally grown SiO_2 layer (thickness 35nm) at 900°C in dry O_2 is shown in Fig.2. The direction of Si<110> axis is shifted away from 45° relative to the <100> direction perpendicular to the surface. This result implies the tensile strain in the interface region of Si substrate is introduced by a SiO_2 layer formed by a thermal oxidation.

The angular misalignment values were independent of the scanning window width from 50nm to 400nm. The fact is due to the steering effect.[8] Therefore, in fact, the observed values indicate the strain in the shallower region (~10nm), and the symmetry of angular scan profiles in the deeper region is altered by the steering effect.

Figure 3 shows angular misalignment $\Delta\theta$ between <100> and <110> axes of Si substrates covered with the SiO_2 layer (35nm) at 900°C for various ion dose. The angular misalignment decreases with increasing of the dose. This result suggests that the strain of Si at SiO_2/Si interface is relaxed by the ion

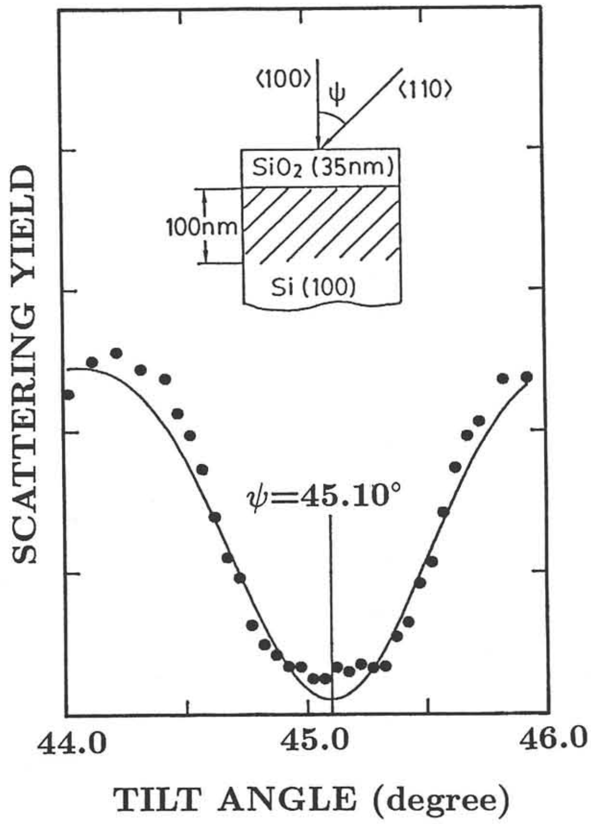

Fig.2 : Channeling angular yield profile for Si(100) substrate covered with the thermally grown SiO_2 layer (thickness 35nm) at 900°C in dry O_2.

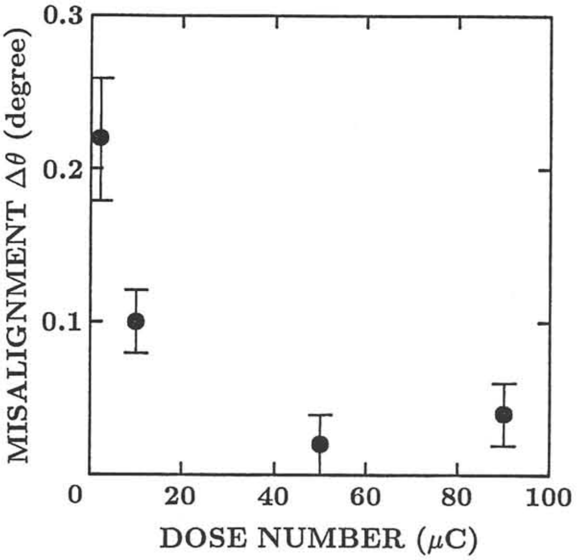

Fig.3 : Angular misalignment $\Delta\theta$ between <100> and <110> axes of Si substrates covered with the SiO_2 layer (35nm) at 900°C for various ion dose.

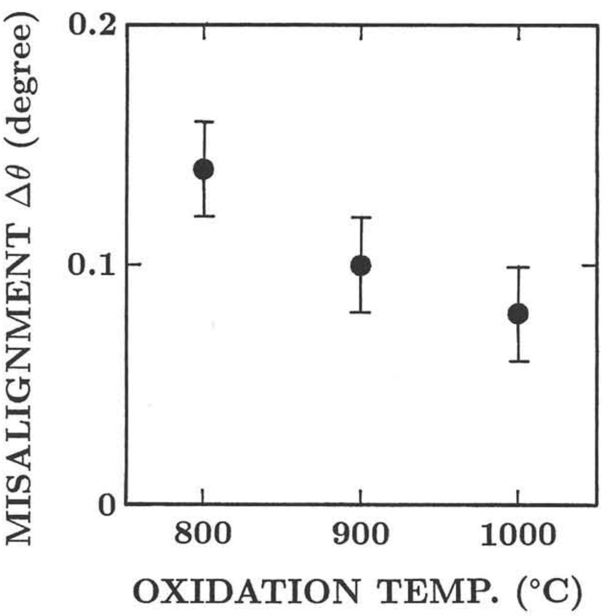

Fig.4 Angular misalignment $\Delta\theta$ of Si substrates covered with the SiO_2 layer (35nm) for various oxidation temperature.

beam radiation. The abrupt decrease of the angular misalignment at first 10μC of dose results in an experimental error. From RBS spectra of these samples, silicon and oxygen contents were not changed by the ion beam radiation.

Angular misalignment $\Delta\theta$ of Si substrates covered with the SiO_2 layer (35nm) for various oxidation temperature is shown in Fig.4. The misalignment increases at the lower oxidation temperature. This means that the the strain of the Si substrate at Si/SiO_2 interface increases with decreasing oxidation temperature.

Figure 5 shows angular misalignment of Si substrates covered with the SiO_2 layer grown at 900°C for various oxide thickness. The ion dose at each data is 2μC. Then, the strain of Si substrate at Si/SiO_2 interface increases with decreasing with SiO_2 thickness.

The studies of SiO_2 film stress have reported that the film stress increased with decreasing oxidation temperature and decreasing film thickness.[1,2]

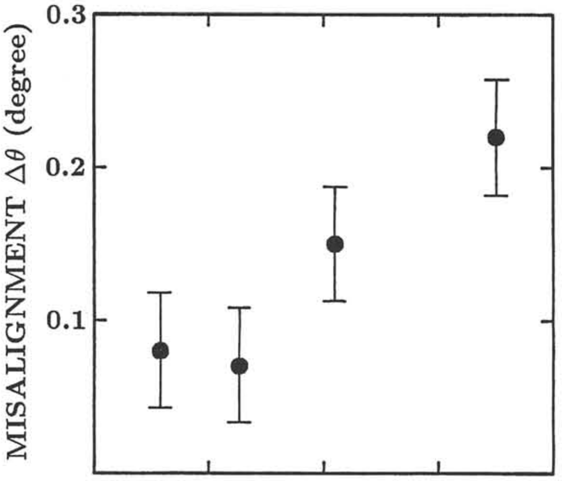

Fig.5 Angular misalignment of Si substrates covered with the SiO_2 layer grown at 900°C for various oxide thickness.

However, the total stress of SiO_2 film increases with film thickness. Then, the total stress of SiO_2 film results in the strain of the underlying Si crystal at Si/SiO_2 interface. The tensile stress in the Si crystal covered with the SiO_2 layer (35nm) grown at 900°C is estimated to be 8×10^{-9} dyn/cm^2 from the angular misalignment value, which is comparable to the compressive stress in thermally grown SiO_2.[1,2)]

4. CONCLUSION

Strain of the underlying Si crystal at Si/SiO_2 interface formed by thermal oxidation of Si has been investigated by ion beam channeling. The ion beam channeling is sensitive to the strain of the underlying Si crystal at SiO_2/Si interface. The strain decreases with increasing oxidation temperature and increases with oxide thickness. The strain of Si at SiO_2/Si interface is relaxed by the ion beam radiation. The strain alteration of the Si crystal at Si/SiO_2 interface is attributed to the stress in the SiO_2 layer.

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