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Depth Profile of Thermally Grown SiO_2 Film Density

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Abstract

Depth profile of density of thermally grown SiO_2 films was measured by using a microbalance and an ellipsometer. Influence of the oxide density distribution on electrical characteristics properties was investigated. It was found that non-uniform density profile enhanced TDDB lifetime dispersion.

1. Introduction

Reliability of the gate SiO_2 films in MOSFETs is so important that it could determine the performance and reliability of the devices. Among the physical properties of SiO_2 films, density is one of the most common principal properties, and it is considered as strongly related with electric properties. Recently, we have demonstrated that SiO_2 film density was easily evaluated by measuring the weight and thickness of the film. The weight is measured using a microbalance with precision of 0.1 μg. Figure 1 summarizes SiO_2 densities and refractive index obtained by our method (colored plots) with other reported values for various phases [1]. Our data are for 30 nm- thick SiO_2 films thermally grown at various temperatures. These are in good agreement with the reported values, which grantees it was proper analysis.

In this paper, we report the depth profile of SiO_2 film density, which was obtained by measuring the weight decrease associated with etching of the films. With our system, it was confirmed that the weight decrease due to 3 nm etching could be measured.

2. Experiment

The experimental procedure is shown in Fig. 2. After RCA clean, the Si(100) substrates were oxidized in dry O_2 at 800 or 1000°C (referred to as sample A and B, respectively). The target thickness was 30 nm. Some of the SiO_2 films formed at 800°C were post-oxidation annealed at 1000°C for 3 hours in Ar (referred to as sample C). Weight of the substrates and oxide thickness were measured. Then the samples were moved to step etching of 3 nm thickness of the SiO_2 films in diluted HF. The weight of the substrates and the oxide thickness were measured again to obtain density of the etched films. This process was repeated until whole SiO_2 films are etched off. To analyze oxidation process, surface roughness of the SiO_2 films was characterized by AFM. Further, MOS capacitors with Al electrodes were fabricated to characterize electrical properties of these SiO_2 films.

3. Results and discussion

Figure 3 summarizes the depth profiles of the oxide densities. There is common tendency that the density is higher at interface region and lower near the surface. In detail, however, there is some differences, and the density is most uniform for sample C. For the capacitors with oxides of sample A, B, and C, the leakage current was measured as shown in Fig. 4. The *C-V* curves are also shown in Fig. 5. Despite of differences in the density profile, there is no significant difference in the electric properties. Figure 6 is FN plots for the samples, and the barrier height was all evaluated as 3.1 eV.

It was found, however, that TDDB lifetime distribution strongly depends on oxidation processes, as seen in Fig. 7 (stress current was 10^{-3} A/cm^2). The lifetime for sample B capacitors are apparently short and widely distributed, which seems to be related to widely distributed density profile. Now the question is how the lifetime distribution, which is considered as reflection of non-uniformity in x-y plane, relates with density profile which is non-uniformity in z direction. Figure 8 shows the AFM images of the as grown oxide films, and the RMS values of the roughness is plotted in Fig. 9 as a function of residual thickness. The roughness increases as step etching proceeds (from right to left in the figure), since etching rate is not uniform on the surface. For sample B, the RMS values increases more rapidly than others, that is, sample B is not uniform in –y plane. The non-uniformity probably results from relaxation of the film during oxidation. Actually, the density at surface region can be well fit by a relaxation theoretical curve, as shown in Fig. 10. The density decreases by relaxation, and it vigorously occurs during enhanced oxidation regime (see Fig. 10 and 11). It is not cleared yet that why annealing in Ar does not contribute much to relaxation (sample C). Emission of Si induced by oxidation may be necessary for relaxation [2].

4. Conclusions

It was concluded that wide distribution of lifetime resulted from relaxation of SiO_2 films during oxidation, which occurs non-uniformly in x-y plane.

References

[1] K. Hubner, physica status solidi (a) **40** (1977) 487.

[2] H. Kageshima *et al*, Jpn. J. Appl. Phys. **38** (1999) L971.

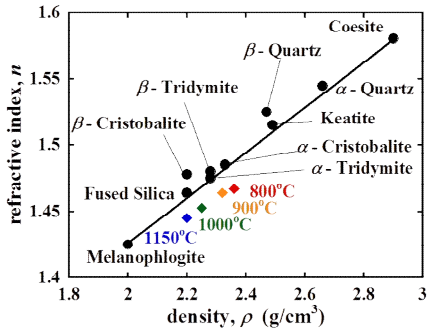

Fig. 1 Density and refractive index for various phases of SiO_2. The colored plots are ours.

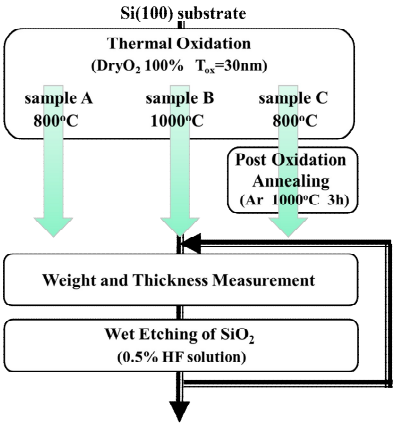

Fig. 2 Experimental procedure.

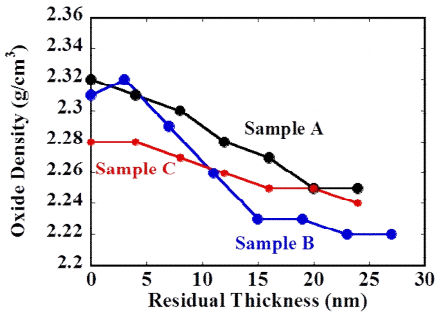

Fig. 3 Depth profiles of density for sample A, B, and C. Th residual thickness of 0 nm corresponds to SiO_2/Si interface.

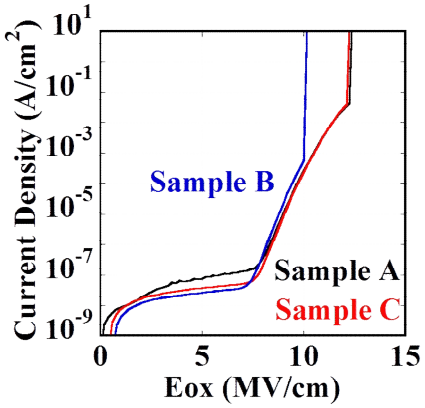

Fig. 4 *I-V* curves obtained for MOS capacitors with sample A, B, and C. The capacitor size is 100 x 100 μm^2.

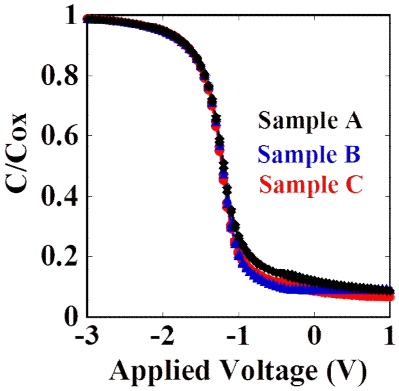

Fig. 5 *C-V* curves obtained for MOS capacitors with sample A, B, and C. The capacitor size is 100 x 100 μm^2.

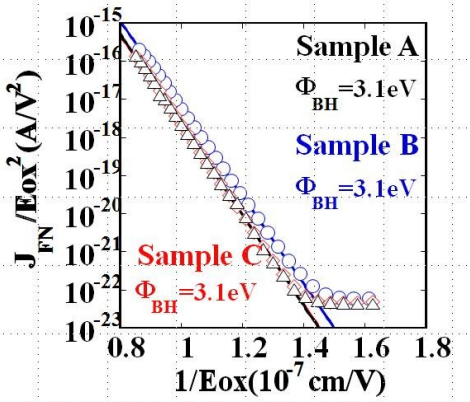

Fig. 6 FN plots obtained from the *I-V* curves shown in Fig. 4.

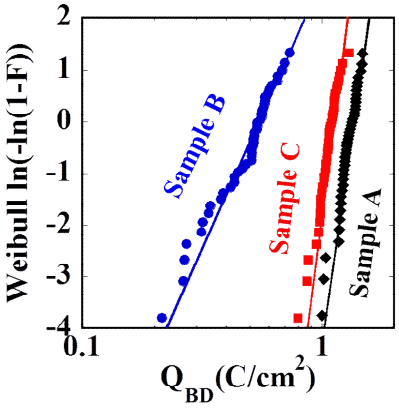

Fig. 7 Weibull plots for TDDB lifetime of the MOS capacitors with sample A, B, and C.

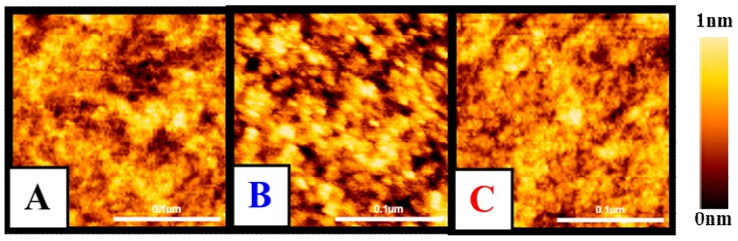

Fig. 8 200 x 200 nm^2 AFM images of SiO_2 surfaces of sample A, B, and C. The RMS values for the surface roughness were 0.16, 0.20, and 0.15 nm for A, B, and C, respectively.

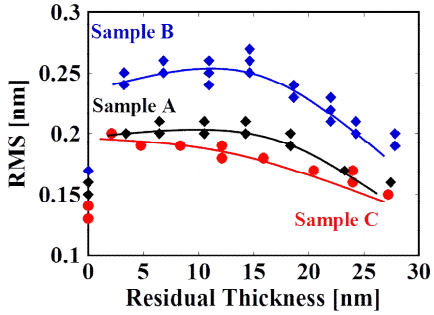

Fig. 9 SiO_2 surface roughness vs residual thickness.

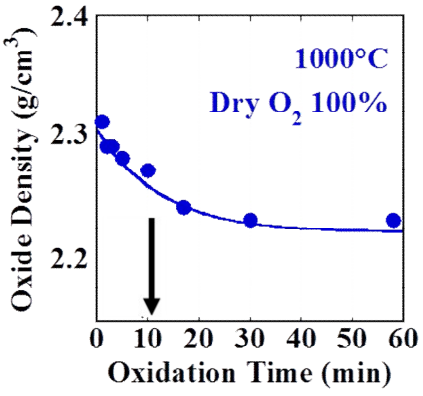

Fig. 10 Relaxation-induced density decrease during oxidation.

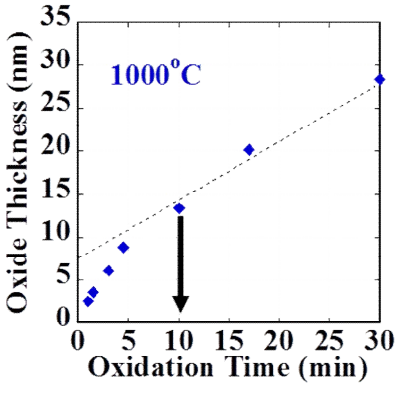

Fig. 11 Oxidation rate.