AC Hot-Carrier-Induced Degradation in NMOSFET's with N_2O-Based Gate Dielectrics

Xu Zeng, P. T. Lai, and W. T. Ng

Abstract—**Frequency-dependent ac-stress-induced degradation in NMOSFET's with N_2O-grown and N_2O-nitrided gate oxides was investigated. Suppressed device degradation is observed in both N_2O-based devices as compared to SiO_2 device for frequency up to 100 kHz, which is attributed to nitrogen incorporation in the gate oxides. Moreover, when comparing the two N_2O-based oxides, N_2O-grown oxide device exhibits enhanced degradation than N_2O-nitrided oxide device. Charge pumping measurements reveal that N_2O-nitrided oxide has better immunity to interface-state and neutral-electron-trap generation under dynamic stress.**

I. Introduction

In RECENT years, N_2O-based gate oxides have been extensively studied [1]–[3]. Compared to NH_3 nitridation, since N_2O oxidation or nitridation is hydrogen-free, the resulting oxides are more reliable. Furthermore, the process is simpler since no reoxidation step is required. However, recent studies [4], [5] have revealed that NMOSFET's with N_2O-grown gate oxide may have enhanced off-state leakage, especially for thick gate oxide where prolonged N_2O oxidation is needed [6]. In this paper, these two N_2O-based gate oxides are further compared in terms of ac-stress-induced degradations. The involved degradation mechanisms are discussed.

II. Experimental

NMOSFET's (effective $W/L = 12$ μm/1.0 μm) were fabricated on p-type (100) Si wafer (6–8 Ω·cm), using a four-mask n^+-poly-gate NMOS process. Conventional thermal gate oxide (OX) was grown in dry O_2 at 850 °C for 70 min plus 25 min of N_2 anneal. N_2O-nitrided (N_2ON) gate oxide was grown in the same conditions, but for a shorter time of 50 min to compensate for the thickness increase associated with an ensuing 20-min N_2O nitridation at 950 °C. These nitridation conditions were also used to oxidize Si in N_2O-grown (N_2OG) gate oxide for 120 min to achieve the same thickness as the other two oxides, around 150 Å from CV techniques. DC stress was chosen to roughly correspond to maximum substrate current $(I_{\mathrm{sub,max}})$ with $V_g = 1/2V_d = 4$ V. Correspondingly, ac stress was performed at the same $V_d = 8$ V, and V_g was pulsed between 0 V and 4 V, with source and substrate grounded, which also corresponds to $I_{\mathrm{sub,max}}$ for more appropriate comparison between the two kinds of stresses. Both V_T shift and peak linear transconductance (G_m) degradation were monitored. Changes in interface-state density (D_{it}) and charge trapping of the gate oxides were also analyzed by charge-pumping (CP) technique [7], [8].

Manuscript received June 6, 1996; revised September 26, 1996.

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Publisher Item Identifier S 0741-3106(97)01241-X.

III. Results and Discussion

Fig. 1(a) shows the percentage G_m degradation under dc and ac stresses. As expected, oxynitrides exhibit suppressed G_m degradation as compared to thermal oxide, which can be attributed to increased interface hardness against hot-carrier-induced interface-state generation (ΔD_{it}) and reduced charge trapping through the incorporation of nitrogen during N_2O processing [9]. It is, however, worth noting that N_2ON oxide is superior to N_2OG one, especially in high-stress frequency region, where, after a turnaround, ac-stress-induced degradation is even less than the dc one. The stress-induced D_{it} generation is one of the causes of G_m degradation. Therefore, ΔD_{it} as a function of ac stress frequency was measured by CP technique. The results are presented in Fig. 1(b). The trend of ΔD_{it} data quite resembles the G_m degradation behavior shown in Fig. 1(a), suggesting that ΔD_{it} should be partially responsible for the G_m degradation. Nevertheless, due to the presence of the low-V_g half-cycle during ac stress with V_d fixed at high voltage, the hole trapping and the creation of neutral electron traps cannot be neglected [10]. Consequently, a short phase of channel-hot-electron (CHE) injection was performed immediately after the ac and dc stresses to manifest this kind of damage. As shown in Fig. 2(a), subsequent 50-s CHE-induced V_T shift ($\Delta V_{T2} = 640$ mV) is much larger than 1000-s ac-stress-induced V_T shift ($\Delta V_{T1} = 62$ mV) for the OX oxide, indicating a large amount of neutral electron traps (N_{et}) is created during the dynamic stress. This kind of damage is significantly suppressed in the N_2OG oxide ($\Delta V_{T2} = 87$ mV, $\Delta V_{T1} = 7.3$ mV), and especially in the N_2ON oxide ($\Delta V_{T2} = 10$ mV, $\Delta V_{T1} = 3.8$ mV). In contrast to ac stress case, negligible N_{et} is created during the dc stress for the N_2O-based oxides, because little ΔV_T is observed for the two oxides, as shown in Fig. 2(b), verifying the importance of N_{et} damage in ac stress degradation. It is believed that hole trapping is closely related to N_{et} generation [11]. Charge pumping current (I_{cp}) data measured on the ac-stressed devices and after the subsequent CHE injection, given in Fig. 3, confirms that negligible hole trapping is induced by the ac stressing for the N_2ON oxide, since little difference between the two I_{cp} curves before and after the CHE injection is observed for the N_2ON device. However, apparent difference in the I_{cp} curves does exist for the OX

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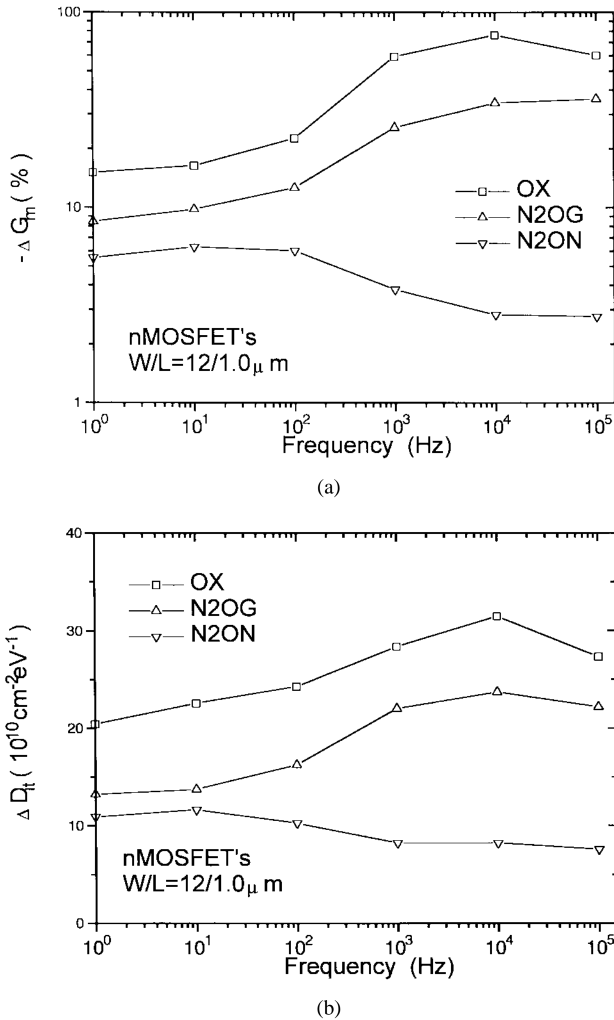

Fig. 1. Frequency dependence of (a) peak linear transconductance degradation, and (b) generated interface-state density after a 5000-s ac stress at $V_d = 8$ V, V_g was pulsed between 0 and 4 V with 50% duty cycle, 200 ns rise/fall time. DC stress was carried out at $V_g = 4$ V, $V_d = 8$ V (data points lie on the y axis). $D_{\rm it}$ was extracted from the difference between the maximum and minimum $I_{\rm cp}$, with initial value between 3.5 and 4.5×10^{10} $\rm eV^{-1} \cdot cm^{-2}$ for the three kinds of devices.

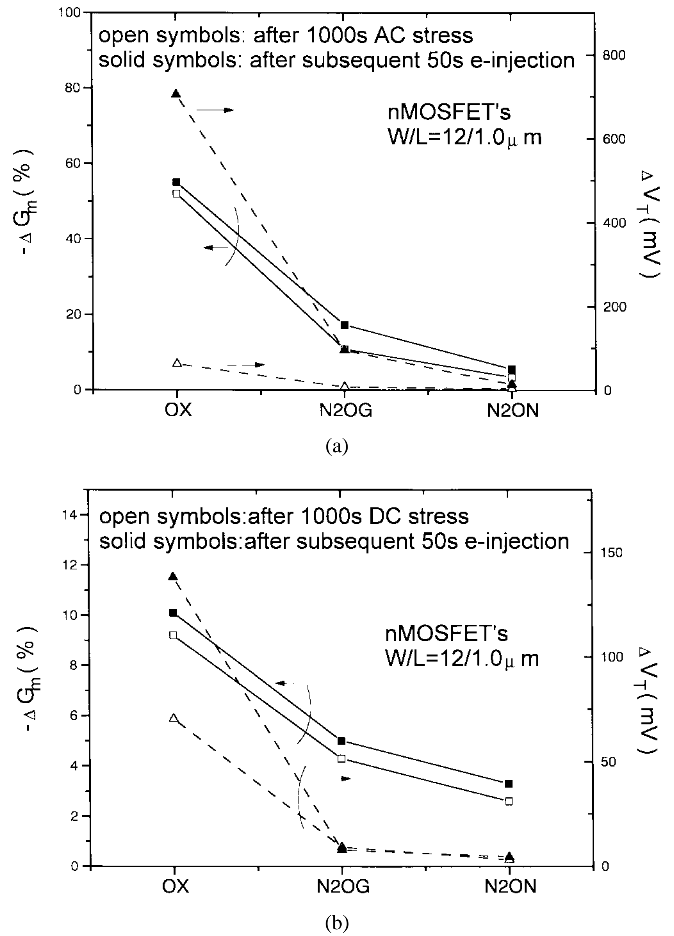

Fig. 2. G_m and V_T changes of three kinds of devices after 1000-s (a) ac stress, and (b) dc stress. Short phase (50 s) of channel hot electron injection was performed after ac and dc stresses. Stress conditions were the same as the ones in Fig. 1, with ac-stress frequency $= 10^4$ Hz.

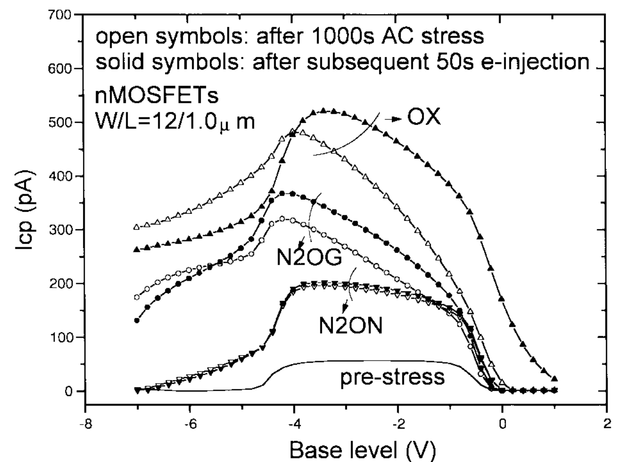

Fig. 3. Charge-pumping current $I_{\rm cp}$ versus gate pulse base level for the three kinds of devices after 1000-s ac stress and subsequent 50-s channel-hot-electron injection. ac-stress condition is identical with that of Fig. 2. Charge pumping was performed with gate voltage swing = 5 V, frequency = 100 kHz, pulse rise/fall time = 100 ns, source/drain reverse bias = 0.1 V. The pre-stress $I_{\rm cp}$ data for the three devices are similar.

and N_2OG oxides. In detail, a positive shift in the low-voltage tail of the $I_{\rm cp}$ curve for the OX and N_2OG devices after CHE is found, which is resulted from the neutralization of trapped holes by the subsequently injected electrons [8], indicating some hole trapping is induced near the drain by the ac stress. The magnitude of the low-voltage tail shift for the N_2OG device, shown in the Fig. 3, is much smaller than that of the OX device, demonstrating much suppressed hole trapping in the N_2OG oxide as compared to the OX oxide. Moreover, a large positive shift in the right falling edge of the $I_{\rm cp}$ curve after the CHE injection is found for the OX device as a result of electron trapping in the generated $N_{\rm et}$, while such shift is very small in the two N_2O oxynitrides, in agreement with the ΔV_T data presented in Fig. 2(a). The observed difference between the two N_2O oxynitrides may arise from the different way of nitrogen (N) incorporation in the dielectrics. For N_2O-nitrided oxide, N incorporation takes place after a stable Si/SiO_2 interface is formed. Such incorporation, therefore, happens most probably at the weak or strained Si–Si and Si–O bonds, and thus effectively improves the oxide quality. In contrast, N_2O-grown oxide is formed by

oxidizing Si in N_2O gas. There exists an initial accelerated growth phase [6], resulting in an inferior structural transition layer at the interface with more defects than the N_2ON oxide. Moreover, N distributions in N_2ON and N_2OG oxides are different, as confirmed by both SIMS measurements [12] and chemical step-etching analysis [13]. N_2ON oxide has N peak only at the interface, with much less N in the bulk than N_2OG oxide. The N atoms in the bulk are bonded to only two Si atoms with the remaining bond acting as a trap centre, while the N atoms at the interface are bonded with three Si atoms [14] contributing to a more robust interface. Therefore, the larger amount of bulk N in our N_2OG oxides should be one of the causes of inferior degradation property to the N_2ON oxides shown in Fig. 1(a), like the way bulk N degrades the $Q_{\rm bd}$ characteristics of N_2OG oxides [12]. As for the decreased degradation of N_2ON device with increasing frequency, charge detrapping near the interface might be partially responsible, while in N_2OG and OX devices, charge is mainly trapped in the oxide bulk and is difficult to detrap. Last but not least, it must be noted that the lower oxide-growth temperature for OX device could also contribute to its inferior characteristics to a certain extent [15].

IV. Conclusion

Degradation under dynamic stress of NMOSFET's with thermal SiO_2, N_2O-grown, and N_2O-nitrided oxides as gate dielectrics has been investigated. Compared to conventional oxide device, the N_2O-based oxide devices show significantly improved immunity to dc- and ac-stress-induced damages in terms of both interface-state generation and charge trapping due to nitrogen incorporation in the oxides. When comparing the two N_2O-based oxides, charge pumping measurements reveal that N_2O-nitrided oxide is better than N_2O-grown oxide in suppressing $\Delta D_{\rm it}$, hole trapping, and thus, neutral electron trap generation under ac stress. This difference is interpreted by the way N is incorporated in the two N_2O oxides. In summary, directly oxidizing Si in N_2O ambient may not be a good technique especially when the target oxide thickness is large.

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