IMPROVEMENT IN RELIABILITY OF *n*-MOSFETs BY USING RAPID THERMAL N₂O-REOXIDIZED NITRIDED GATE OXIDES

YOU-LIN WU, ZHAO-YIN WU and JENN-GWO HWU†

Department of Electrical Engineering, National Taiwan University, Taipei, Taiwan, Republic of China

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Abstract—Instead of oxygen, pure N₂O gas was used as the reoxidizer for rapid thermal reoxidized nitrided oxide in this work. The performance of *n*-MOSFETs with this new gate dielectric is dramatically improved in both the radiation-hardness and channel-hot-carrier stress when compared with those with pure O₂-grown and O₂-reoxidized nitrided oxides. Higher mobility is observed for the *n*-MOSFETs with N₂O-reoxidized nitrided oxides in both the high field and low field regions. These improvements are attributed to the additional nitridation effect during the N₂O reoxidation process, which will incorporate more nitrogen at the SiO₂/Si interface.

1. INTRODUCTION

It has been proved that the incorporation of nitrogen at SiO₂/Si interface by various methods can improve the oxide reliability and device performance[1-4]. One of the promising methods is the use of O₂ as the oxidant to reoxidize the NH₃-nitrided oxides. MOSFETs with this O₂-reoxidized nitrided oxide (O₂-RNO) have been shown to have superior characteristics compared to those with the conventional furnace-grown gate oxides[5-7]. However, the hydrogen-related species that are incorporated into the oxide during NH₃ nitridation are thought to be the main cause of the high levels of electron trapping in these oxides. A long O₂ reoxidation time or a high O₂ reoxidation temperature is required to reduce the electron traps in the NH₃-nitrided oxides[8]. Recently, N₂O-grown and N₂O-annealed oxides have drawn much attention due to no hydrogen-related species involved during the process[2,3,9,10]. However, the thickness of the N₂O-grown oxide is self-limited and a high growth temperature has to be used if a thicker oxide is required[11]. It is also reported that long N₂O annealing time or high N₂O oxidation temperature may degrade the oxide quality[12,13], while O₂-RNO samples exhibit no such problem. Recently, Fukuda *et al.*[4] showed excellent performance of electrically erasable programmable read only memories (EEPROMs) with N₂O-annealed NH₃-nitrided oxide as the tunnel oxide, and their SIMS data showed that the hydrogen content was reduced while the nitrogen content was increased when the oxides were subjected to N₂O annealing after NH₃-nitridation. Thus, if one changes the reoxidizer of

RNO structures from O₂ to N₂O, in addition to the change of the hydrogen content in oxides caused by NH₃-nitridation, more nitrogen will incorporate into the oxides during N₂O reoxidation. Hence, it is believed that, instead of using O₂ as the reoxidizer, the N₂O-reoxidized nitrided oxides (N₂O-RNO) can be another promising candidate for the gate dielectrics of reliable MOSFETs. In this work, it is found that *n*-MOSFETs with N₂O-RNO gate oxides are superior to those with fresh and O₂-RNO gate oxides in both radiation hardness and resistance to hot-carrier degradation.

2. EXPERIMENTAL

The *n* channel MOSFETs (*W*/*L* = 400 μm/5 μm) used in this study were fabricated on (100)-oriented *P*-type silicon wafers with a resistivity of 8.51-8.75 Ω · cm. The source and drain were formed by POCl₃ diffusion at 950°C for 15 min and were then driven-in at 1000°C for 25 min. After the oxide of the active regions was removed, the starting (fresh) gate oxide (152 Å) was grown at 1000°C in dry O₂ using a conventional furnace and then annealed in N₂ at the same temperature for 10 min. Nitridation were then performed at 1000°C for 120 s in pure NH₃ ambient at 500 torr by using a lamp-heated rapid thermal annealer. Some samples were then subjected to O₂ reoxidation at 1000°C for 120 s, and others were reoxidized in pure N₂O at 1000°C for 60 s in the same rapid thermal processing system. Due to the retarded oxide growth, as a result of the nitrogen incorporation, the same final oxide thickness of 170 Å can be achieved for both the N₂O-RNO and O₂-RNO devices. Finally, after Al (1% Si) metallization and patterning, the devices were annealed in N₂ at 380°C

†To whom all correspondence should be addressed.

for 10 min. MOS capacitors (MOSC) with fresh, O₂-RNO and N₂O-RNO oxides were also fabricated using the same process.

Channel hot-electron stress (CHES) was applied to all the *n*-MOSFETs at a gate voltage of $V_g = V_d/2 = 5$ V which could result in maximum interface trap generation and hence maximum peak transconductance G_m degradation. All the samples were also subjected to 1 Mrad(SiO₂) Co-60 irradiation in order to study their radiation hardness. The threshold voltage shift ΔV_{th} and the peak transconductance shift $\Delta G_m/G_{m0}$ and/or the drain current shift $\Delta I_d/I_{d0}$ after CHES and irradiation were then measured.

3. RESULTS AND DISCUSSION

Figure 1 shows typical normalized quasi-static capacitance-voltage ($C-V$) curves for the fresh, O₂-RNO and N₂O-RNO MOSCs. The capacitances in the accumulation region obtained from the $C-V$ curves are 210, 207 and 193 nF/cm² for the fresh, O₂-RNO and N₂O-RNO devices, respectively. The dielectric constants as calculated from the capacitance data were 4.01 for N₂O-RNO and 4.32 for O₂-RNO devices. It is noted that the N₂O-RNO device exhibits more positive fixed oxide charges (2.71×10^{11} cm⁻²) than the O₂-RNO device (2.03×10^{11} cm⁻²) does. These nitridation-induced fixed oxide charges are mainly caused by NH₃-nitridation[8]. However, the nitridation effect is also involved during the N₂O-reoxidation process, which will result in more fixed oxide charge. The threshold voltages for fresh, O₂-RNO and N₂O-RNO *n*-MOSFETs are 0.47, 0.43 and 0.30 V, respectively, which reflects the fact that more nitridation-induced oxide charge is produced in N₂O-RNO devices.

Figure 2 shows the effective mobility μ_{eff} and the drain current I_d as a function of gate drive, $V_g - V_{th}$, for the fresh oxide, O₂-RNO and N₂O-RNO *n*-MOSFETs. It is observed that the O₂-RNO device exhibits lower peak μ_{eff} than that of the fresh oxide device, while higher μ_{eff} is seen in the high V_g region. This is

Fig. 1. Normalized quasi-static $C-V$ curves for fresh, N₂O-RNO and O₂-RNO MOS capacitors.

Fig. 2. Effective mobility μ_{eff} and drain current I_d vs the gate drive $V_g - V_{th}$ for the *n*-MOSFETs with fresh, O₂-RNO and N₂O-RNO gate oxides. (measured at $V_d = 100$ mV).

in agreement with other researchers' work[14]. The N₂O-RNO *n*-MOSFETs show improved μ_{eff} in both the high and low V_g regions. The mobility degradation of O₂-RNO device in the low V_g region has been attributed to the increasing interface state located 0–0.2 eV below the conduction band edge caused by NH₃ nitridation[15]. The μ_{eff} improvement in the high V_g region for both the N₂O-RNO and the O₂-RNO devices has been reported to be due to the reduction of the acceptor-like interface states above the conduction band caused by nitridation[14]. Such interface states could be of quite high density for fresh oxide devices. It is seen from Fig. 2 that μ_{eff} in the high V_g region for the N₂O-RNO device is higher than that of the O₂-RNO device. This result indicates that N₂O reoxidation can largely reduce the acceptor-like interface states above the conduction band due to its heavy nitridation effect. Although the nitridation could induce fixed oxide charges which might act as the Coulombic scattering center, nitridation-induced strain relaxation seems to be more effective in affecting the inversion layer channel mobility. The $I_d - V_d$ curves for the three devices are plotted in Fig. 3 which further confirms the mobility improvement in the N₂O-RNO device.

In order to investigate the degradation of *n*-MOSFETs after channel hot-carrier stress, fresh oxide, O₂-RNO and N₂O-RNO devices were subjected to

Fig. 3. The $I_d - V_d$ curves for the fresh, O₂-RNO and N₂O-RNO *n*-MOSFETs.

Fig. 4. Threshold voltage shift ΔV_{th} as a function of stress time in ($L = 5 \mu m$) n -MOSFETs with fresh, O₂-RNO and N₂O-RNO gate oxides. The stress condition is $V_g = V_d/2 = 5 V$. The threshold voltages are determined by the extrapolated V_{th} .

Fig. 6. Peak transconductance shift $-\Delta G_m/G_{m0}$ as a function of stress time in ($L = 5 \mu m$) n -MOSFETs with fresh, O₂-RNO and N₂O-RNO gate oxides. The samples were stressed at $V_g = V_d/2 = 5 V$.

CHES at $V_g = V_d/2$ which will produce maximum substrate current. Figure 4 shows the stress-induced threshold voltage shift ΔV_{th} vs stress time curves for fresh oxide, O₂-RNO and N₂O-RNO devices during the CHES. The typical extrapolated threshold voltage from the I_d - V_g curve was used. Electron trapping occurred in both the fresh and the O₂-RNO devices, consistent with the observation in the literature[7,16]. It is noted that the O₂-RNO device exhibits higher ΔV_{th} than that of the fresh device. This is believed to be related to the hydrogen-induced electron trapping during NH₃ nitridation and insufficient O₂-reoxidation.

Figure 5 shows the gate charge shift $\Delta V_g \cdot C_{ox}$ vs the stress time of the MOSCs with the three kinds of gate oxide structures during constant current stressing ($J = 10 \mu A/cm^2$, gate biased negatively), which confirms the result of high electron trapping in the O₂-RNO device, and the N₂O-RNO MOSC exhibits the lowest electron trapping. As can be seen from

Fig. 5. The gate charge change $\Delta V_g \cdot C_{ox}$ as a function of the stress time for the fresh, N₂O-RNO and O₂-RNO MOS capacitors during the Fowler-Nordheim constant current stress (gate biased negatively) at $J = 10 \mu A/cm^2$.

Fig. 4, hole trapping occurs in N₂O-RNO n -MOSFETs after CHES, but no apparent hole trapping phenomenon is observed in N₂O-RNO MOSC under the constant current stressing in Fig. 5. This is because for MOSFETs under the stressing condition $V_d > V_g > V_{th}$, both electrons and holes are emitted into the gate oxides in considerable amounts[17,18], and N₂O reoxidation can largely reduce the electron traps in the oxide, hence the effect of hole trapping becomes more pronounced in the N₂O-RNO n -MOSFETs. It is also noted that the N₂O-RNO device has the smaller stress-induced $|\Delta V_{th}|$ among the three devices.

Figure 6 shows the peak transconductance shift $\Delta G_m/G_{m0}$ caused by CHES for devices with three kinds of oxide structures. It is clear from this figure that the N₂O-RNO device exhibits the smallest shift. The hydrogen-related species involved during the NH₃-nitridation process will result in electron traps generation near the SiO₂/Si interface, which is the dominant factor that degrades the mobility (transconductance) of n -MOSFETs[15]. It is reported that these electron traps can be reduced by the following reoxidation process[8], and our result shows that 60 s N₂O-reoxidation is more effective than 120 s O₂-reoxidation in reducing the near-interface electron traps of the NH₃-nitrided oxide. The drain current degradation $\Delta I_d/I_{d0}$ vs stress time for n -MOSFETs operated in the linear region ($V_d = 0.1 V$, $V_g = 5 V$) and in the saturation region ($V_d = 2 V$, $V_g = 3 V$) are shown in Figs 7 and 8, respectively. It is observed that the drain current shift increases positively with the stress time for the N₂O-RNO device, which means that net hole trapping occurred near the interface due to CHES. The improved interface hardness and suppressed charge-trapping in the N₂O-RNO device is suggested to be due to interfacial strain relaxation and dangling-bond passivation by nitrogen at the interface. Because the

Fig. 7. Drain current shift— $\Delta I_d/I_{d0}$ as a function of stress time in ($L = 5 \mu\text{m}$) n -MOSFETs with fresh, O_2 -RNO and N_2O -RNO gate oxides. The samples were stressed at $V_g = V_d/2 = 5\text{V}$ and the I_d was measured at $V_g = 5\text{V}$ and $V_d = 100\text{mV}$ (linear region).

nitrogen-induced tensile stress reduced the compressive stress in SiO_2 near the Si/SiO_2 interface and the stronger Si-N bonds replace the strained Si-O bonds through the formation of SiO_xN_y , thus interface traps generation by CHES is reduced [10,19]. The interfacial stress compensation and dangling-bond passivation can be confirmed from the initial sub-threshold swings of the devices which are 120, 95 and 82 mV/decade for the fresh, O_2 -RNO and N_2O -RNO n -MOSFETs, respectively. It is emphasized that the reoxidation with O_2 and N_2O can result in dramatically different characteristics for identical nitrided gate oxides. From the experimental results and discussions given above, it can be ascertained that the subsequent N_2O -reoxidation to NH_3 -nitridation not only reduces the atomic percentage of hydrogen in the oxide but also incorporates more nitrogen atoms

Fig. 8. Drain current shift— $\Delta I_d/I_{d0}$ as a function of stress time in ($L = 5 \mu\text{m}$) n -MOSFETs with fresh, O_2 -RNO and N_2O -RNO gate oxides. The stress condition is at $V_g = V_d/2 = 5\text{V}$ and the I_d is measured at $V_g = 2\text{V}$ and $V_d = 3\text{V}$ (saturation region).

Fig. 9. Radiation-induced threshold voltage shift— ΔV_{th} for n -MOSFETs with fresh, O_2 -RNO and N_2O -RNO gate oxides after 1 Mrad Co-60 irradiation.

into the Si/SiO_2 interface [4]. The N_2O -RNO device is therefore able to have better reliability than the fresh and O_2 -RNO devices.

The radiation-induced flatband voltage shift ΔV_{fb} and the radiation-induced peak transconductance shift $\Delta G_m/G_{m0}$ after 1 Mrad (SiO_2) Co-60 irradiation for the n -MOSFETs with three kinds of gate structures are shown in Figs 9 and 10, respectively. It is obvious that the N_2O -RNO device shows the least shifts in both ΔV_{th} and $\Delta G_m/G_{m0}$, which indicates much radiation hardness for N_2O -RNO device. These improvements are readily explained by the nitrogen pile-up at Si/SiO_2 interface which decreases the strain gradient and therefore lowers the value of the radiation-induced interface trap density [9,19,20].

4. CONCLUSION

The n -MOSFETs with N_2O -reoxidized nitrided oxides prepared by rapid thermal processes are studied in this work. It is shown that, in contrast to

Fig. 10. Radiation-induced peak transconductance shift— $\Delta G_m/G_{m0}$ for n -MOSFETs with fresh, O_2 -RNO and N_2O -RNO gate oxides after 1 Mrad Co-60 irradiation.

conventional O₂-RNO MOSFET, the N₂O-RNO device provides improved mobility in both the high and low V_g regions. The N₂O-RNO device also exhibits the least degradations in ΔV_{th} and $\Delta G_m/G_{m0}$ after CHES and 1 Mrad Co-60 irradiation among the three devices. The improvements are believed to be related to the nitrogen that is incorporated into the SiO₂/Si interface during nitridation and reoxidation. For the O₂-RNO device, nitrogen incorporation into the oxides occurs only during NH₃ nitridation, but for N₂O-RNO device, nitrogen can be introduced through both the nitridation and reoxidation process, and more nitrogen is piled up at the SiO₂/Si interface. Also, due to its higher activity, N₂O reoxidation can reduce more hydrogen content at the SiO₂/Si interface and hence reduce more electron trapping in oxides. It is suggested that N₂O-RNO may be a promising candidate for thin and reliable gate oxides for future ULSI devices.

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