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Deuterium Effect on Both Interface-State Generation and Stress-Induced-Leakage-Current under Fowler-Nordheim Electron Injection

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1. Introduction

The need for high reliability of thin gate oxides is one of the critical issues in view of the shrinking of ULSI devices. Recently, it has been reported that a significant improvement of the hot carrier induced degradation of the SiO,/Si interface was observed when deuterium was substituted for forming gas annealing during CMOS processing [1],[2]. The model by the dynamic characteristics of Si-D bonds at Si/SiO2 interfaces under the hot-electron stress has been proposed [3]. In this work, we expected this deuterium effect on both the interface-state generation and the stress-induced-leakage-current (SILC) under Fowler-Nordheim (F-N) electron injection. Although the reliability of the deuterated oxide grown by the heavy water (D₂O) has been reported [4], there has been no systematic study on the defect of F-N electron injection stress. Therefore, we have investigated the improvement of SiO, quality using deuterium pyrogenic oxidation. As results, we found that both the interface-state generation and SILC are reduced by the deuterium pyrogenic oxidation, and that the polarity dependence of the deuterium effect is clearly observed in the SILC.

2. Experimental

The devices used in this work were n-channel MOSFETs and MOS capacitors. The gate oxides were grown in the pyrogenic ambient using hydrogen or deuterium at 850°C. MOSFETs were annealed in hydrogen or deuterium ambient at 450°C in order to control the initial interface-state densities. In this paper, we denote MOS capacitors as " H_2 -pyro. oxide" and " D_2 pyro. oxide", and MOSFETs as " H_2 -pyro. oxide + H_2 -anneal" and " D_2 -pyro. oxide + D_2 -anneal", respectively.

The electrical stressing was performed under the constantcurrent F-N injection conditions at room temperature. The interface-state density (Dit) and SILC are respectively evaluated by the charge-pumping method and by the current-voltage (I-V) characteristics, periodically interrupting the F-N stress. The oxide thickness (tox) of each device was evaluated from the capacitance-voltage (C-V) measurement by using the same or adjacent MOS capacitors with the Dit or SILC measurement.

3. Results and Discussions

Figure 1 shows the Dit of both " H_2 -pyro. oxide + H_2 -anneal" and " D_2 -pyro. oxide + D_2 -anneal" as a function of the oxide thickness. Here, we note that the thickness of " D_2 -pyro. oxide + D_2 -anneal" becomes thinner than that of " H_2 -pyro. oxide + H_2 -anneal" under the same oxidation condition. This result indicates that the growth rate of the deuterium pyrogenic oxide is slower than that of the hydrogen pyrogenic oxide. In addition, both the Dit values and SILC are sensitive to the oxide thickness even within 0.1nm. Therefore, consideration of the statistical distribution is essential in order to accurately evaluate the effect of the deuterium incorporation into the gate oxide. As shown in Fig. 1, it is found that the Dit is suppressed by the



Fig. 1. Generated interface-state densities (Dit) of MOSFETs under constant current F-N stress as a function of oxide thickness (tox). (a) electrons are injected from the substrate and (b) from the gate-electrode, and the electron fluences plotted in this figure correspond to Qinj= 0, 0.5, 2.0 and 10.0 C/cm².

deuterium pyrogenic oxidation under both polarities of F-N stress and that the difference between the " H_2 -pyro. oxide+ H_2 -anneal" and " D_2 -pyro. oxide+ D_2 -anneal" increase with the electron fluence (Qinj) under the gate injection condition.

In order to quantitatively evaluate the deuterium effect on the interface-state generation, we have compared between the Dit values of " H_2 -pyro. oxide + H_2 -anneal" and that of " D_2 -pyro. oxide + D_2 -anneal", under the same oxide thickness (=6.2 nm) which is indicated as a broken line in Fig. 1. Figure 2 shows the Dit as a function of Qinj. It is found that the interface-state generation is suppressed by the deuterium pyrogenic oxidation under the both polarities of F-N stress.

The SILC of both "H,-pyro. oxide" and "D,-pyro. oxide" is



Fig. 2. Generated interface-state densities (Dit) of MOSFETs under both polarities of F-N stress as a function of electron fluence (Qinj). It is clarified that the Dit is suppressed by the deuterium pyrogenic oxidation under both polarities of F-N electron injection.



Fig. 3. Stress-induced-leakage-current (SILC) of MOS capacitors under constant current F-N stress as a function of oxide thickness (tox). (a) electrons are injected from the substrate and (b) from the gate-electrode, and the electron fluences plotted in this figure correspond to Qinj= 0.5, 2.0 and 10.0 C/cm². Here, we define the SILC value as follows. At first, we measure the I-V characteristics of unstressed devices and defined the sensing gate voltage (Vgs) at which the gate current reaches at $10^{.9}$ A/cm². Then the SILC is evaluated as the increase of gate current at Vgs after the constant-current stressing.



Fig. 4. Stress-induced-leakage-Current (SILC) of MOS capacitors under both polarities of F-N stress as a function of electron fluence (Qinj). It is clarified that the SILC is suppressed by the deuterium pyrogenic oxidation under Jg>0, but the SILC is not improved both under Jg<0.

compared as shown in Fig. 3. And the deuterium effect on the SILC is evaluated in the same way as the Dit case. Figure 4 shows the SILC as a function of Qinj under both polarities of F-N stress. Note that the polarity dependence of the deuterium effect on the SILC is clearly observed. Namely, under the substrate injection condition, the SILC of "D₂-pyro. oxide" is clearly reduced compared with that of conventional "H₂-pyro. oxide". However, under the gate injection condition, the SILC of "D₂-pyro. oxide". This trend is observed under both Jg= \pm 0.1A/cm² and \pm 0.01A/cm².

Figure 5 shows the decrement of SILC value by deuterium pyrogenic oxidation (Δ SILC) in the case of a substrate injection condition as a function of the SILC of " H_2 -pyro. oxide" (SILC^H). Note that Δ SILC is linearly dependent of SILC^H. Moreover, this trend is independent of Jg under this experimental condition. This result implies that SILC of " D_2 -pyro. oxide" (SILC^D) is expressed as SILC^D = (1- α)SILC^H, where α is a slope of the line

in Fig. 5, and that the efficiency of a substitution hydrogen atoms with deuterium atoms, α , is universal, irrespective of the injected-electron energy. From this result, we think that the deuterium effect on SILC in the substrate injection case is explained either by the relaxation of S-D vibration energy to the Si-O-Si rocking mode vibration, which is similar to that is proposed for the improvement of SiO, interface by deuterium under hot-electron stress [3], or by the two-times larger mass effect, which may affect the slower diffusion process in SiO₂. On the contrary, the no decrement of SILC by deuterium pyrogenic oxidation under the gate injection condition is observed in spite of the remarkably large SILC value. Although further studies will be needed for understanding on the physical origin of the stressing polarity dependence of SILC, we speculate that it might be caused by either the nonuniform distribution of deuterium concentration in SiO, film, or the contribution of another defect generation mechanism which is unrelated with hydrogen.

4. Conclusion

Using deuterium pyrogenic oxidation, we have investigated the deuterium effect on both the interface-state generation and SILC of gate oxides under F-N electron injection. As results, we have found that the deuterium effect on Dit is clearly observed in both polarities of F-N stress, and that the SILC is suppressed by deuterium pyrogenic oxidation under F-N electron injection from the substrate, but no deuterium effect is observed in the gate injection case. Furthermore, we have also found that the decrement of SILC by deuterium pyrogenic oxidation is directly correlated with the SILC of "H₂-pyro. oxide", irrespective of Jg.

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Fig. 5. Correlation between SILC^{*H2-pyro. oxide*} and Δ SILC. SILC^{*H2-pyro. oxide*} means SILC value of "H₂-pyro. oxide", and Δ SILC means the decrement of SILC by the deuterium pyrogenic oxidation (Δ SILC=SILC("H₂-pyro. oxide") - SILC("D₂-pyro. oxide")). Note that Δ SILC is linearly correlated with SILC^H and this trend is independent of Jg.