Evaluation and Evolution of Low κ Inter-Layer Dielectric (ILD) Material and Integration Schemes

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Disclaimer

• I am neither a Chemical Engineer nor a Material Scientist
  – I am an Electrical Engineer with expertise in microfabrication process development
Outline

• Motivation and Goals
• Low $\kappa$ ILD Material Trend
• Evaluation
  – Phase 1-Materials Analyses
  – Phase 2-Unit Integration Assessment
  – Phase 3-MLM Integration
    • Line-to-Line $\kappa$ Value Extraction
• Conclusion and Summary
Motivation and Goals

- Interconnect RC delay and power consumption have become performance-limiting factors in ULSI.
  - Need high conductivity interconnect (Cu) and low dielectric constant (κ) ILD.
  - Efficient screening of new ULκ materials for successful integration
### ILD Material Trend

- The widely used ILD material for 0.13 μm and older technologies are PECVD SiO₂ and SiOF.

<table>
<thead>
<tr>
<th>Materials/Technology</th>
<th>0.13 μm or 0.09 μm</th>
<th>0.07 μm</th>
<th>0.05 μm</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Organic</strong></td>
<td>SiLₖ™, Flare™, Paralyne-F(N), αFC, PAE, etc.</td>
<td>Porous SiLₖ™, porous Flare™ OXD, etc</td>
<td>Partial Air Gap, Complete Air Gap</td>
</tr>
<tr>
<td><strong>Organosilicates</strong></td>
<td>Carbon Doped Oxide, SOG, etc.</td>
<td>Porous CVD CDO, Porous SOD CDO, etc.</td>
<td>Partial Air Gap, Complete Air Gap</td>
</tr>
<tr>
<td><strong>Range of κ</strong></td>
<td>2.8 to 3.0</td>
<td>1.9 to 2.6</td>
<td>1.0 to 1.5</td>
</tr>
</tbody>
</table>
Decreasing the Dielectric Constant

- Lowering the material density
  - Add Porosity (air) or lighter elements
  - $\kappa$ decreases due to $\kappa_{\text{air}} \approx 1$
  - Thermal-Mechanical properties degrade
  - Pore size and pore connectivity is a major integration concern

- Lowering the polarizability of bonds
  - Reduce number of Si-O bonds
  - Include Si-F or Si-C bonds in film
  - Organic materials such as Teflon.
  - Outgassing, adhesion and other TM properties degrade.
Trend for Organosilicate Films

CVD Film $k$ Value vs. Film Hardness

$k$ vs. Hardness (GPa)
## Evaluation Phases

<table>
<thead>
<tr>
<th>Phase 1</th>
<th>Material Analyses, Material failure-GRC</th>
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</table>
Phase 1 Evaluation-Material Analyses

- We propose that material/film suppliers use phase 1 evaluation methodology listed here before introducing new materials to customers.
- Understanding composition and material properties requires 3 wafers.
- Screen-out Materials with unacceptable properties.

<table>
<thead>
<tr>
<th>Wafer No.</th>
<th>Intended Analyses</th>
<th>Film Stack/Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>W1</td>
<td>$\kappa$ measurement, film stress</td>
<td>500 nm low $k$ film on low resistivity Si</td>
</tr>
<tr>
<td>W2</td>
<td>Thermal/mechanical and Material composition, Cracking thickness threshold</td>
<td>2 $\mu$m low $k$ film on Si</td>
</tr>
<tr>
<td>W3</td>
<td>Outgassing and adhesion</td>
<td>200 nm PECVD SiN on 2 $\mu$m low $k$ film on Si</td>
</tr>
</tbody>
</table>

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Compositional Analyses

- Know the film before introducing it into the fab
- Use the Best Known Method (BKM) with standards for these analyses

<table>
<thead>
<tr>
<th>Analysis</th>
<th>FTIR</th>
<th>Species concentration atomic%</th>
<th>Chemical Structure</th>
<th>Depth composition Uniformity</th>
<th>Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technique</td>
<td>FTIR Spectroscopy</td>
<td>XPS</td>
<td>ToFSIMS</td>
<td>SIMS</td>
<td>XRR, weight</td>
</tr>
<tr>
<td>Purpose</td>
<td>Chemical bonds, composition</td>
<td>Chemical composition</td>
<td>Chemical structure of composition</td>
<td>Film depth and within wafer Composition uniformity</td>
<td>K correlation for inorganic</td>
</tr>
</tbody>
</table>
# Thermal & Mechanical Analyses

- **Avoid particle contamination in the fab**

<table>
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<tr>
<th>Analysis</th>
<th>Hardness/Modulus</th>
<th>Thermal Desorption</th>
<th>Stress Hysteresis</th>
<th>Adhesion/Cohesion/ Materials Toughness</th>
<th>Surface Roughness</th>
<th>Pore Metrologyyy</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Technique</strong></td>
<td>Nanoindentation</td>
<td>Thermal Desorption Spectroscopy</td>
<td>Stress vs. temperature</td>
<td>4-pt bending, Channel Cracking</td>
<td>AFM</td>
<td>EP, PALS, SANS, SAXS</td>
</tr>
<tr>
<td><strong>Purpose</strong></td>
<td>Mechanical properties</td>
<td>Quantification of outgassing species, thermal properties</td>
<td>Thermal properties</td>
<td>Adhesion or Cohesion assessment</td>
<td>Film roughness</td>
<td>Size, Size Distribution, Connected or close pores</td>
</tr>
</tbody>
</table>
Phase 1 Analyses-The $\kappa$

- Is $\kappa$ value acceptable for the current generation of technology?
- Is there a practical roadmap to improve $\kappa$?
- $\kappa$ extendibility for the next generation
Phase 1 Analyses - Quick Turn Monitor TM

- 2 µm film cracks?
  - Film crack threshold thickness must be greater than maximum required thickness

- Film outgassing at 425 ºC for 1 hour?
  - No blisters or delamination

- Chemical composition
  - Can not contaminate the down stream process tools with heavy metals, etc.

- Center-Edge chemical composition uniformity
  - Etch and CMP process WIW uniformity depends on composition uniformity
  - WIW κ uniformity
Phase 1 Analyses-Film Cracking

- Film cracks at the maximum required thickness
Phase 1 Analyses-Outgassing

- Downstream process tool contamination
Phase 1 Analyses -SIMS and ToFSIMS Analyses

- Compositional uniformity of the films are important, WIW and WIF.
Phase 1 Analyses - FTIR Analyses

Chemical bonds peak area ratios can be used for process control and film consistency.
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Phase 2 Evaluation-Unit Module Integration Interaction

- 25 wafers with 1 µm of film needed for phase 2 evaluation
  - Low and high resistivity wafers
- CMP, Pre-Treatment, Ash, Etch process evaluation
- Analysis:
  - Etch rates, ash rates, impact to k, FTIR, SIMS, adhesion, metrology recipe development, etc.
Phase 2 Evaluation - Unit Integration Module Interaction

- CMP process impact
  - Film delamination - Wafer edge is more susceptible
  - Post CMP clean - some films are hydrophobic
Phase 2 Evaluation - Plasma impact

- Plasma exposure impacts film
  - Top layer is carbon depleted - CDO
  - Moisture absorption in the carbon-depleted layer
  - $\kappa$ increase

*Figures showing CDO film as deposited and CDO after O2 plasma.*
Phase 2 Evaluation - Plasma impact

- Carbon depletion depth is a function of process parameters and duration.

\[
y = 5.93x + 0.54
\]

\[R^2 = 1.00\]
Phase 2 Evaluation - $\kappa$ Measurement

- Accurate $\kappa$ measurement is essential for material selection
  - Mercury probe measured $\kappa$ is only a relative value. More accurate measurement is required.
  - CV dots deposited by shadow mask produces uncertain electrode area.
  - A simple subtractive metal process with multiple size square dots produces the most accurate electrode area.
  - Use of low resistivity wafer is recommended to avoid substrate damage by a plasma deposited film and to avoid substrate depletion capacitor complexity.
  - Film thickness must be measured in close vicinity of the measured dots.
    - New materials may require accurate SEM/TEM thickness measurement.
Phase 2 Evaluation - Adhesion

- Adhesion of the new materials to hardmask, etch stop, and Cu diffusion barrier must be quantified with 4-pt bend.

- Plasma, thermal or wet clean (Pretreatment) is required in most cases to improve adhesion to new materials.
  - Impact of pre-treatments on $\kappa$ must be investigated.
  - Avoidance of $\kappa$ increase or means to restore the $\kappa$ value is required.
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Phase 3 Evaluation - Plasma impact

- κ and etch profile are impacted by the ash process
- The carbon depleted layer is attacked by post ash clean
- Cu CMP process is impacted by the pattern profile
Phase 3 Evaluation - Line to Line \( \kappa \) Measurement

- All dimensions must be measured to extract the line-to-line \( \kappa \).
- Trench profile introduce difficulty in measuring \( \kappa \).
- \( \kappa_{\text{eff}} \) measurement requires the second integrated layer.
- Ultimate performance measurement is the ring oscillator \( f_{\text{max}} \).

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Line to Line Capacitance

- C_{Line to Line}
- Al, SiOF, Yang et al. 1998
- Cu, SiOF, Tyagi et al. 2000
- Cu, CDO (This Work)*

*Thompson et al. IEDM 2002
Interconnects

Low k ILD

Thin Etch Stop Layer

Transistors

CDO

Cu

Oxide

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Backend RC Delay

- Thompson et al. IEDM 2002

* Thompson et al. IEDM 2002
Reliability

- Low k materials are soft and/or brittle.
- Assembly processes must be developed to address the poor material properties.
- They are susceptible to delamination and cracking during reliability test cycles.
Conclusions

- Interconnect engineers face many challenges in evaluating and integrating new materials.

- It is important to screen out new materials and focus resources on minimum number of potential candidates.

- A methodology has been outlined to evaluate the new material efficiently and effectively.

- We have successfully integrated CVD CDO low κ ILD film in 90 nm technology.

- Use of CVD CDO low k ILD can reduce LτL capacitance >20% compared to SiOF.
Acknowledgements

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Biography for Eb Andideh

Eb Andideh received his PhD in Electrical and Computer engineering from University of Illinois at Urbana in 1990. He joined Intel Corporation Portland Technology Development as a Thin Films process development engineer in March of 1990. He has worked on numerous process development projects including ILD gap fill, CMP, selective Si/SiGe epitaxy, and low k ILD material development and integration. He is currently director of Polymer Memory Technology Development.