# Fabrication and Characterization of High-k, $Al_2O_3$ and $HfO_2$ 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 ($Al_2O_3$)

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

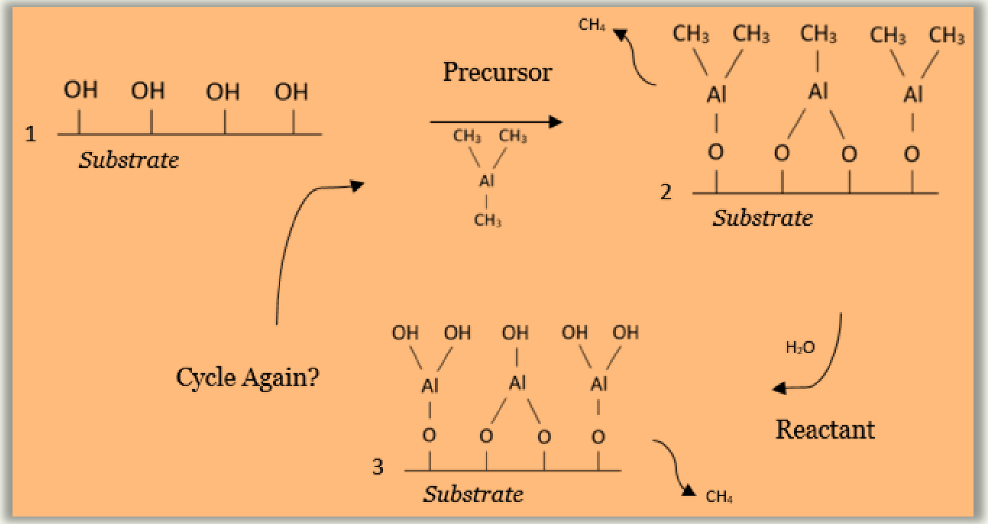


Fig. 1: Chemical vapor deposition of aluminum in thermal ALD

# Experimental Results: ALD

## To target a specific capacitance, deposition rates were validated

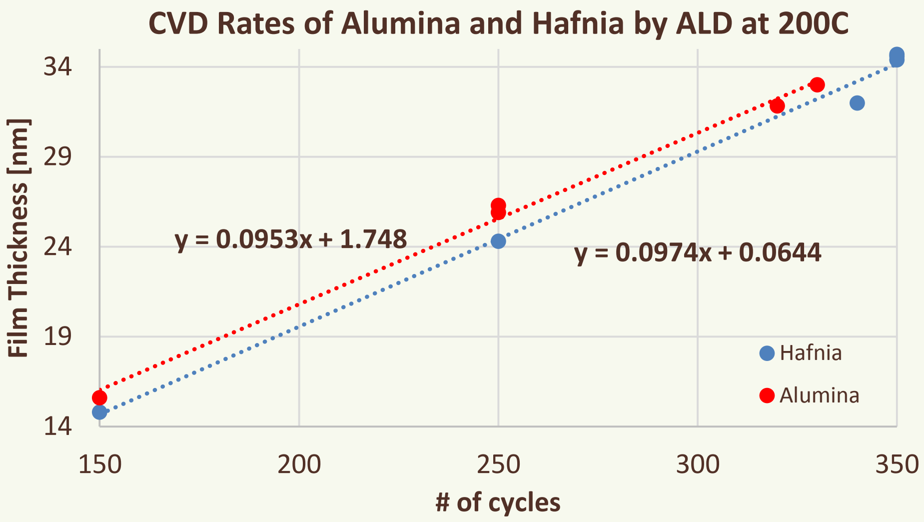


Fig. 2: Deposition rates of thermal ALD alumina and hafnia

| | | $Al_2O_3$ | $HfO_2$ |
|---|---|---|---|
| | $t_{ox}$ [nm] | 31.8 | 34.7 |
| | Cycles | 320 | 350 |
| | Rate [Å/s] | 0.950 | 0.970 |
| Refractive Index | Experimental | 1.69 | 2.07 |
| | Literature | 1.64[1] | 2.05-2.12[2] |

Fig. 3: ALD dielectric film characterization

# Experimental Results: CV Characteristics I

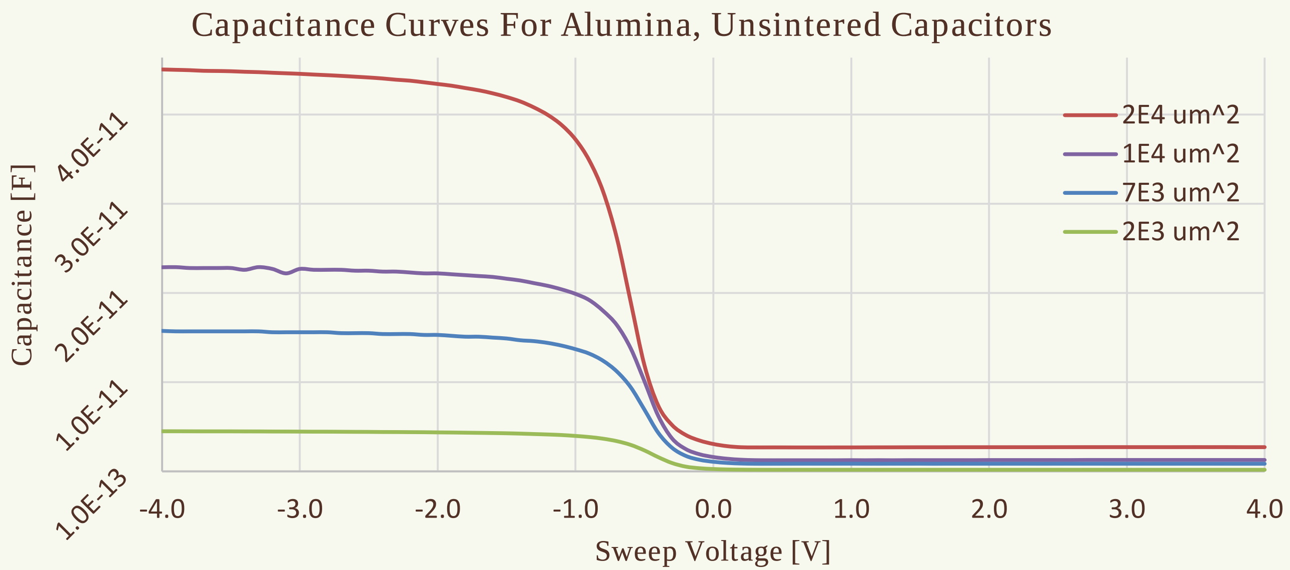


Fig. 4: CV curves for alumina, unsintered capacitors of various area

# Experimental Results: CV Characteristics II

$$C(A) = \frac{\epsilon_r \epsilon_o A}{t_{ox}} \text{ [F]} \qquad (1)$$

*C(A)* – Capacitance as a function of area [F]
*A* – Area [m²]
$\epsilon_r$ - Relative permittivity [F/m]
$\epsilon_o$ - Permittivity of free space
$t_{ox}$ - Dielectric thickness [m]

Once *C(A)* and $t_{ox}$ are known, the relative permittivity of alumina and hafnia can be experimentally found.

| | Dielectric Constant | |
|---|---|---|
| | Alumina | Hafnia |
| Literature | 9[3] | 25[3] |
| Experimental | 8.36 | 24.8 |

Fig. 5: Dielectric constants of alumina and hafnia

# Experimental Results: CV Characteristics III

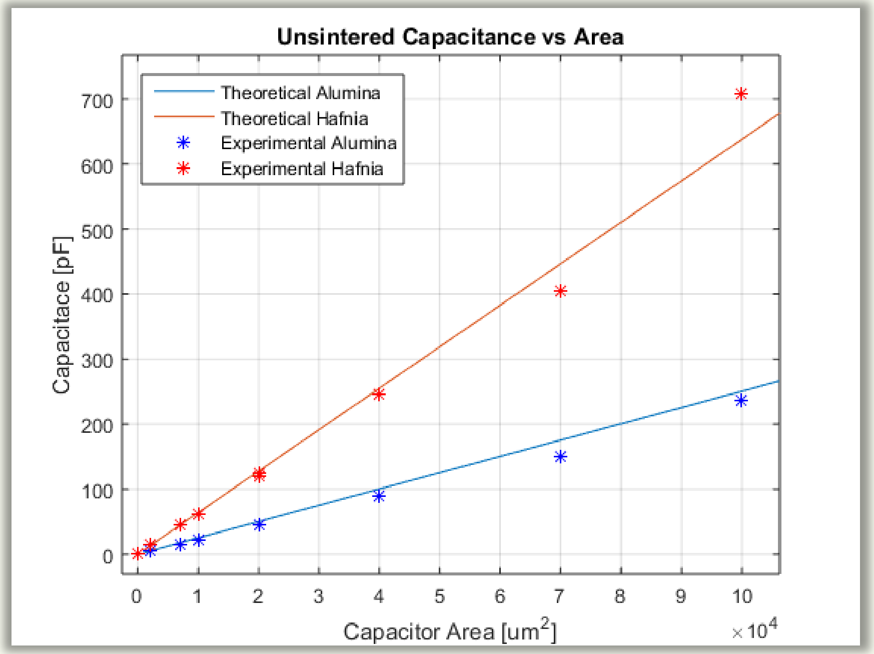


Fig. 6: Experimentally collected data from CV curves plotted with theoretical capacitor trend

- 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

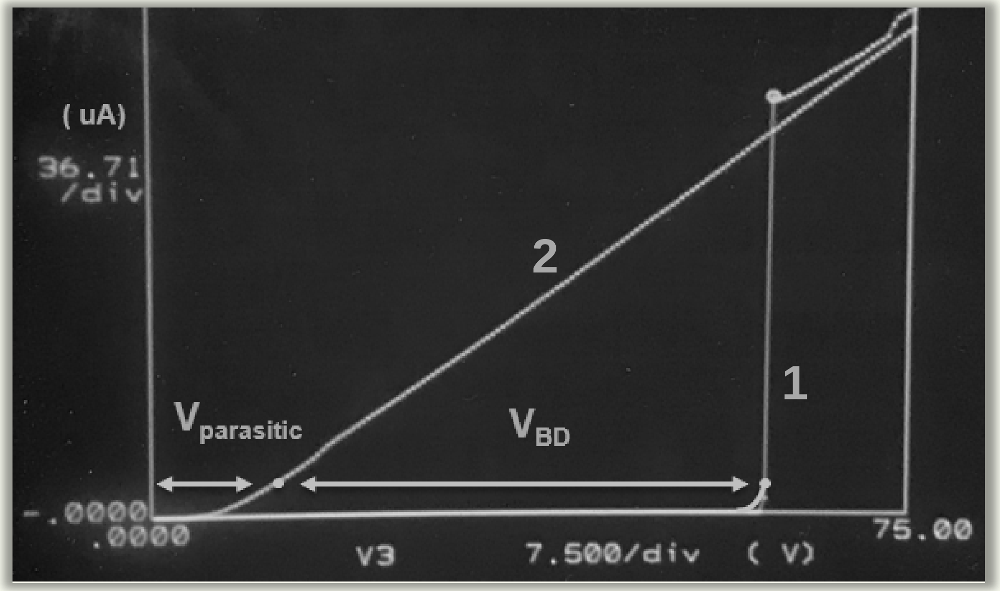


Fig. 7: IV breakdown curves for alumina, unsintered, square capacitor. (1) First voltage sweep where breakdown occurs. (2) Sweep of broken capacitor

$$\mathcal{E}_{BD} = \frac{V_{BD}}{t_{ox}} \quad [\text{V/m}] \qquad (2)$$

$\mathcal{E}_{BD}$ – Dielectric Strength [V/m]
$V_{BD}$ – Breakdown potential [V]
$t_{ox}$ – Dielectric thickness [m]

| | Dielectric Strength [MV/cm] | |
|---|---|---|
| | Alumina | Hafnia |
| Literature | 0.08-0.43[4] | 40[5] |
| Experimental | 17.0-24.5 | 16.8-27.0 |

Fig. 8: Dielectric strength of alumina and hafnia

# Experimental Results: Accelerated Breakdown II

The effect of sintering lowered the dielectric strength

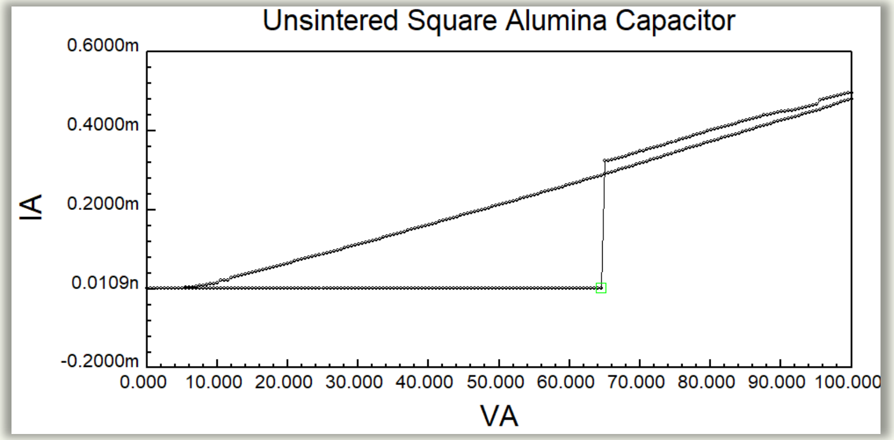


Fig. 9: IV breakdown curves for unsintered, square, alumina capacitors

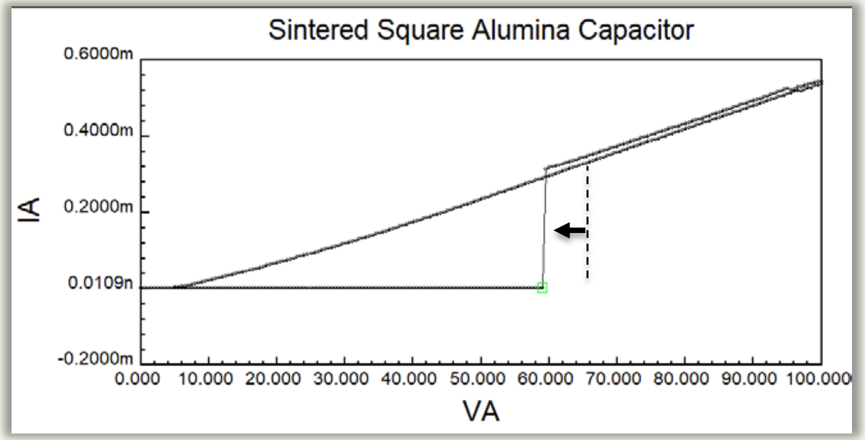


Fig. 10: IV breakdown curves for sintered, square, alumina capacitor

# Experimental Results: Accelerated Breakdown III

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

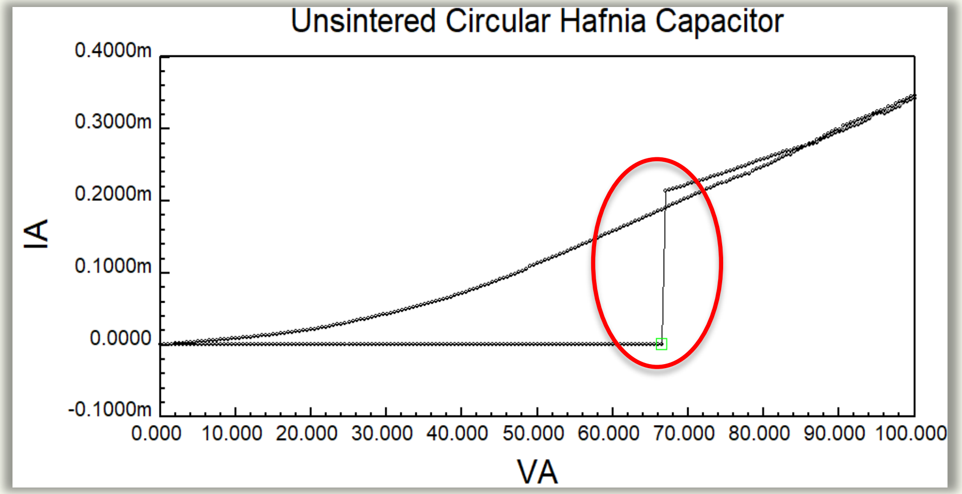


Fig. 11: IV breakdown curves for unsintered, circular, hafnia capacitor

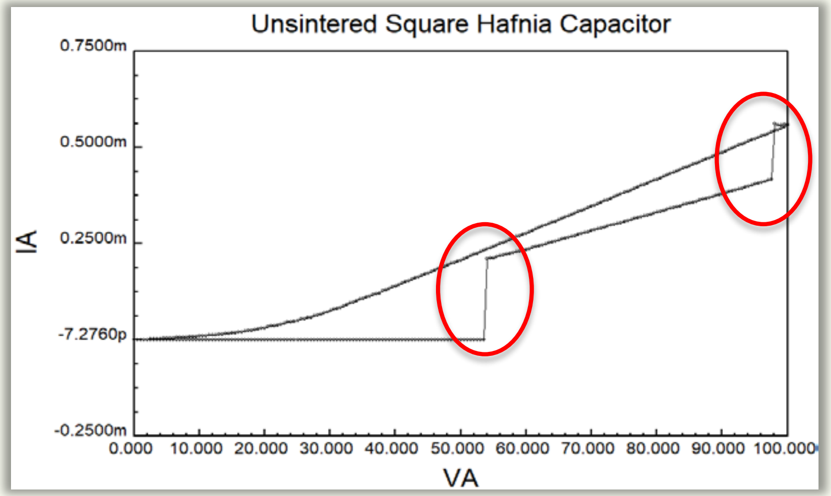


Fig. 12: IV breakdown curves for unsintered, square, hafnia capacitor

# Experimental Results: Accelerated Breakdown IV

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

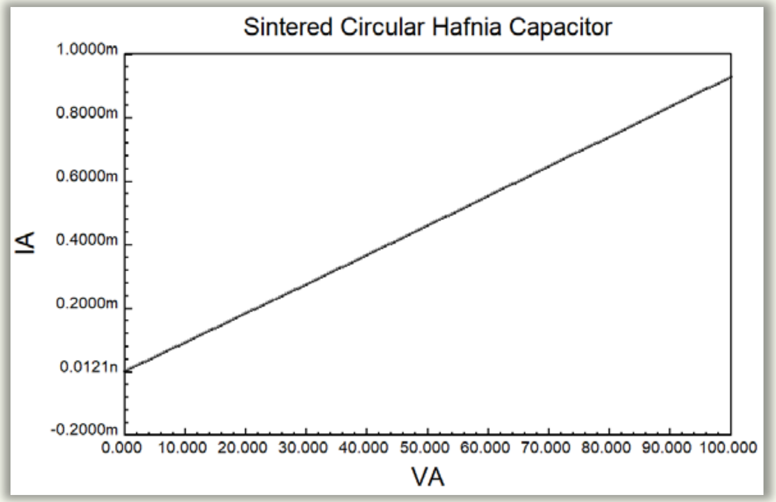


Fig. 13: IV ‘breakdown curve’ for sintered, circular, hafnia capacitor

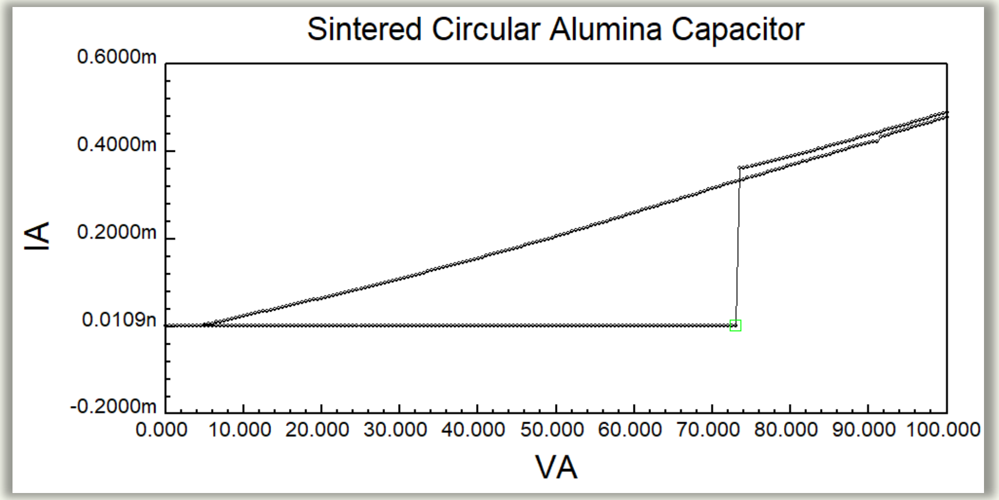


Fig. 14: IV breakdown curves for sintered, circular, alumina capacitor

# 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

# References

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# Acknowledgements


- Dr. Dale Ewbank
- Dr. Lynn Fuller
- Dr. Karl Hirschman
- Dr. Michael Jackson
- Dr. Robert Pearson
- Dr. Sean Rommel
- SMFL staff