HYDROGEN-RELATED EXTRINSIC OXIDE TRAP GENERATION IN THIN GATE OXIDE FILM DURING NEGATIVE-BIAS TEMPERATURE INSTABILITY STRESS

Jae-Sung Lee, Joseph W. Lyding*, Karl Hess*
Division of Information and Communication Eng., Uiduk University, Gyongju, 780-713 Korea
(*) Beckman Institute, University of Illinois, 405 N. Mathews, Urbana, IL 61801
+82-54-760-1643; fax: +82-54-760-1649; e-mail: jaesung@uiduk.ac.kr

ABSTRACT

This paper presents an extended model for the negative-bias temperature instability in p-MOSFET's with 3 nm gate oxide film. The devices, annealed with a standard forming gas (FG) process, have been subjected to an additional annealing process under high pressure, using both hydrogen and deuterium. We found that NBTI was accelerated by the high-pressure hydrogen (or deuterium) annealing compared to the standard FG annealing. This is attributed to the higher hydrogen (deuterium) density, and that in turn causes higher densities of oxide charges under NBTI stress. Our investigation of recovery and isotope effect shows that both interface-reaction and bulk-reaction, which can be plausible by extrinsic defect, are among the origins of NBTI degradation in ultra-thin gate oxide. [*Keywords:* negative-bias-temperature instability, oxide trap, Hydrogen, Deuterium]

INTRODUCTION

Negative-bias-temperature instability (NBTI) is generally attributed to an increase of both interface-trap density and positive-oxide-fixed charge density during the operation of these devices. There have been some reports on empirical degradation models based on first-order electrochemical reactions at the SiO_2/Si interface [1,2]. Effects of replacing hydrogen with deuterium and fluorine have also been reported, indicating involvement of interfacial hydrogen in the NBT degradation process [3,4].

In this study, we investigate hydrogen-enhanced oxide trap generation related to the extrinsic defect for sub-micron p-MOSFET's under NBTI stress. Positive-bias temperature instability (PBTI) is also investigated to clarify recovery phenomena. From this analysis, we propose an extended model for the generation of oxide traps during NBTI stress.

EXPERIMENT

The devices used in this work were p^+-gate p-MOSFETs fabricated with standard CMOS technology, W=20 μm and L=0.15 μm. Gate oxide films were produced with a conventional furnace in H_2-O_2 atmosphere. NO gas annealing followed by gate oxidation and finally forming gas (H_2) annealing was performed in the process lines for all samples. For additional annealing processes one group was annealed in H_2 and the other group was annealed in D_2, both at 450°C for 3 hours. The pressure for each annealing was increased to 5 atmospheres. Shifts of threshold voltage (ΔV_{th}) and the percent shifts (%) of saturation drain current (I_d) were measured to determine device parameter degradation. The threshold voltage was determined under saturation conditions as the gate bias at which I_d = 40 nA × W/L. The change of integrated interface-trapped charge(ΔN_{it}) and oxide-fixed charge(ΔN_f) under stress were also monitored with subthreshold-current measurements [5]. The calculated mid-gap current to determine threshold voltage shift due to oxide charge (V_f) was 0.1pA in our device.

RESULTS AND DISCUSSION

Fig. 1(a) and 1(b) show the degradation of I_d and the threshold voltage shift for the devices annealed at the different hydrogen atmospheres. A significant decrease of I_d and shift of V_{th} were observed at the high-hydrogenated devices (FG+H_2 5atm device). In Fig. 1(b), the control device (FG device) tends to saturate after some stress time, but the device having hydrogenated (FG+H_2 5atm) gate oxide did not show this saturation trend for our stress time. It implies that the general NBTI model including a diffusion-controlled reaction needs to be modified to explain NBTI for the high-hydrogenated device. Fig. 2 shows ΔN_{it} and ΔN_f as a function of stress time for both the control and the high-hydrogenated devices. The control device shows the prevailing NBTI mechanism that both ΔN_{it} and ΔN_f are commensurate with the conjecture that the origin of NBTI is linked to Si-H bond breaking at the Si/SiO_2 interface. On the other hand, the high-hydrogenated device shows that ΔN_f is higher than ΔN_{it} for the whole stress time, and oxide-fixed charge generation is likely more susceptible to V_{th} degradation shown in Fig. 1(b).

The hydrogen-related precursors for oxide-fixed charge generation likely exist in the high-hydrogenated gate oxide, and those precursors, acts as hole traps, degrade the gate oxide reliability during NBTI stress. Instead of the hydrogen, using the deuterium can suppress the hydrogen-related precursors because the bonds to deuterium are more difficult to break than bonds to hydrogen (known as kinetic isotope effect) [6]. Fig. 3 shows the effect of annealing gas ambience, and the isotope effect in NBTI. Fig. 4 shows the generation of ΔN_{it} and ΔN_f for two devices. There is no isotope effect at the SiO_2/Si interface. However, for the oxide-fixed charge we can see the isotope effect so that deuterium annealing suppressed effectively the generation of the precursor for hole trap, and then the positive oxide charge. Obtained isotope effect is proposed to explain the chemical reaction between hydrogenated trivalently bonded silicon defect (the precursor for oxide-fixed charges) and the injected hole under NBTI stress condition.

We now examine the detrapping phenomena of hole during positive bias temperature stress(PBTI) in the control and the hydrogenated devices. Fig. 5(a) and 5(b) show ΔV_{th} for NBRI-PBTI-NBTI and PBTI-NBTI-PBTI stress sequences, respectively. When the device has the hydrogenated gate oxide, Fig. 5(a) clearly shows that a significant amount of traps are still filled with hole during PBTI. Fig. 5(b) shows that the hole injected from gate polysilicon is trapped during PBTI, but those trapped hole is likely not detrapped through the next NBTI-PBTI process. Fig. 6(a) and 6(b) show the shift of mid-gap voltage (V_{mg}), which is due to the generation of oxide-fixed charge, when the stress sequences were NBTI-PBTI and PBTI-NBTI, respectively. Interface-trap charges generated during

NBTI stress do not decrease in PBTI stress, however, as can be seen clearly in Fig. 6(a), even when PBTI following NBTI was applied, the oxide-fixed charges still exist in the high-hydrogenated gate oxide. When PBTI stress was applied first, as shown in Fig. 6(b), the generation of oxide-fixed charge was built up in high-hydrogenated gate oxide.

We assume that there are two types of hole traps that determined by the dynamic balance between trapping and detrapping. For the oxide traps generated by extrinsic defect, such as a by-product trivalent silicon defect, their detrapping probability is sufficiently low, so the effects on the filling during next NBTI is negligible. However, for the oxide trap generated by general NBTI model, including the diffusion of hydrogen ion from Si/SiO_2 interface, their detrapping is easier, so the recovery of NBTI could be expected for the next PBTI process. It is possible that this is caused by the differences in their energy levels. The intrinsic defect by diffused hydrogen ion can be energetically shallower than the traps by extrinsic defect, so that the detrapping of the former is easier by tunneling to the conduction band.

Conclusion

A more detailed physical mechanism, responsible for NBTI, has been proposed and supporting experimental result has been presented. In addition to the typical NBTI mechanism, the precursor for oxide-fixed charge is probably created in the bulk of the gate oxide depending on process variations and extrinsic defect levels. Our model can qualitatively explain the asymmetry between the effect under negative and positive BT stress and the isotope effect in NBTI stress.

Acknowledgement

This work was supported by the Post-doctorial Fellowship Program of Korea Science & Engineering Foundation (KOSEF).

References

[1] K. O. Jeppson et al, *J. Appl. Phys.*, vol. 48, pp. 2004-2014, 1977.
[2] S. Ogawa et al, *J. Appl. Phys.*, vol. 77, pp. 1137-1148, 1995.
[3] N. Kimizuka et al, *Symp. on VLSI Technol.*, 1999, pp. 73-75.
[4] T. B. Hook et al, *IEEE Trans. Electron Devices*, vol.48, pp.1346-1353, 2001.
[5] P. J. McWhorter et al, *Appl. Phys. Lett.*, vol.48, pp. 133-135, 1986.
[6] K. Hess et al, *IEEE Trans. Electron Devices*, vol. 45, pp. 406-416, Feb. 1998.

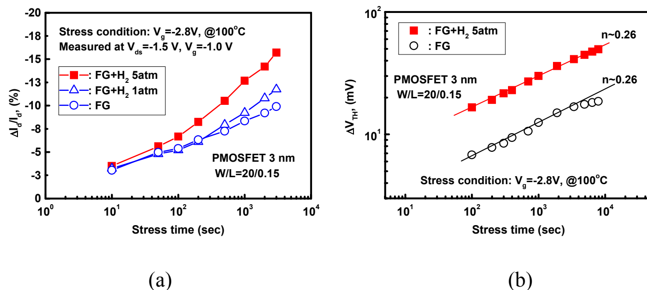

FIGURE 1. TIME DEPENDENCE OF THE SATURATION DRAIN CURRENT DEGRADATION(a) AND THE THRESHOLD VOLTAGE SHIFT(b). FG AND FG+H_2 MEANS THE STANDARD FORMING GAS PROCESS AND THE ADDITIONAL HYDROGEN ANNEALING AT CORRESPONDING CONDITIONS.

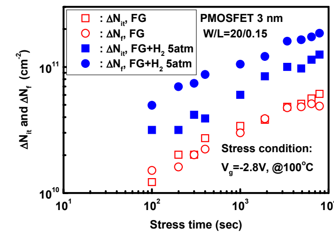

FIGURE 2. TIME EVOLUTION OF INTEGRATED INTERFACE-TRAP DENSITY (ΔN_{it}) AND OXIDE-FIXED CHARGE DENSITY (ΔN_f) FOR THE TWO HYDROGEN ANNEALING CONDITIONS.

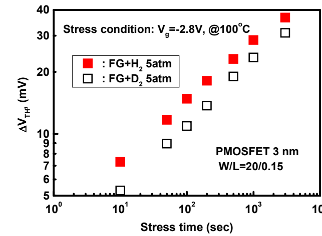

FIGURE 3. TIME DEPENDENCE OF ΔV_{th} FOR BOTH HYDROGEN(H_2) AND DEUTERIUM(D_2) HIGH-PRESSURE ANNEALING.

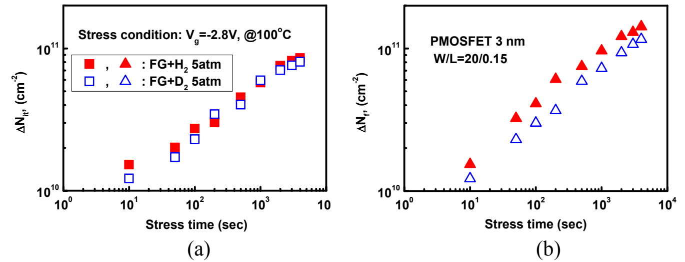

FIGURE 4. TIME EVOLUTION OF ΔN_{it}(a) AND ΔN_f(b) FOR BOTH HYDROGEN(H_2) AND DEUTERIUM(D_2) HIGH-PRESSURE ANNEALING.

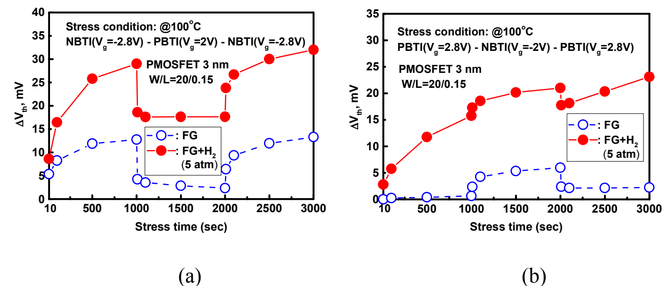

FIGURE 5. TIME DEPENDENCE OF ΔV_{th} UNDER UNIFORM DYNAMIC BT STRESS HAVING NBTI-PBTI-NBTI STRESS SEQUENCE(a) AND PBTI-NBTI-PBTI STRESS SEQUENCE(b).

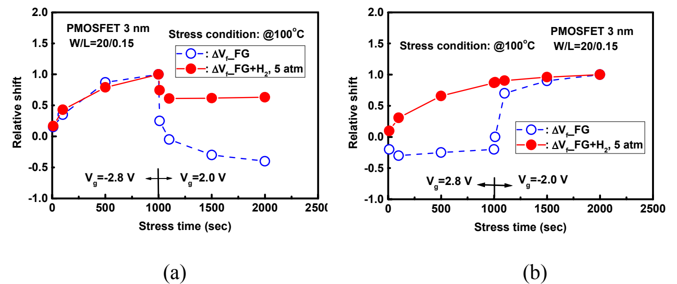

FIGURE 6. TIME DEPENDENCE OF RELATIVE SHIFT OF MID-GAP VOLTAGE UNDER UNIFORM DYNAMIC BT STRESS HAVING NBTI-PBTI STRESS SEQUENCE(a) AND PBTI-NBTI STRESS SEQUENCE(b).