

Observation of Oxide Thickness Dependent Interface Roughness in Si MOS Structure

Junji KOGA Shin-ichi TAKAGI Akira TORIUMI

ULSI Research Laboratories, Toshiba Corporation
1, Komukai Toshiba-cho, Saiwai-ku, Kawasaki 210, Japan

Si/SiO₂ interface roughness was investigated from the viewpoint of thermal oxidation. It was demonstrated that Si/SiO₂ interface roughness recovers with increasing oxide thickness, using a non-destructive measuring method. This recovery process is discussed in terms of the transition from the initial oxidation stage to the Deal-Grove growth regime. Interface defect generation, correlating with the interface roughness, was also observed. Possible mechanisms for the defect generation are presented.

1 Motivation

Roughness of Si/SiO₂ interface is a serious concern in Si LSI, and the Si/SiO₂ interface quality was intensively investigated, for example, by means of AFM [1] and TEM [2], [3]. As CMOS devices are scaled down, it becomes increasingly difficult to maintain a smooth channel surface and high-quality interface, because of the complicated fabrication processes.

In this paper, we report that Si/SiO₂ interface roughness recovers with increasing oxide thickness, using a non-destructive measuring method. We also discuss the recovery processes of both roughness and defects at Si/SiO₂ interface through thermal oxidation.

2 Experimental

An alkaline treatment (TRT A) prior to gate oxidation was employed to roughen the channel surface intentionally. For comparison, a conventional treatment (TRT B) was also employed. Typical condition for gate oxidation was at 800 °C in dry O₂ ambient.

The devices used in the present study were conventional n-MOSFETs fabricated on (100) Si surface. The substrate impurity concentration was nearly uniform and about $4 \times 10^{15} \text{ cm}^{-3}$. Channel mobility (μ_{eff}) and interface state density (D_{it}) were measured to investigate Si/SiO₂ interface quality. μ_{eff} was accurately evaluated by the improved split C - V method [4], while D_{it} was measured by the charge pumping method.

3 Results

First, the correlation between Si/SiO₂ interface roughness and channel mobility was investigated in terms of oxide thickness (T_{ox}).

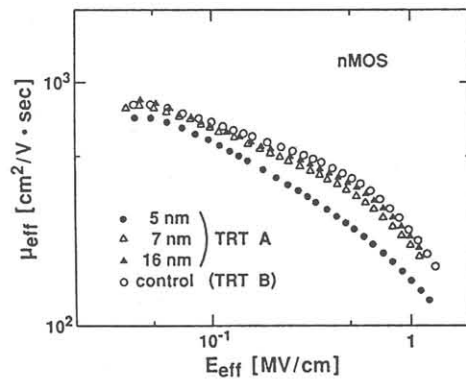


Figure 1: $\mu_{\text{eff}}-E_{\text{eff}}$ relationship as a function of T_{ox} .

Experimental results of $\mu_{\text{eff}}-E_{\text{eff}}$ relationship are shown in Fig. 1. E_{eff} is an effective normal field in the MOS inversion layer. TRT B was employed in the control device, and it was confirmed in advance that μ_{eff} behavior does not depend on T_{ox} in the TRT B device. Figure 1 clearly shows that μ_{eff} is degraded significantly in the TRT A device with 5 nm oxide, especially at high E_{eff} . This fact indicates that mobility degradation due to interface roughness is very severe in the 0.1 μm MOS regime, where ultra-thin gate oxide of less than 5 nm will be employed.

In Fig. 2, the mobility limited by surface roughness scattering (μ_{sr}) is extracted by using the Matthiessen rule, assuming the same phonon scattering contribution to μ_{eff} in each device [5]. Different dependences of μ_{sr} on E_{eff} result from the different correlation length (L) of interface roughness [5]. Figure 2 indicates that Si/SiO₂ interface roughness recovers with increasing T_{ox} .

In order to exclude the possibility of T_{ox} effect on μ_{eff} degradation in the TRT A device, the following experiment was performed. Two kinds of MOSFET with 5 nm oxide were prepared, as shown in Fig. 3.

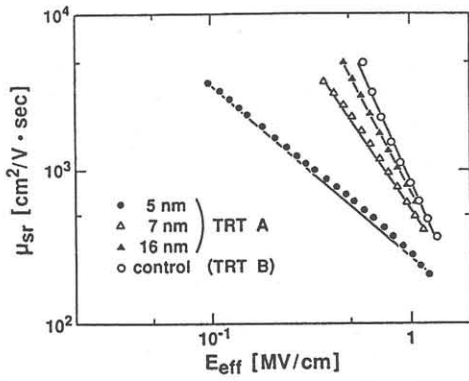


Figure 2: $\mu_{sr}-E_{eff}$ relationship as a function of T_{ox} .

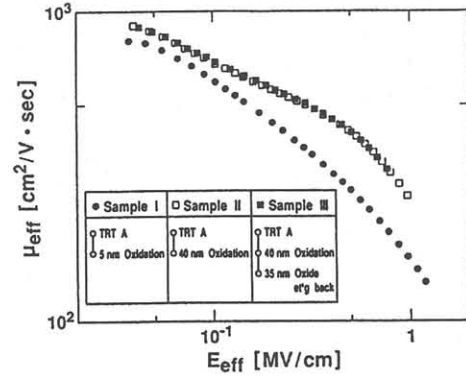


Figure 3: $\mu_{eff}-E_{eff}$ relationship in Sample I ~ III.

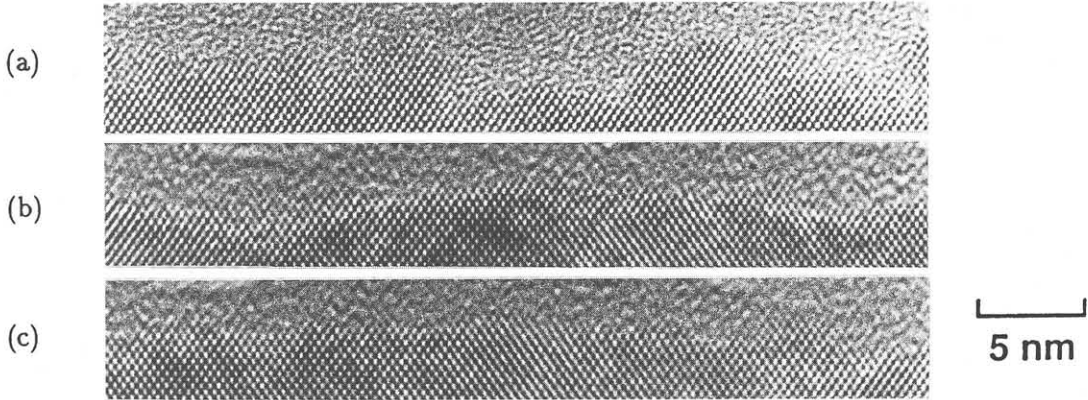


Figure 4: TEM image of Si/SiO₂ interface in TRT A device; (a) initial, (b) $T_{ox} = 5\text{nm}$, (c) $T_{ox} = 16\text{nm}$.

In the Sample III, 5 nm gate oxide was formed by etching back 35 nm oxide from the device with 40 nm oxide. No degradation of μ_{eff} is observed in the Sample III, which means that the interface roughness is certainly recovered from the Sample I to the Sample III through thermal oxidation.

Consequently, it has been demonstrated by the non-destructive measuring method that Si/SiO₂ interface roughness recovers with increasing oxide thickness. This fact has also been verified by direct TEM observation, as shown in Fig. 4.

Next, the correlation between interface roughness and interface defects was investigated.

Figure 5 shows T_{ox} dependence of interface state density (D_{it}). It is noted that D_{it} sharply decreases with increasing T_{ox} in the TRT A device. This dependence is consistent with the μ_{eff} result, which was obtained from Fig. 1. These interface states also degrade the channel mobility by Coulomb scattering [4]. However, this effect is negligible in the present discussion, because Coulomb scattering is dominant at low E_{eff} .

To relate the D_{it} result with the degree of Si/SiO₂ interface roughness, D_{it} is plotted in Fig. 6 as a function of $\sqrt{\tau_{sr}}^{-1}$, which is roughly proportional to $L \cdot \Delta$ in the formulation of μ_{sr} [6], where L and Δ denote the correlation length and height of Si/SiO₂

interface roughness, respectively. τ_{sr} is a relaxation time of surface roughness scattering, which is proportional to μ_{sr} . τ_{sr} in Fig. 6 was estimated from the μ_{sr} data shown in Fig. 2. Figure 6 illustrates that D_{it} generation is linearly dependent on the amount of interface roughness. This fact clearly demonstrates that the interface roughness is one of the physical origins which bring about interface defects.

4 Discussions

First, the recovery process of Si/SiO₂ interface roughness through thermal oxidation is discussed.

It was speculated that the smoothing effect on interface roughness is comparatively poor in the initial stage of oxidation growth, because of the local stress effect on the oxidation reaction rate at Si/SiO₂ interface [2]. It was also reported that further oxidation reduces the interface roughness [2]. This is because the local variation in interface roughness is diminished by the feedback effect whereby oxidation reaction accelerates in the thinner oxide region, when the linear-parabolic Deal-Grove oxidation growth becomes dominant. In the present work, this recovery process is clearly observed by the mobility measurement, as mentioned in the previous section.

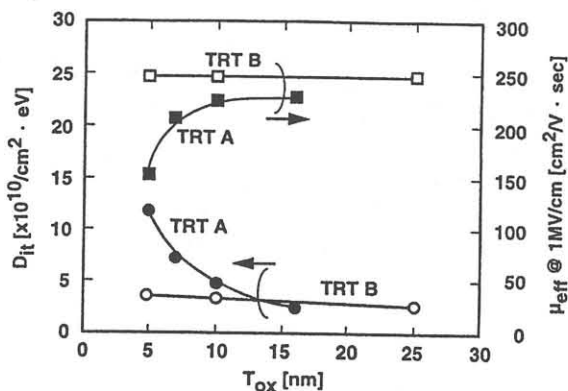


Figure 5: Dependences of μ_{eff} and D_{it} on T_{ox} .

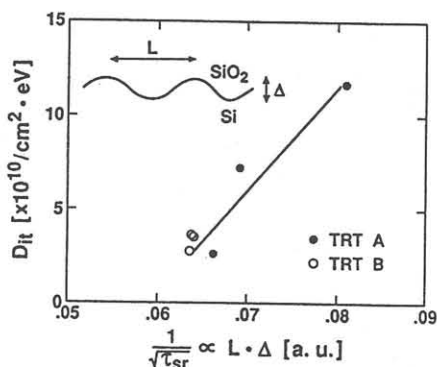


Figure 6: $D_{\text{it}} - \sqrt{t_{\text{sr}}}^{-1}$ relationship.

Now, the recovery process is discussed in terms of the transition from the initial oxidation stage to the Deal-Grove growth regime. We introduce the critical oxide thickness ($T_{\text{ox}}^{\text{cr}}$), beyond which the oxidation rate follows the Deal-Grove model. Since $T_{\text{ox}}^{\text{cr}}$ is much smaller in wet oxidation than in dry oxidation [3], the Si surface undergoes the Deal-Grove growth longer in wet oxidation, compared with dry oxidation at the same T_{ox} . It is, therefore, expected that the smoothing effect is more pronounced in wet oxidation. In fact, it has been confirmed that μ_{eff} is enhanced in wet oxidation at the very thin T_{ox} of 5 nm, as shown in Fig. 7, though there was no difference in μ_{eff} behavior between dry and wet oxidations in the TRT B device.

Although the reported value of $T_{\text{ox}}^{\text{cr}}$ is nearly 14 nm in dry oxidation [3], the smoothing of interface roughness is noticeably observed in a thinner T_{ox} region (Fig. 5). It is possible to speculate that the value of $T_{\text{ox}}^{\text{cr}}$ is smaller, especially on a roughened Si surface, which significantly affects the electronic properties in the MOS inversion layer.

Next, the defect generation due to Si/SiO₂ interface roughness is discussed.

One possible mechanism for D_{it} generation is as follows. Oxide compressive strains and corresponding silicon tensile strains at Si/SiO₂ interface are enhanced in the valley region of a roughened in-

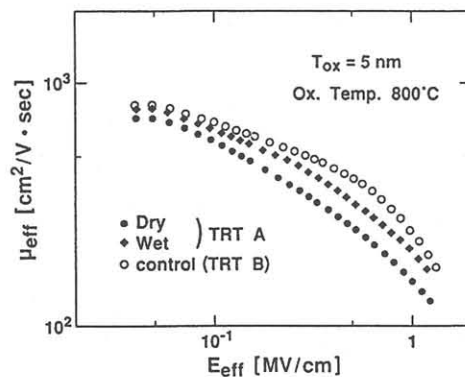


Figure 7: Comparison of $\mu_{\text{eff}}-E_{\text{eff}}$ relationship between dry and wet oxidations.

terface, compared with the case of a flat interface [2]. These strains lead to deformations of interface structure, resulting in defect generation.

Another mechanism involves the appearance of various surface orientations in addition to (100) surface. This leads to D_{it} enhancement, because D_{it} generation rate at Si/SiO₂ interface is the smallest on (100) surface. The appearance of various surface orientations was confirmed by the high-frequency C-V measurement as well as by the TEM observation (Fig. 4). In the C-V measurement, larger value of T_{ox} was obtained in the TRT A MOS capacitor, which clearly demonstrates the different oxide growth rate, depending on the surface orientation. It should be noted that the oxide growth rate is the smallest on (100) surface.

5 Conclusion

It was demonstrated by a non-destructive measuring method that Si/SiO₂ interface roughness recovers with increasing oxide thickness. This recovery process was discussed in terms of the transition from the initial oxidation stage to the Deal-Grove growth regime. Interface defect generation, correlating with the interface roughness, was also observed, and its mechanism was speculated.

References

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