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AC Hot-Carrier-Induced Degradation in NMOSFET’s with N$_2$O-Based Gate Dielectrics

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

Abstract—Frequency-dependent ac-stress-induced degradation in NMOSFET’s with N$_2$O-grown and N$_2$O-nitrided gate oxides was investigated. Suppressed device degradation is observed in both N$_2$O-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 two N$_2$O-based oxides, N$_2$O-grown oxide device exhibits enhanced degradation than N$_2$O-nitrided oxide device. Charge pumping measurements reveal that N$_2$O-nitrided oxide has better immunity to interface-state and neutral-electron-trap generation under dynamic stress.

I. INTRODUCTION

In recent years, N$_2$O-based gate oxides have been extensively studied [1]–[3]. Compared to NH$_3$ nitridation, since N$_2$O 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$_2$O-grown gate oxide may have enhanced off-state leakage, especially for thick gate oxide where prolonged N$_2$O oxidation is needed [6]. In this paper, these two N$_2$O-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 ($6–8$ Ωcm), using a four-mask $p^+$/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$_2$O-nitrided (N$_2$O ON) 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$_2$O nitridation at 950 °C. These nitridation conditions were also used to oxidize Si in N$_2$O-grown (N$_2$O ON) 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 ($I_{sub,max}$) 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 $I_{sub,max}$ 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 ($D_E$) and charge trapping of the gate oxides were also analyzed by charge-pumping (CP) technique [7], [8].

III. RESULTS AND DISCUSSION

Fig. 1(a) shows the percentage $G_m$ degradation under dc and ac stresses. As expected, oxy-nitrides 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 ($\Delta D_E$) and reduced charge trapping through the incorporation of nitrogen during N$_2$O processing [9]. It is, however, worth noting that N$_2$O ON oxide is superior to N$_2$O ON 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 $D_E$ generation is one of the causes of $G_m$ degradation. Therefore, $\Delta D_E$ as a function of ac stress frequency was measured by CP technique. The results are presented in Fig. 1(b). The trend of $\Delta D_E$ data quite resembles the $G_m$ degradation behavior shown in Fig. 1(a), suggesting that $\Delta D_E$ 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 ($\Delta V_{T2} = 62$ 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$_2$O ON oxide ($\Delta V_{T2} = 87$ mV, $\Delta V_{T2} = 7.3$ mV), and especially in the N$_2$O ON oxide ($\Delta V_{T2} = 10$ mV, $\Delta V_{T2} = 3.8$ mV). In contrast to ac stress case, negligible $N_{ET}$ is created during the dc stress for the N$_2$O ON-based oxides, because little $\Delta V_T$ 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$_2$O ON oxide, since little difference between the two $I_{CP}$ curves before and after the CHE injection is observed for the N$_2$O ON device. However, apparent difference in the $I_{CP}$ curves does exist for the OX.
Fig. 1. Frequency dependence of (a) peak linear transconductance degradation, and (b) generated interface-state density after a 5000-s ac stress at $V_{dd} = 8$ V. $V_d$ 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, $V_{dd} = 8$ V (data points lie on the y axis). $\Delta G_m$ was extracted from the difference between the maximum and minimum $G_m$, with initial value between 3.5 and $4.5 \times 10^{10}$ eV$^{-1}$ cm$^{-2}$ for the three kinds of devices.

and N$_2$O oxides. In detail, a positive shift in the low-voltage tail of the $I_{CP}$ curve for the OX and N$_2$O 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$_2$O device, shown in the Fig. 3, is much smaller than that of the OX device, demonstrating much suppressed hole trapping in the N$_2$O oxide as compared to the OX oxide. Moreover, a large positive shift in the right falling edge of the $I_{CP}$ curve after the CHE injection is found for the OX device as a result of electron trapping in the generated $N_{it}$. While such shift is very small in the two N$_2$O oxynitrides, in agreement with the $\Delta V_T$ data presented in Fig. 2(a). The observed difference between the two N$_2$O oxynitrides may arise from the different way of nitrogen (N) incorporation in the dielectrics. For N$_2$O-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$_2$O-grown oxide is formed by
oxidizing Si in N$_2$O 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$_2$ON oxide. Moreover, $N$ distributions in N$_2$ON and N$_2$OG oxides are different, as confirmed by both SIMS measurements [12] and chemical step-etching analysis [13]. N$_2$ON oxide has $N$ peak only at the interface, with much less $N$ in the bulk than N$_2$OG 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$_2$OG oxides should be one of the causes of inferior degradation property to the N$_2$ON oxides shown in Fig. 1(a), like the way bulk $N$ degrades the $Q_{bd}$ characteristics of N$_2$OG oxides [12]. As for the decreased degradation of N$_2$ON device with increasing frequency, charge detraping near the interface might be partially responsible, while in N$_2$OG 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$_2$O-grown, and N$_2$O-nitrided oxides as gate dielectrics has been investigated. Compared to conventional oxide device, the N$_2$O-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$_2$O-based oxides, charge pumping measurements reveal that N$_2$O-nitrided oxide is better than N$_2$O-grown oxide in suppressing $\Delta D_{it}$, 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$_2$O oxides. In summary, directly oxidizing Si in N$_2$O ambient may not be a good technique especially when the target oxide thickness is large.

REFERENCES