Electrical and Reliability Characteristics of HfSiON Gate Dielectric

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Outline of Presentation

• High-k R&D
  ➢ Motivation
  ➢ General High-k requirements
  ➢ Why HfSiON?

• HfSiON Material Characteristics
  ➢ Amorphous structure
  ➢ Effective boron diffusion-barrier

• Device Characteristics
  ➢ MOSCAPs
  ➢ MOSFETs

• Reliability Characteristics
  ➢ Thermal stability
  ➢ Hysteresis
  ➢ BTS Stress
  ➢ TDDDB

• Additional R&D Opportunities
Nitrided SiO₂ dielectrics will have difficulties meeting gate leakage requirements for devices beyond the 70 nm node.
Key Gate-Dielectric Requirements

• Structure: Amorphous or Single Crystal Preferred

• Low-Leakage: High $E_g$, $\Delta E_{CB}$, $\Delta E_{VB}$

• High-k: Scalable EOT $[\text{EOT} = (3.9/k) t_{\text{high-k}}]\$

• Low $D_{it}$: Similar to SiO$_2$ or nitrided SiO$_2$

• Barrier to impurity/dopant diffusion

• Thermal Stability: Stable in contact with
  ➢ Si
  ➢ poly-Si, poly SiGe?
  ➢ metal gates (longer term)
Medium-k Approach

- Take advantage of SiO₂ and SiON properties and structure
- Increase dielectric constant by introducing a metal M in the SiON matrix such as Zr, Hf etc.
- Permits interface engineering using SiO₂ or SiON
- Minimizes dopant diffusion

\[
\begin{align*}
\text{SiO}_2 & \rightarrow \text{SiON (PNO)} \\
\text{SiON} + M & \rightarrow \text{MSiON}
\end{align*}
\]
**Chemistry and Physics**

SiO$_2$  

**Silicates**

Coordination  
- **Si**: 4 fold  
- **Hf**: 4 and 8 fold

Electronegativity  
- **Si**: 1.9  
- **Hf**: 1.3

M-O Bond length (Å)  
- **Si**: 1.7  
- **Hf**: 2.2

M-O Bond Strength (eV)  
- **Si**: 5.4  
- **Hf**: 8.0

* Pauling method of estimation
Hf-based Medium-k Materials

- HfO$_2$: High- $k(\sim25)$, crystalline, B- permeable
- (Hf,Si)O$_2$: Medium- $k(7-12)$, crystalline, phase separation
- HfON: High- $k$, nano-crystalline, B-blocking?
- HfSiON: Medium- $k$, amorphous, B-blocking, thermally stable
Why is Amorphous Desirable?

- Linear, isotropic and homogeneous
  - Minimal surface re-construction / roughness
  - Minimal phase change / separation

- No extended defects
  - Grain boundaries
  - Dislocations
  - Lower diffusion of dopants or metals (in the case of metal gates)

- If point defects in SiO$_2$ and SiON are deleterious---then extended defects in high-k could be disastrous
Thermal Stability of HfSiON

HfSiON is structurally stable after annealing at 1100°C for 60 s.

(Hf,Si)O$_2$ nano-crystalline

1100°C $\text{N}_2$ Anneal

HfSiON amorphous

1100°C $\text{N}_2$ Anneal

Glancing Angle XRD

As-deposited
1100 °C, N$_2$, 60 sec

HfSiO$_2$

~100 Å Thick

Normalized Intensity (arb)

10 20 30 40 50 60 70

Two Theta (deg)

Normalized Intensity (arb)

10 20 30 40 50 60 70

Two Theta (deg)
Diffusion Barrier Characteristics
### V$_{fb}$ Shifts due to Boron Penetration

<table>
<thead>
<tr>
<th>Gate Dielectric</th>
<th>EOT (Å)</th>
<th>$\Delta$V$_{fb}$ (mV) 950°C - 15 s</th>
<th>$\Delta$V$_{fb}$ (mV) 1050°C - 15 s</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO$_2$</td>
<td>16.6</td>
<td>30-40</td>
<td>Broken Down</td>
</tr>
<tr>
<td>SiON</td>
<td>~13</td>
<td>30-40</td>
<td>Broken Down</td>
</tr>
<tr>
<td>HfSiON</td>
<td>14.6</td>
<td>&lt;4</td>
<td>~130</td>
</tr>
</tbody>
</table>

**Conclusion:** For similar EOT, HfSiON is a more effective boron diffusion-barrier than either SiO$_2$ or SiON.
Device Characteristics
C-V, J-V and Scaling of HfSiON

- **Capacitance (pF)**
  - Voltage (V) range: -1.5 to 1.0
  - Values: 0, 20, 40, 60, 80, 100

- **Jg (A/cm²)**
  - Voltage (V) range: -2 to 2
  - Values: 10⁻⁶, 10⁻⁵, 10⁻⁴, 10⁻³, 10⁻², 10⁻¹, 10⁰, 10¹, 10²

- **EOT = 13.1 ± 0.2 Å**
- **Jg ~ 0.3 A/cm²** for PMOS
- **Jg ~ 0.5 A/cm²** for NMOS

- **Poly-Si Electrode**
- **5x10⁻⁵ cm²**
- **18 sites**

- **NMOS**
- **EOT = 13.1 ± 0.2 Å**
- **Jg ~ 0.5 A/cm²**

- **PMOS**
- **EOT = 13.1 ± 0.2 Å**
- **Jg ~ 0.3 A/cm²**

- **5x10⁻⁵ cm²**
- **98 sites each**
MOSFET characteristics seem to be well behaved
Subthreshold slope of ~ 90mV/dec
Electron and Hole Channel Mobility

(HfSiON as Gate Dielectric)

- Carrier Mobility is ~ 80% of Universal Curve at high field for both n and p-channels
Thermal Stability of Devices during Standard CMOS Processing
HfSiON is electrically stable even after annealing at high temperature, >1000°C, in N₂ gas for both pMOS and nMOS devices.
• High temperature annealing in N\textsubscript{2} for 15 sec has minimal impact on flat band and EOT of NMOS & PMOS HfSiON capacitors.
$V_{fb}$ shift (PMOS)

950 °C 15 sec anneal IN ADDITION TO standard dopant activation

- < 4 mV shift for HfSiON
- ~ 35 mV shift for SiO$_2$
- > 100 mV shift reported for HfO$_2$ (Onishi et al., VLSI Symp. 2001) with a 10 sec 950°C anneal
Device Stability under Electrical Stress
HfSiON shows minimal C-V hysteresis for both pMOS and nMOS capacitors.
MOSCAP Stability Under BTS

Burnin-Like Stress Conditions: 1.4V, 140°C, 1hr

- C-V is stable (negligible Vfb shift)
- J-V is stable (negligible charge trapping)
TDDB Characteristics
HfSiON films show soft breakdown characteristics.
Time-to-failure was defined as first soft-breakdown event.
TDDB for HfSiON Follows Weibull Distribution

- Observed Weibull slope $\beta \sim 1.4$
- $\beta$ for HfSiON is similar to RPNO and better than thermal SiO$_2$ (for same EOT)
TDDB Field (Voltage) Dependence

- HfSiON breakdown strength (~7 MV/cm) is lower versus SiO₂ (~15 MV/cm)
- Field (voltage) acceleration seems acceptable for burnin
Opportunities for Reliability Research

- Source of mobility degradation (~20% for both n and p-channel)
- Vtp offset with High-k gate-dielectric and poly-gate electrodes
- Metal gate-electrode research
- Extensive TDDB data and physical model needed
- Extensive NBTI and PBTI data needed for HfSiON
- Impact of BEOL (e.g., plasma damage) on HfSiON
- Low defect-density HfSiON deposition method which is suitable for high volume manufacturing
Summary and Conclusions

• HfSiON remains amorphous up to ~ 1100°C

• HfSiON tends to block boron diffusion

• Channel mobility for electron and holes is ~ 80% of the universal curve --- higher than that reported for HfO₂ and Al₂O₃ at 1 MV/cm

• The stability and scalability of HfSiON make it an attractive medium-k gate dielectric candidate

• Many opportunities for future Reliability R & D