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Plasma Nitridation of HfO_2 Enabling a 0.9 nm EOT with High Mobility for a Gate First MOSFET

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Abstract

Plasma nitridation (N*) of HfO_2 with metal gate enables equivalent oxide thickness (EOT) scaling to 0.90 nm with 81% univ. SiO_2 mobility (1 MV/cm). N* pressure and N dose were studied to improve the dielectric interface and mobility vs. thermal nitridation. With HfO_2 and optimized metal gate, N* enables scaling and drive current enhancements.

1. Introduction

Plasma nitridation has been shown to enable HfSiON/polySi EOT scaling [1, 2]. However, N* of HfO_2 may be more challenging because Si-N bonding is not possible in HfO_2. N bonds to Hf immediately after nitridation, but after 1000°C, some N typically moves to the Si/SiO_x interface and bonds to Si [3, 4]. Excessive Si-N bonding has been shown to degrade transconductance [5] and carrier mobility [6]. In this report, we apply N* to HfO_2 with the intention of achieving a 0.9 nm EOT, good interface quality, good mobility, and enhanced drive current. Results show that N* successfully scales the EOT to 0.9 nm without a large mobility tradeoff, thereby enhancing drive current.

2. Experimental

Devices used in this study were gate-first field-effect transistors (FETs) including a 1070°C-spike source/drain anneal. Atomic layer deposition (ALD) HfSiO and HfO_2 were deposited on a SiO_2 interface. N was placed in the films with either a) thermal processes or b) plasma processes. A 10 nm metal gate electrode was deposited and then capped with 100 nm amorphous Si. EOT was extracted from measured capacitance-voltage (C-V) curves using the North Carolina State University (NCSU) CVC model. Current-voltage (I_d-V_g) characteristics were measured on 10×1μm and 10×0.1μm FETs. The Si channel doping for nFETs was ~3×10^{17} B/cm^3. Mobilities were extracted from 10×1μm devices using the NCSU mob2d model.

3. Results and Discussion

Fig. 1 shows X-ray photoelectron spectroscopy (XPS) results for N* of HfSiO and HfO_2. Fig 1(a) displays the N 1s spectra for HfSiO; Fig. 1(b) displays the N 1s spectra for HfO_2. The results show increasing amounts of N in these dielectrics and that N is likely bonded as both Hf-N and Si-N. The N profile is important for device performance [7]. Fig. 2 shows secondary ion mass spectroscopy (SIMS) N profiles using plasma pressure as the parameter. At high N* pressure, the N peak is closer to the Si substrate. Therefore, low pressure N* was implemented and yielded results shown in Fig. 3. Low pressure N* results in better peak mobility at a given EOT, consistent with the SIMS result. With an optimized N* process, thermal nitridation and N* were compared over a common N dose range. Fig. 4 shows that N* enables better mobility than thermal nitridation for a given N dose. This 3-5% improvement for N* over thermal N is consistent with previous results for HfSiON/PolySi [2]. Charge pumping results (Fig. 5) suggest that N* results in fewer interface traps than thermal nitridation. For low frequencies, such as 1000Hz, the charge pumping technique is sensitive to the Si/dielectric interface. An almost 100× improvement in trap density (N_{it}) is observed for N* at 1000Hz. This result is consistent with the SIMS N profile in Fig. 2 and mobility data in Fig. 4.

Because of promising results obtained with HfSiO, optimized N* processes were applied to HfO_2. Transistor C-V characteristics of plasma nitrided HfO_2 are shown in Fig. 6. Specific capacitance is improved in both accumulation and inversion for N*-nitrided devices. EOT improves from 1.06 nm to 0.90 nm for the N*-nitrided dielectric. Capacitance equivalent thickness in inversion (CET_{inv}) improves to 1.40 nm for the N*-nitrided sample. Flatband voltage is unchanged, suggesting the Si/dielectric interface is unperturbed by N, in agreement with SIMS. The scaling benefit of N* is illustrated in Fig. 7. Approximately 0.1 nm EOT scaling is achieved with nitrided HfO_2 at a constant leakage current relative to stacks without N*. At EOT=0.9 nm, nearly 1000× leakage current (J_g) reduction is achieved relative to SiO_2/PolySi.

Fig. 8 shows HfO_2 mobility improvement due to scaling and HfO_2+N* results on scaled HfO_2. Mobility does not significantly change with N* as EOT scales to 0.90 nm. Fig. 9 shows mobility as a function of effective field. Scaling to 0.82 nm shows peak mobility loss possibly due to coulomb scattering. Fig. 10 compares drain current-gate voltage (I_d-V_g) in the linear (V_d=0.050V) and saturation (V_d=1.2V) regimes for HfO_2 with and without N*. HfO_2 + N* scales EOT and CET_{inv} ~0.15 nm (Fig. 6), but with a small mobility penalty (Fig. 9). Despite the penalty, nFET drive current improves ~8% ($I_{d,sat}$) and ~3% ($I_{d,lin}$) due to CET_{inv} scaling from N*. pFET drive current is nearly unchanged, suggesting that the pFET may be more sensitive to N [5, 6]. Fig. 11 suggests that N* is favorable for sub-1 nm EOT with >80% mobility. Fig. 12 shows that V_{TH} stability is similar for HfO_2 with and without N*.

4. Conclusions

Plasma nitridation is a promising option to continue high-k/metal gate stack scaling below EOT=1.00 nm. Optimizing N dose and profile can improve electron mobility and N_{it} relative to thermal nitridation. Our results show that N*-treated HfO_2 scales EOT=0.90 nm with 81% univ. SiO_2 mobility (1 MV/cm). Scaling to 0.9 nm results in a small mobility loss, but ~8% nFET $I_{d,sat}$ improvement.

5. References

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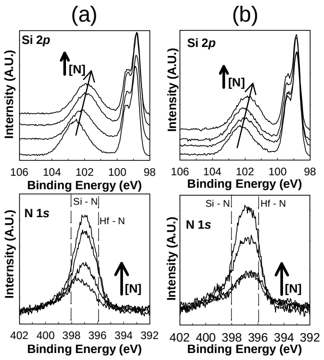

Figure 1. Si 2p & N1 XPS for N* treated (a) HfSiO and (b) HfO_2. Samples were capped with MeN/a-Si, annealed (1000°C-5s), etched before analysis. Hf-N and Si-N may exist in both (a) and (b).

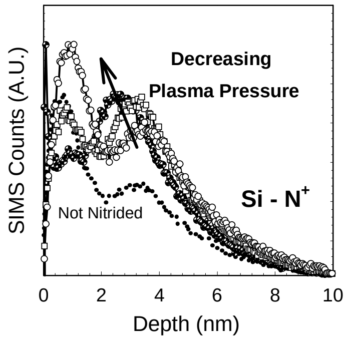

Figure 2. SIMS N profile for N* nitrided HfSiO. With decreasing pressure, the interfacial N feature moves away from the Si/dielectric interface.

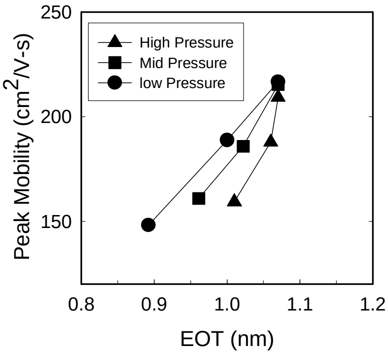

Figure 3. Electrical confirmation that lower pressure N* is desired for improved NFET mobility at a given EOT.

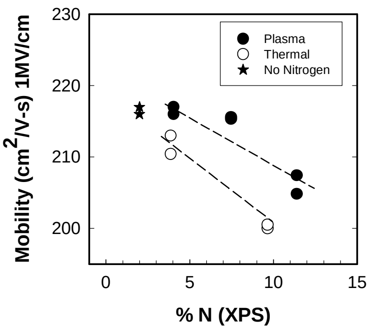

Figure 4. Comparison of thermal and N* showing that for a given N composition, a small improvement in mobility may be achieved with N*.

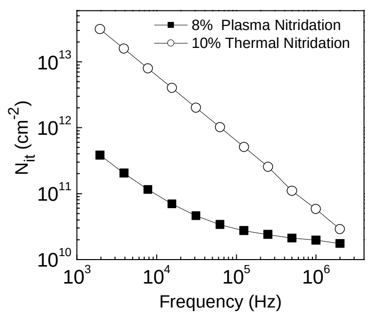

Figure 5. N_{it} as a function of frequency. Low frequency (1000 Hz) estimates N_{it} near the Si/dielectric interface. Lower N_{it} for N* suggests a better interface explaining mobility result.

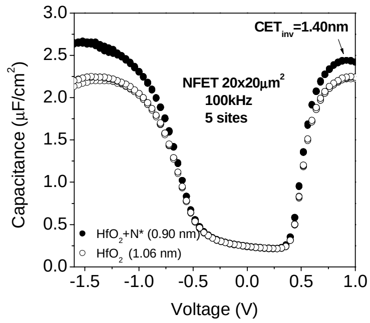

Figure 6. nFET C-V characteristics. The N* process improves accumulation and inversion capacitance without significant shift in V_{fb}.

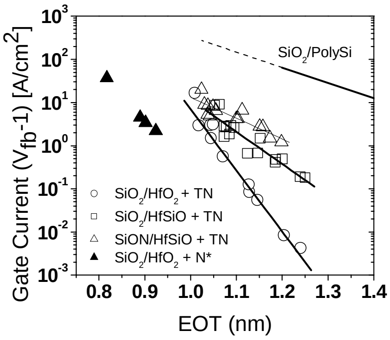

Figure 7. Scaling advantage of HfO_2 + N* relative to HfO_2 with thermal nitridation (TN). N* allows 0.1 nm of EOT scaling at constant leakage current. ~1000× reduction vs. SiO_2/PolySi.

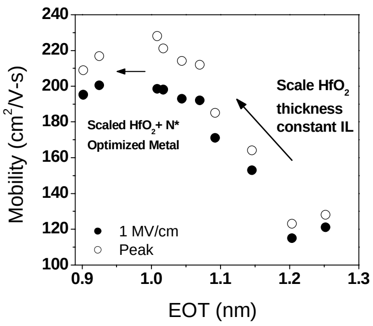

Figure 8. Scaling HfO_2 thickness can improve mobility, but N* and optimized metal gate electrode provides further advantage enabling similar mobility but at EOT=0.90nm.

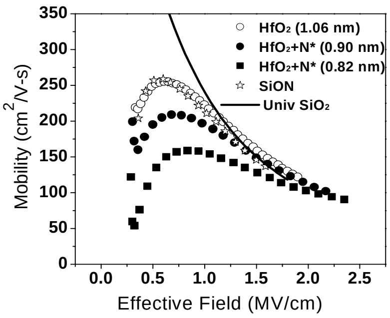

Figure 9. Mobility response to plasma nitridation. HfO_2 (1.06nm) is capable of peak and high field mobility similar to SiON, while N* scaling to 0.9 nm shows a small trade-off.

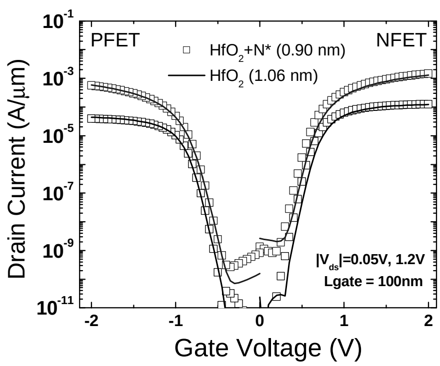

Figure 10. Id-Vg for HfO_2 (lines) and HfO_2 +N* (symbols). Scaling the EOT results in nFET Id improvement in both linear and saturation regions, despite mobility trade-off. Data from 10×0.1 um FETs.

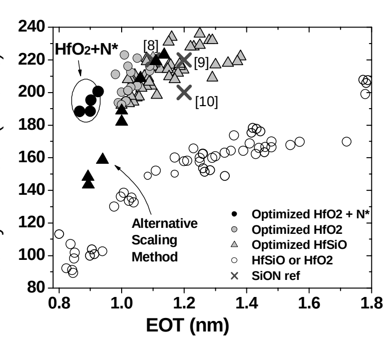

Figure 11. Mobility response to EOT scaling for multiple scaling methods. N* (black circles) moves scaling off recent trend (gray) and is superior to alternative scaling methods (black triangles).

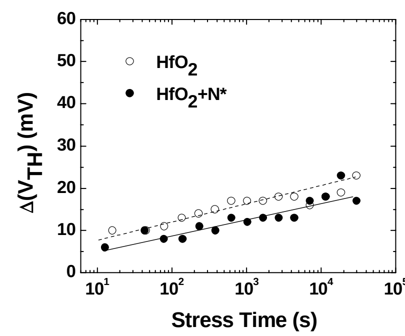

Figure 12. Constant Voltage Stress at 23°C and 1.8V. Threshold voltage (V_{TH}) stability is similar with and without N*. HfO_2 thickness is constant in both cases, possibly dominating the