Fabrication and Characterization of High-k, $\text{Al}_2\text{O}_3$ and $\text{HfO}_2$ Capacitors

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Project Objective

Use atomic layer deposition (ALD) to fabricate high-k capacitors. Implement electrical testing to derive film characteristics.
Motivation

Fabrication
ALD
• High uniformity
• High-k dielectrics
• Support IC scaling

Characterization and Testing
CV test
• Device behavior validation
• Permittivity
IV test
• Dielectric strength
Atomic Layer Deposition (Al\textsubscript{2}O\textsubscript{3})

Chemical vapor deposition by ALD provides monolayer control of high-k, dielectric films

1. Unreacted surface with hydroxyl groups
2. Pump precursor trimethylaluminum; methane expelled
3. Pump precursor water; methane expelled

Fig. 1: Chemical vapor deposition of aluminum in thermal ALD
Experimental Results: ALD

To target a specific capacitance, deposition rates were validated.

Fig. 2: Deposition rates of thermal ALD alumina and hafnia

**CVD Rates of Alumina and Hafnia by ALD at 200°C**

<table>
<thead>
<tr>
<th></th>
<th>Alumina</th>
<th>Hafnia</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t_{ox}$ [nm]</td>
<td>31.8</td>
<td>34.7</td>
</tr>
<tr>
<td>Cycles</td>
<td>320</td>
<td>350</td>
</tr>
<tr>
<td>Rate [Å/s]</td>
<td>0.950</td>
<td>0.970</td>
</tr>
<tr>
<td>Refractive Index: Experimental</td>
<td>1.69</td>
<td>2.07</td>
</tr>
<tr>
<td>Refractive Index: Literature</td>
<td>1.64[1]</td>
<td>2.05-2.12[2]</td>
</tr>
</tbody>
</table>

Fig. 3: ALD dielectric film characterization

**Fig. 3: ALD dielectric film characterization**
Experimental Results: CV Characteristics I

Fig. 4: CV curves for alumina, unsintered capacitors of various area

Capacitance Curves For Alumina, Unsintered Capacitors

-4.0 -3.0 -2.0 -1.0 0.0 1.0 2.0 3.0 4.0
Capacitance [F]

Sweep Voltage [V]

2E4 um^2
1E4 um^2
7E3 um^2
2E3 um^2

1.0E-13
1.0E-11
2.0E-11
3.0E-11
4.0E-11

Capacitance

Fig. 4: CV curves for alumina, unsintered capacitors of various area
Once $C(A)$ and $t_{ox}$ are known, the relative permittivity of alumina and hafnia can be experimentally found.

\[ C(A) = \frac{\varepsilon_r \varepsilon_0 A}{t_{ox}} \, [F] \]  

$C(A)$ – Capacitance as a function of area [F]  
$A$ – Area [$m^2$]  
$\varepsilon_r$ – Relative permittivity [F/m]  
$\varepsilon_0$ – Permittivity of free space  
$t_{ox}$ – Dielectric thickness [$m$]

Fig. 5: Dielectric constants of alumina and hafnia

<table>
<thead>
<tr>
<th>Dielectric Constant</th>
<th>Alumina</th>
<th>Hafnia</th>
</tr>
</thead>
<tbody>
<tr>
<td>Literature</td>
<td>9$^3$</td>
<td>25$^3$</td>
</tr>
<tr>
<td>Experimental</td>
<td>8.36</td>
<td>24.8</td>
</tr>
</tbody>
</table>
Experimental Results: CV Characteristics III

Fig. 6: Experimentally collected data from CV curves plotted with theoretical capacitor trend

- 94% of the collected capacitance values fell between 2-9% below the theoretical capacitance
- Values in excess of 10% more than theoretical were likely subject to processing defects
Experimental Results: Accelerated Breakdown I

Fig. 7: IV breakdown curves for alumina, unsintered, square capacitor. (1) First voltage sweep where breakdown occurs. (2) Sweep of broken capacitor

\[ \varepsilon_{BD} = \frac{V_{BD}}{t_{ox}} \text{ [V/m]} \]  

- \( \varepsilon_{BD} \): Dielectric Strength [V/m]
- \( V_{BD} \): Breakdown potential [V]
- \( t_{ox} \): Dielectric thickness [m]

Fig. 8: Dielectric strength of alumina and hafnia

<table>
<thead>
<tr>
<th></th>
<th>Alumina</th>
<th>Hafnia</th>
</tr>
</thead>
<tbody>
<tr>
<td>Literature</td>
<td>0.08-0.43 \cite{4}</td>
<td>40 \cite{5}</td>
</tr>
<tr>
<td>Experimental</td>
<td>17.0-24.5</td>
<td>16.8-27.0</td>
</tr>
</tbody>
</table>
Experimental Results: Accelerated Breakdown II

The effect of sintering lowered the dielectric strength

Fig. 9: IV breakdown curves for unsintered, square, alumina capacitors

Fig. 10: IV breakdown curves for sintered, square, alumina capacitor
Experimental Results: Accelerated Breakdown III

Unsintered, square, hafnia capacitors exhibit partial conductance and two breakdowns

Fig. 11: IV breakdown curves for unsintered, circular, hafnia capacitor

Fig. 12: IV breakdown curves for unsintered, square, hafnia capacitor
Experimental Results: Accelerated Breakdown IV

Sintered hafnia capacitors displayed dead-short behavior while alumina capacitors remained capacitive.

Fig. 13: IV ‘breakdown curve’ for sintered, circular, hafnia capacitor

Fig. 14: IV breakdown curves for sintered, circular, alumina capacitor
Conclusions

- ALD was shown to be capable of depositing uniform, alumina and hafnia films repeatedly
- Refractive index, permittivity, and capacitance were consistent with theory
- Sintered hafnia capacitors were dead-shorts
- Alumina’s dielectric strength was found to be ~100x higher than reported by other studies

Future Work

- Observe effect of deposition temperature on dielectric strength
- Implement ALD into advanced CMOS process at RIT
- Scalability with high-k, gate dielectrics


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