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Effect Of Starting Interface in Scalability/Device Performance of Ultra-Scaled ALD HfSiON/TiN Gate Stacks

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1. Abstract

We demonstrate that starting interface plays a key role in scaling and performance of ultra-scaled ALD HfSiON/TiN stacks. In particular, the effect of SiO_2 vs. SiON as starting interface for ALD deposition of HfSiON is investigated. It is demonstrated that SiON might be a desirable interface to scale HfSiON without compromising device performance. SiON/HfSiON/TiN stacks resulted in reliable films with < 10 mV of V_{th} shift (ΔV_{th}) after 1000s stress.

2. Introduction

Hf-based high-k dielectric materials bring new challenges such as electron mobility degradation with EOT scaling.[i] Transient charge trapping, fixed charge traps and remote phonon scattering have been proposed as responsible for mobility degradation in scaled MOSFET's1. [ii,iii,iv] In general, a thicker interfacial oxide improves direct current (D. C.) mobility. The distance between bulk traps and the channel reduces the transient charging effects and increases D.C. carrier mobility.[i] Also, in the case of remote phonon scattering, this oxide acts as a barrier to dampen the phonon penetration and reduces the scattering effect of the soft optical phonons.[ii] Therefore, from a device performance point of view, a thicker SiO_2 interface might be desirable, but this also compromises EOT scaling.[v] In this work, we present the effect of surface treatment on scaling, mobility and V_{th} stability for ultra-scaled HfSiON films.

3. Experimental

ALD Hafnium silicate films (HfSiO) with a thickness range of 18 - 24Å deposited on ~ 10Å SiO_2 or SiON interface were studied. The deposition included ozone (O_3) as the oxidizing agent.[vi] The HfSiO (30% Si) films were annealed in NH_3 (700°C) to introduce nitrogen in the bulk of the HfSiO structure. 100Å ALD TiN films followed by 1000Å amorphous Si was used as the gate electrode. All devices were processed using conventional CMOS flow that included 1000°C-5s activation anneal. Equivalent oxide thickness (EOT) was extracted from measured C-V curves using the NCSU CVC model. Channel mobility, Id-Vg and Id-Vd were measured on 10×1 μm MOSFETs with channel doping of ~2×10^{17} B/cm^3. Mobilities were extracted using mob2d.

4. Results And Discussion

Fig. (1) shows cross-sectional HRTEM results for the thinnest (18Å) and thickest (24Å) HfSiON films studied in this work. This thickness range corresponds to 25 and 40 ALD cycles. No evidence of film crystallization or film discontinuity is observed in the HRTEM. The interfacial SiO_2-like layers seems to be independent of surface treatment and HfSiON thickness. However, as we will show below, the starting interface has a direct impact in the resulting EOT. Fig. (2) shows the C-V characteristics for the HfSiON/TiN transistor gate stack. Excellent C-V characteristics were observed for both surface treatments (broken line corresponds to ~18Å control SiO_2). The arrow in each figure represents the decrease in HfSiON physical thickness, which also results in effective EOT decrease. The flat band voltage (V_{fb}) for the thinnest and the thickest HfSiON ranged from -480 to -510 mV and –500 to -530mV for SiO_2 and SiON interfaces, respectively. The V_{fb} shift to more negative values with increased HfSiON thickness indicates net positive charge in the high-k dielectric. The negative shift for SiON interface compared with SiO_2 interface can be attributed to the slightly higher nitrogen in the SiON/Si interface. Independently of the HfSiO thickness, N_{it} values evaluated using charge pumping methods showed values of ~1.5E10 cm^{-2} for SiO_2 interface and ~ 1.9E10 for SiON interface. The slightly increased N_{it} for SiON is due to slightly more nitrogen at the interface.

As HfSiON is scaled, gate leakage current (J_g) reduction relative to SiO_2/polySi must be maintained.[vii] Fig. (3) shows that the SiON interface has slightly higher gate leakage current than the SiO_2 interface. This is consistent with the reduced barrier height for SiON vs. SiO_2 interface.[vii] The inset in Fig. (3) shows the EOT response to starting interface and number of ALD cycles. Clearly, EOT scales by reducing the number of ALD cycles (decreasing HfSiON physical thickness). The lower EOT for SiON *vs.* SiON is attributed to the higher k for SiON.[vii] This additional EOT scaling is relevant, considering the difficulty of scaling high-k films below 12 Å EOT.[v] For a given EOT, SiON/HfSiON films show 3x J_g increase vs. SiO_2/HfSiON [Fig (4)]. However, SiON/HfSiON still shows a Jg reduction >100× relative to SiO_2 (solid line).

Electron mobility vs. effective field for both interfaces is shown in Fig. (5). Although the SiON interface enables EOT scaling, a small reduction in peak mobility occurs simultaneously. Fig (6) further demonstrates the impact of EOT scaling on peak and high field (1 MV/cm) electron mobility. The slightly larger dependence of peak mobility vs. high field mobility with EOT scaling can be attributed to additional nitrogen at the interface resulting from the NH_3 anneal.[vii] For comparison, HfO_2 films deposited in SiO_2 and SiON are also shown. Reduced mobility for HfO_2 compared with HfSiON is due to soft optical phonons from HfO_2.[ii]

Peak and high field mobility follow a different trend line; this suggests a different degradation mechanism for peak mobility vs. high field mobility. In order to further investigate this, Fourier Transform Infrared Spectroscopy (FTIR) studies were performed. Fig. (7) shows that the interfacial Si – O – Si bonds increase with increasing HfSiON thickness. We attribute this growth to the extended O_3 exposure time during ALD deposition. Therefore, thinner HfSiON films have thinner interfacial SiO_2. This results in enhanced phonon scattering from the HfSiON, which results in mobility loss as function of EOT scaling.[ii] Also, the shift in the Si – O – Si to higher wavenumbers for thicker HfSiON films is attributed to more stocihiometric SiO_2.[viii] This results in better mobilities for thicker EOT's. Although DSIMS analyses [fig. (8)] do not show appreciable difference between SiON vs. SiO_2, the difference in V_{fb} and N_{it} for SiON vs. SiO_2 suggests a slight increase in [N] for SiON vs. SiO_2. Fig (9) shows the FTIR results for the thinnest films for each interface. The slight shift of (+)6 cm^{-1} for HfSiON films deposited in SiON interface demonstrates that this interface have a slight higher [N] compared with the SiO_2 interface.

Charge trapping in high-k has also been identified as an important reliability issue.[ix] Pulsed Id-Vg (Fig. (9)] show negligible ΔV_{th} between the up trace and the down trace, indicating minimal transient charge trapping for both interfaces. Minimal stress-induced leakage current is observed in the films during a 22 MV/cm stress [Fig. (11)]. The slight increase in Jg at low voltages may be due to charge trapping resulting from the stress.[x] PBTI measurements for the thinnest films at constant voltage stress (electric field = 22 MV/cm) show less than 15 mV V_{th} shift after 1,000 s. stress at room temperature.

5. Conclusions

We have shown that to scale ALD HfSiON a nitrogen-containing interface might be desirable. SiON interface allows to further scale EOT without compromising device performance and reliability. The SiON/HfSiON EOT improvement is attributed to the slightly higher k of the SiON interfacial layer. It is also shown that FTIR can be a useful technique to evaluate nitrogen incorporation and oxide quality in alternate Hf-based gate dielectrics.

6. References

[i] B. H. Lee, et al. IEDM Tech. Dig., p. 859, (2004)
[ii] B. H. Lee, et al. IEDM Tech. Dig., p. 859, (2004)
[iii] M. V. Fischetti et al. J. appl. Phys. **90** 4587 (2001)
[iv] A. Kerber et al. Elec. Dev. Lett. 24 87 (2003)
[v] A. Callegari et al. IEDM Tech. Dig., p. 825, (2004)
[vi] J. Gutt et al. MRS Symp. Proc. v811 D2.4 (2004).
[vii] G. Lucovsky et al. J. Vac. Sci. Technol. A 18, 1163 (2000)
[viii] K. T. Queeney et al. J. appl. Phys. **87** 1322 (2000)
[ix] C. D. Young et al. JJAP, **44** 2437 (2005)
[x] S. A. Krishnan. p. 642 IRPS (2005)

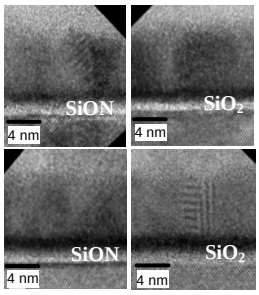

Figure 1. HRTEM results for 25 cycles (top) and 40 cycles (bottom) HfSiON films deposited on SiON (left) and SiO_2 (right) interfaces.

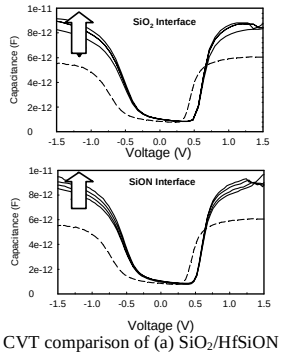

Figure 2. CVT comparison of (a) SiO_2/HfSiON and (b) SiON/HfSiON. Note the almost linear scaling of EOT with film thickness for the SiON interface.

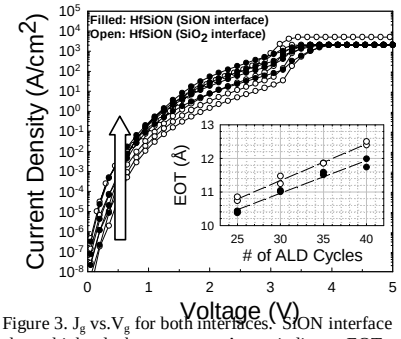

Figure 3. J_g vs.V_g for both interfaces. SiON interface shows higher leakage current. Arrow indicates EOT reduction. SiON interface (inset) yields thinner EOT, with a monotonic EOT decrease with physical thickness.

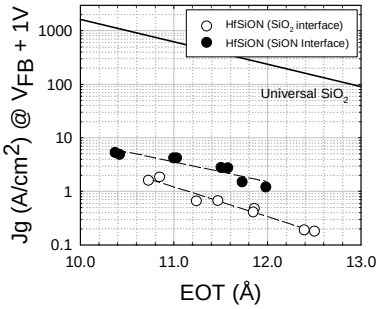

Figure 4. EOT vs. Jg for SiO_2 and SiON interfaces. SiON shows > 100x Jg reduction compared with SiO_2. Leakage for both interfaces seems to converge for EOT's < 10Å

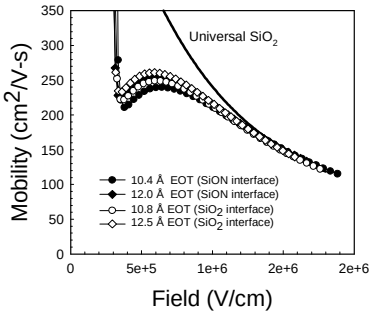

Figure 5. Electric field vs. mobility for the thickest and thinnest EOT's for both interfaces. SiON degrades peak mobility degradation; however, no noticeable difference at high fields is observed

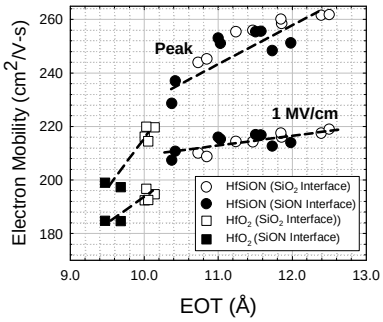

Figure 6. EOT vs. peak (top) and high field (bottom) mobility measured at 1 MV/cm. Mobility degradation is higher for peak mobilities (Note the difference in slope).

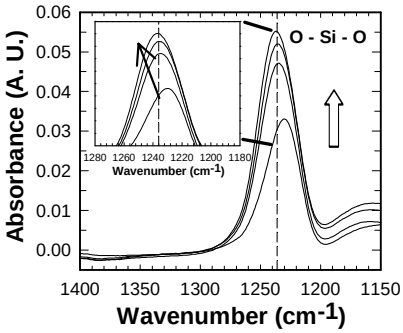

Figure 7. FTIR results for different HfSiON thickness. SiO_2 thickness and quality (insert) monotonically increases with high-k thickness. The arrow indicates increase in HfSiON thickness.

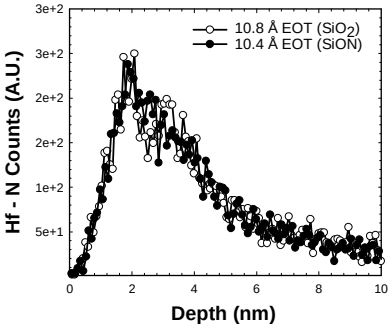

Figure 8 Dynamic Secondary Ion Mass Spectroscopy (DSIMS) results for the thinnest HfSiON deposited on both SiO_2 and SiON interfaces. No difference in N profile or concentration is observed

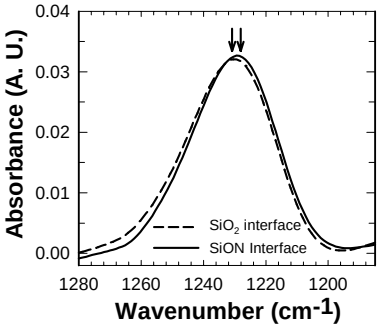

Figure 9. FTIR results for the same films analyzed by DSIMS. Arrow shows the peak position for each interface. The shift to higher wavenumbers is attributed to increased nitrogen in the SiON/HfSiON films.

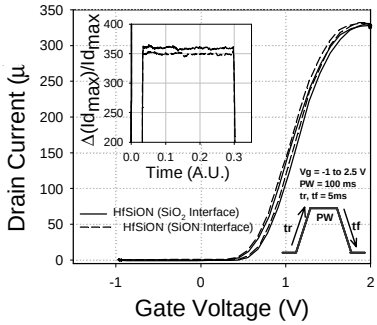

Figure 9 Id-Vg measurements using the single pulse technique. Results show insignificant ΔVth between the up trace and the down trace, indicating minimal charge trapping for both interfaces.

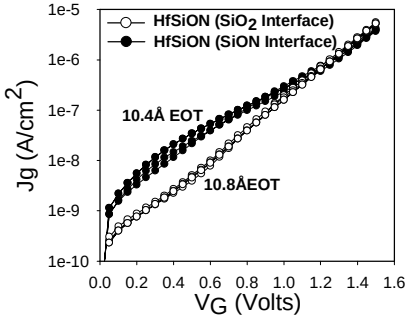

Figure 10. (a) Stress induced leakage current measurements shows some leakage increase for low voltages, indicating some charge trapping in the films.

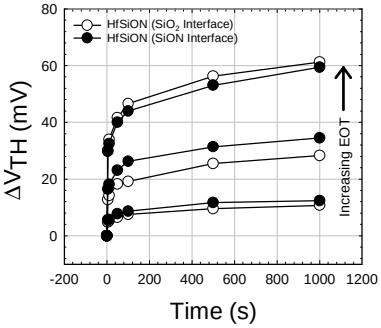

Figure 11. PBTI measurements for SiON/HfSiON and SiO_2/HfSiON at CVS of 22 MV/cm. Data show that after a 1,000 seconds stress at room temperature ΔV_{th} shifts less than 10mV (SiO_2) and 12 mV (SiON)