Time-Dependent Dielectric Breakdown of La$_2$O$_3$-Doped High-$k$/Metal Gate Stacked NMOSFETs

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Abstract—Time-dependent dielectric breakdown (TDBD) characteristics of La$_2$O$_3$-doped high-$k$ dielectric in Hf-based high-$k$/TaN metal gate stack were studied. Unlike the abrupt breakdown in the conventional SiO$_2$, dielectric breakdown behaviors of La-incorporated HfON and HfSiO$_x$ dielectrics show progressive breakdown characteristics. Moreover, the extracted Weibull slope $\beta$ of breakdown distribution is in the range of 0.87–1.19, and it is independent on capacitor areas and stress conditions. Moreover, field dependence of $T_{BD}$ and stress-induced leakage current strongly suggest that the $E$-model is more applicable to explain in TDBD of La-incorporated high-$k$ dielectric in Hf-based high-$k$/metal gate stack structure.

Index Terms—BTI, high-$k$ dielectric, Lanthanide Oxide (La$_2$O$_3$), stress-induced leakage current (SILC), time-dependent dielectric breakdown (TDBD).

I. INTRODUCTION

METAL GATE with high-$k$ dielectric such as Hf-based high-$k$ dielectric [Hafnium oxide (HfO$_2$) and Hafnium silicate (HfSiO$_x$)] has been considered to be inevitable for 45-nm CMOSFET technology node [1]. One of the key issues of MOSFETs with the Hf-based high-$k$/metal gate stack is high threshold voltage ($V_{th}$), which is due to the Fermi-level pinning effect induced by oxygen vacancies at high-$k$ dielectric/metal gate interface [2]. Many research groups have focused on manipulating the Hf-based high-$k$/metal gate stack in order to achieve desired $V_{th}$ value through the shift of effective work function ($\Phi_{m,eff}$) of metal gate [2]–[6]. For example, rare earth metal incorporation into Hf-based high-$k$ dielectrics has been recently shown to yield NMOS with low $V_{th}$ [3]. In particular, lanthanum (La)-incorporation into Hf-based high-$k$ dielectrics have low $V_{th}$ as well as superior device characteristic has been successfully demonstrated with HfO$_2$ and HfSiO$_x$ because La-incorporated high-$k$ dielectrics in Hf-based high-$k$/metal gate stack have a low $\Phi_{m,eff}$ for NMOSFETs as reported by several research groups [4]–[6].

However, the time-dependent dielectric breakdown (TDBD) characteristics of La-incorporated HfO$_2$ and HfSiO$_x$ high-$k$ dielectric have yet not been fully clarified although reliability is one of the main concerns in advanced CMOS technology. In this letter, the TDBD characteristics of La-incorporated high-$k$ dielectrics in Hf-based high-$k$/metal gate stack structure were investigated and discussed for nanoscale CMOS technology.

II. EXPERIMENTS

An advanced CMOS technology is applied to fabricate MOSFETs on an 8-in (100) p-type silicon substrate. HfO$_2$ and HfSiO$_x$ dielectric films were deposited on ultrathin silicon dioxide film (~0.5 nm) by atomic layer deposition and followed by a postdeposition anneal (PDA) at 700 °C in NH$_3$ ambient. To achieve the La-incorporation into Hf-based high-$k$ dielectrics, a molecular beam deposition process was used to deposit 0.5-nm-thick lanthanum oxide (La$_2$O$_3$) layer on the Hf-based high-$k$ dielectric films. A 10-nm TaN metal gate was deposited on the dielectric stack and capped with polysilicon gate. Then, LDD, Sidewall, HDD were subsequently applied and followed by a 1070 °C spike annealing. Both the La-incorporated HfON and HfSiO$_x$ dielectrics have the same final physical thickness ($t_{phy}$ ~ 2.5 nm).

III. RESULTS AND DISCUSSION

Constant voltage stress (CVS) with a positive bias on the top gate (substrate injection) is applied to investigate the TDBD characteristics of La-incorporated high-$k$ dielectrics in Hf-based high-$k$/metal gate stack structure. Fig. 1 shows the $J_G-t$ characteristics of the NMOSFET. La-incorporated HfSiO$_x$ shows shorter time-to-breakdown ($T_{BD}$) compared to La-incorporated HfON due to the greater $J_G$. Unlike the abrupt breakdown in the conventional silicon oxynitrided dielectric (SiON) with the same $t_{phy}$, $J_G$ of La-incorporated HfON...
and HfSiON dielectrics increases progressively with stepwise behavior as stress time increases, as shown in inset in Fig. 1, which indicates that multiple breakdown step is initiated from the interfacial layer even in the La-incorporated high-κ dielectrics, like the pure Hf-based high-κ dielectric (without La) [7], [8].

The statistics of dielectric breakdown is usually described by the Weibull distribution [9] as

$$F(x) = 1 - \exp \left[ \left( \frac{x}{\alpha} \right)^\beta \right]$$

where $F(x)$ is the cumulative provability, $x$ is the $T_{BD}$, $\alpha$ is the scale factor of the distribution, and $\beta$ is the Weibull slope which is an important parameter. Fig. 2(a) and (b) shows the Weibull distribution of La-incorporated HfON and HfSiON with various voltage and temperature, respectively. Moreover, two kinds of MOS capacitors with an area of $1 \times 10^{-6}$ and $1 \times 10^{-5}$ cm$^2$ were measured to evaluate the effect of capacitor area. $T_{BD}$ is defined at the point where first soft breakdown happens as in Fig. 1. The extracted Weibull slopes $\beta$ are in the range of 0.87–1.19 for MOS capacitor with ultrathin film thickness (2.5 nm). It is noteworthy that $\beta$ is independent on capacitor area and stress condition. Moreover, $\beta$ values are lower than the reported values ($\beta \sim 1.4$) of pure Hf-based high-κ dielectrics with thick film (4.0 nm) [8]. Lower Weibull slope for thin film thickness of La-incorporated high-κ dielectrics is in agreement with the percolation model [9]. Therefore, $\beta$ is not affected by La-incorporation in Hf-based high-κ dielectrics [10].

Stress-induced leakage current (SILC) is monitored as a function of the injected charge density ($Q_{inj}$) to clarify the TDDB and decide which of $E$ or $1/E$-model explains better the La-incorporated high-κ dielectrics in Hf-based high-κ/metal gate stack structure, as shown in Fig. 3(a) [11], [12]. Similar SILC slope is observed for both La-incorporated HfON and HfSiON dielectrics. However, although La-incorporated HfSiON shows slightly greater $Q_{inj}$ compared to La-incorporated HfON, SILC of La-incorporated HfON is greater than that of La-incorporated HfSiON for all stress conditions, which indicate that stress-generated defects of HfON are greater than that of HfSiON due to the larger amount of pre-existing bulk traps that act as percolation path and/or defect precursors [7].

This expectation is supported by threshold voltage shift ($\Delta V_{th}$) under positive bias temperature (PBT) stress. $\Delta V_{th}$ of La-incorporated HfON shows greater degradation compared to La-incorporated HfSiON by about three orders of magnitude, as shown in Fig. 3(b), which means that pre-existing bulk traps of HfON are greater than that of HfSiON because $\Delta V_{th}$ by charge trapping under PBT stress is believed to happen due to filling of pre-existing bulk traps [13]. Nevertheless, $T_{BD}$ of La-incorporated HfON is greater than that of La-incorporated HfSiON for all stress conditions and capacitor areas. Therefore, $1/E$-model based on electron injection is not suitable, and $E$-model is used to explain the TDDB in La-incorporated high-κ dielectrics in Hf-based high-κ/metal gate stack structure [11].

Fig. 4 shows the TDBD plot using the $E$-model. The field acceleration parameter $\gamma$ shows the distinct difference between
characterized using advanced NMOSFET. Unlike the conventional SiO₂, Jₜₚ₋ₜ characteristics of La-incorporated HfON and HfSiON dielectrics showed progressive breakdown behavior. Moreover, β is in the range of 0.87–1.19, and parallel slopes suggested that β is independent on capacitor areas and stress conditions. Moreover, field dependence of Tₙₜₚ and SILC strongly suggest that E-model is more applicable to explain the TDDB of La-incorporated high-k dielectrics in Hf-based high-k/metal gate stack structure. TDDB and SILC characteristics showed the distinct difference between La-incorporated HfON and HfSiON dielectrics due to difference of gate leakage current and defect density, respectively.

**IV. CONCLUSION**

TDDB characteristics of the La-incorporated high-k dielectrics in Hf-based high-k/TaN metal gate stack were

Fig. 4. $T_F$ is plotted as a function of electric field using the E-model. Inset shows the $C_{G−V_C}$ characteristic.

La-incorporated HfON and HfSiON dielectrics. The $\gamma$ can be obtained from the slope of the time to failure ($T_F$) versus electric field ($E$) curve and the $\gamma$ can be expressed as [14]

$$\gamma = -\left[\frac{\partial \ln(TF)}{\partial E_{\text{ox}}}\right]_T = \frac{P_o \left(\frac{2}{\gamma} + k\right)}{k_BT}$$

(2)

where $P_o$ is the active dipole moment and $k$ is the dielectric constant. This equation predicts that $\gamma$ should increase with increasing $k$. The $\gamma$ of the La-incorporated HfON is 4.95 cm/MV and that of the La-incorporated HfSiON is 4.03 cm/MV. Therefore, projected ten-year lifetime breakdown field of La-incorporated HfON (7.05 MV/cm) is much higher than La-incorporated HfSiON (6.25 MV/cm). Inserted figure shows the $C_{G−V_G}$ characteristics for both La-incorporated HfON and HfSiON dielectrics. $V_{th}$ and EOT were extracted using the $C_{G−V_G}$ curve. $V_{th}$ of La-incorporated high-k dielectrics (~0.26 V) here is smaller than that of pure Hf-based high-k dielectrics (0.5 V–0.6 V) due to the reduction of $\Phi_{m,\text{eff}}$ as reported [2]–[6]. Moreover, the EOT of La-incorporated HfSiON is thicker than that of La-incorporated HfON by about 0.5 Å, which is consistent with (2). Therefore, this difference of $\gamma$ between La-incorporated HfON and HfSiON dielectrics is caused by different $k$ value. Moreover, La-incorporated high-k dielectrics show about 25% lower $\gamma$ values (4.03–4.95 cm/MV) than reported values of pure Hf-based high-k dielectrics (> 6.0 cm/MV) [16], [17], which attributes to degraded interface quality and/or lower effective dipole moment $p_{eff}$ affected by local bond arrangement. During the S/D anneal, La diffuse into Hf-based high-k dielectric and results in the interfacial dipole formed at high-k/interfacial layer [3]. Therefore, reduction in $p_{eff}$ of at least 25% is expected because La has a lower valence of (+3) while Hf and Si have a valence of (+4) and/or degradation of interface quality is also expected with substitution La in Hf-based high-k dielectric [10], [16], [17].

**REFERENCES**


