Advanced Capacitors for Future Power Conversion Systems

Project # 1853191

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Project Introduction

- **Goal:**
  - Improve the understanding of high voltage breakdown in inorganic dielectric capacitors.
  - This project will investigate alternative materials and structures to significantly enhance the reliability of capacitors.
- **Issues:**
  - Capacitors are critical for voltage source converter functionality.
  - DC-link capacitors are known to have reliability issues.
  - High capacitance density is needed for power conversion systems used in grid storage.
- **Approach:**
  - Improve understanding of the dielectric breakdown of thin-film ALD (atomic layer deposition) Al_2O_3 capacitors.
  - Determine the impact of a thin layer of ALD Al_2O_3 between a cold sintered ceramic material and the electrode material to minimize the chemical interaction of the materials at high operating temperature.
  - Develop a time-dependent dielectric breakdown measurement system to measure 256 capacitors simultaneously at elevated temperature to provide statistically relevant data.
- **Acknowledgement:**

  - This work is supported by the DOE Energy Storage program and Dr. Imre Gyuk

Project plan

- **Proposed research**
  - Fabricate thin film Al_2O_3 capacitors using atomic layer deposition and sputtering
  - Measure dielectric breakdown as a function of capacitor size to determine extrinsic defects (5 µm to 5000 µm diameter capacitors)
  - Measure dielectric breakdown as a function of dielectric thickness to determine intrinsic defects (1 nm to 100 nm thickness)
  - Use physical characterization techniques to determine impact of electrode roughness and microstructure on the initiation of dielectric breakdown
  - Compare thin-film Al_2O_3 capacitors with ceramic capacitors with regards to breakdown characteristics
- **Deliverables**
  - Manuscript on the results of the study on Al_2O_3
  - Fabricate thin film Al_2O_3 capacitors using atomic layer deposition and sputtering
- **Milestones**
  - Determine breakdown voltage as a function of film thickness (6 months)
  - Determine breakdown voltage as a function of temperature (12 months)

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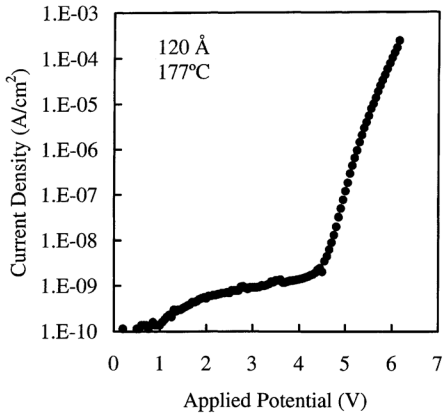
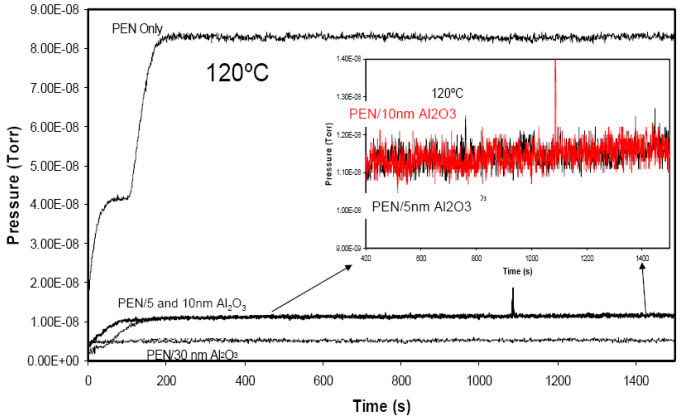
Why ALD Al_2O_3?

- ALD is intrinsically uniform and conformal
- Deposition can be done at low temperature
- Al_2O_3 is thermally and chemically stable
  - Thin film Al_2O_3 stays amorphous to >700°C[1]
  - Thin film Al_2O_3 has good barrier properties[2]
- Al_2O_3 has excellent dielectric properties[2]
  - *k*~ 8
  - Low leakage current





1) S. Jakschik et al., *Thin Solid Films* **425**, 216 (2003).
2) G. L. Graff, R.E. Williford and P.E. Burrows, *Journal of Applied Physics*, 96, No.4, (2004),p 1840-1848
3) M.D. Groner et al., *Thin Solid Films* **413**, 186 (2002).

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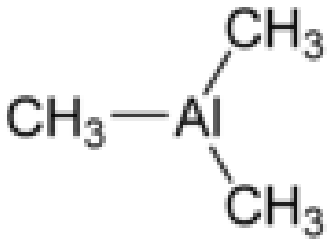
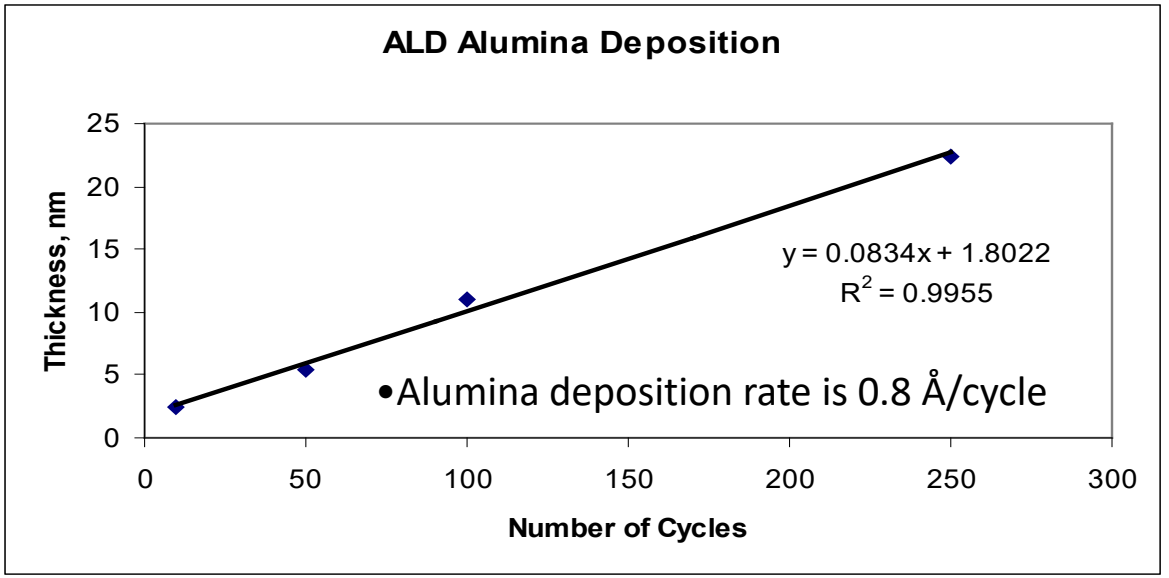
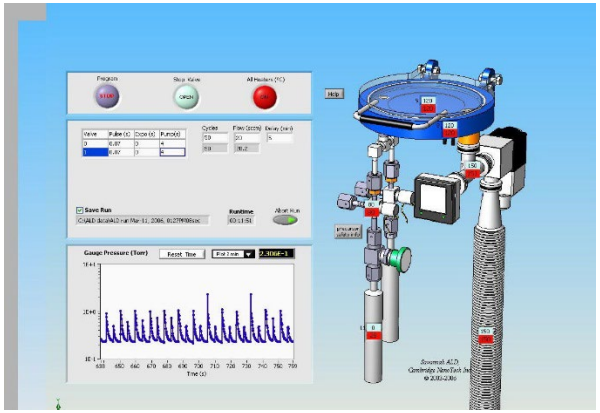
Al_2O_3 deposition



- Trimethyl aluminum precursor
- Vapor pressure of 30 Torr at room temperature



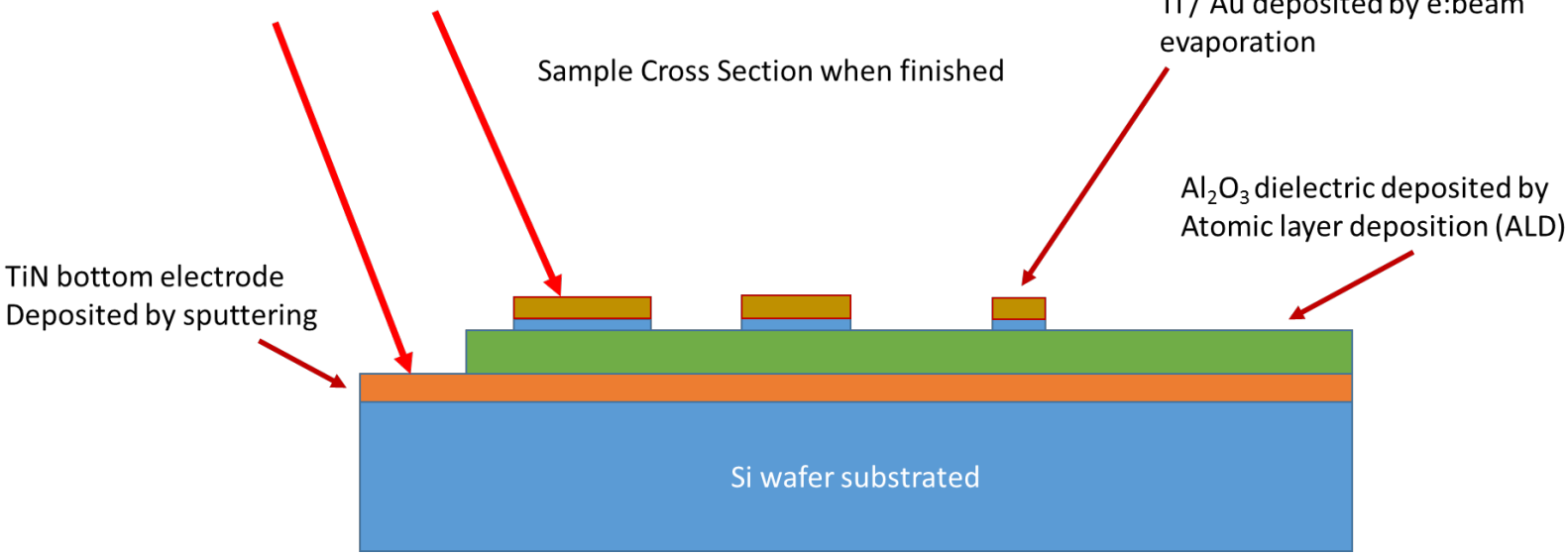


Ultratech / Cambridge Savannah 100 ALD tool

Deposition Conditions:

- Substrate Temperature: 250°C
- 0.2s TMA pulse, 4s exposure, 10s purge
- 0.2s H_2O pulse, 4s exposure, 10s purge

Capacitor Fabrication Process



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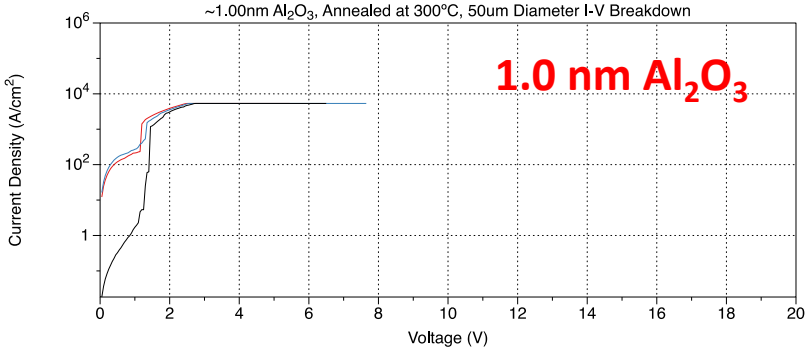
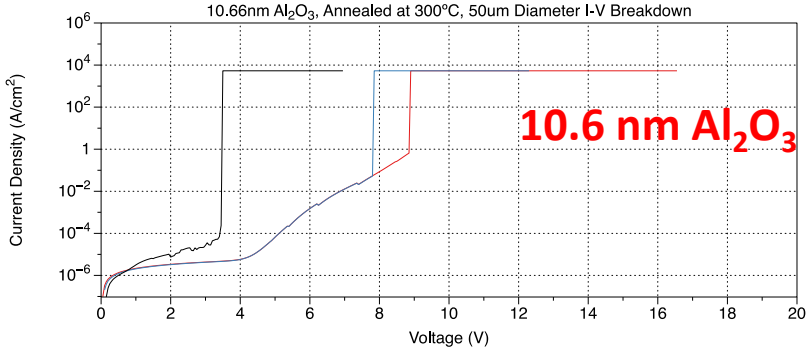
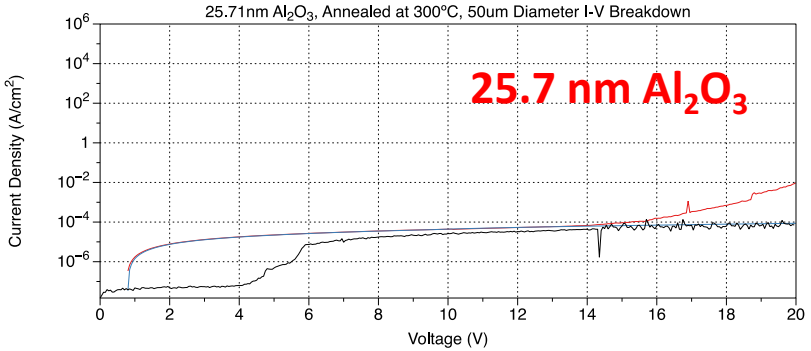
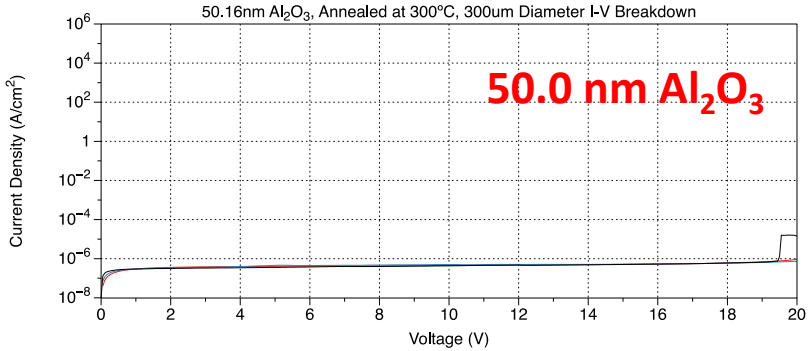
Effect of thickness of Al_2O_3 on Leakage Current and Breakdown Voltage









Al_2O_3 films between 10 and 25 nm thick provide low enough leakage current

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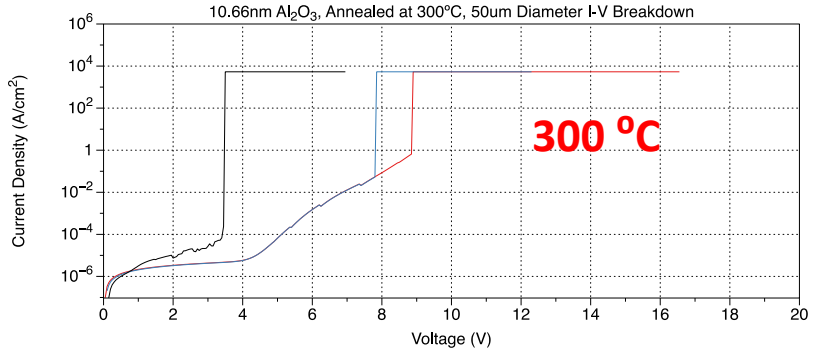
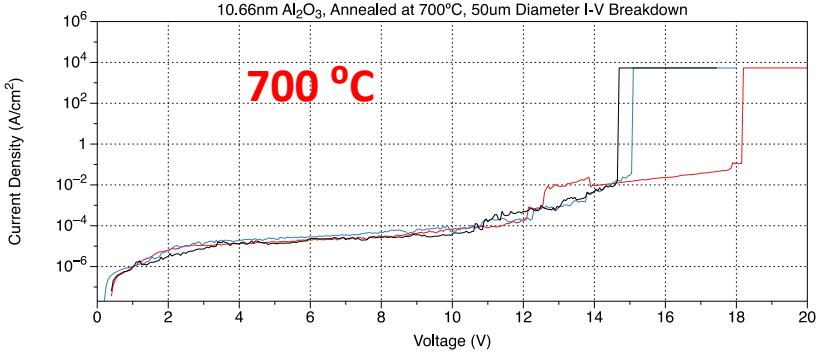
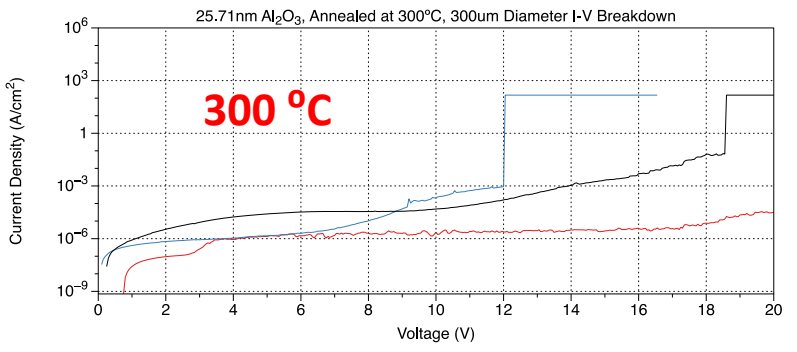
Impact of annealing temperature on leakage current / breakdown voltage

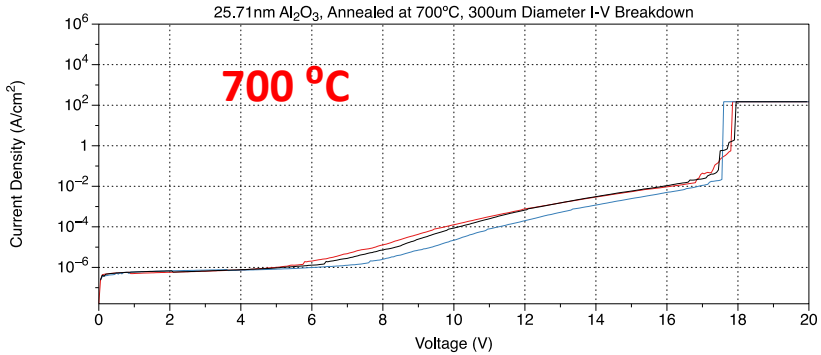
10.6 nm Al_2O_3





25.7 nm Al_2O_3





Annealing at >300 °C improves leakage current and breakdown distribution

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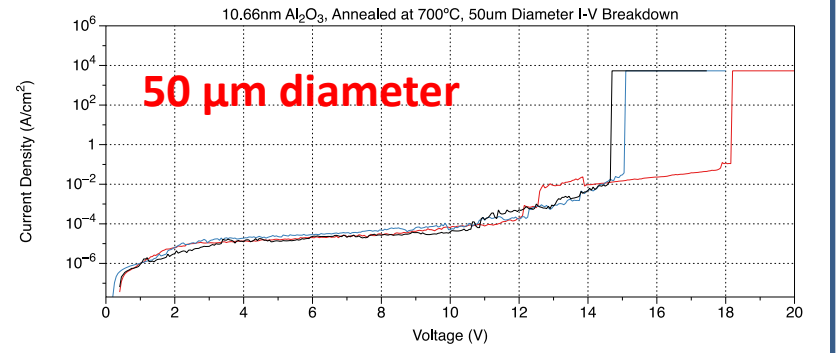
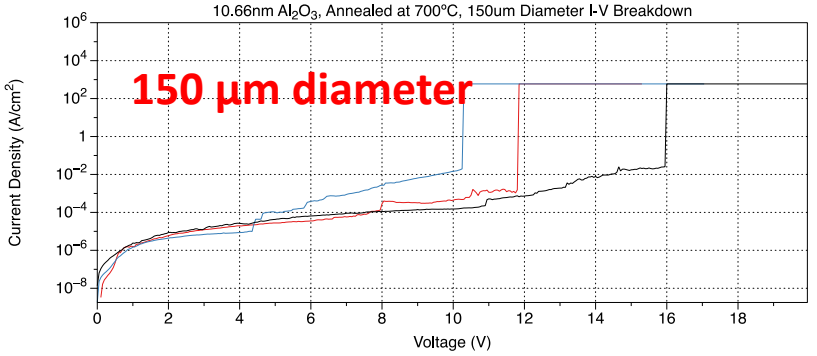
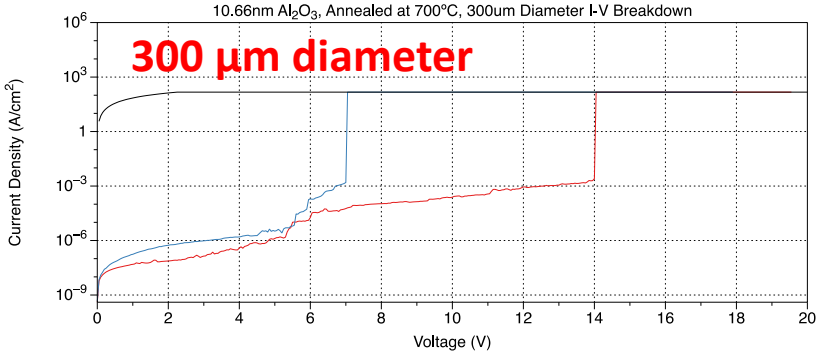
Defect Density for Al_2O_3 films < 1 / 10^4 µm² for 25.7 nm thickness

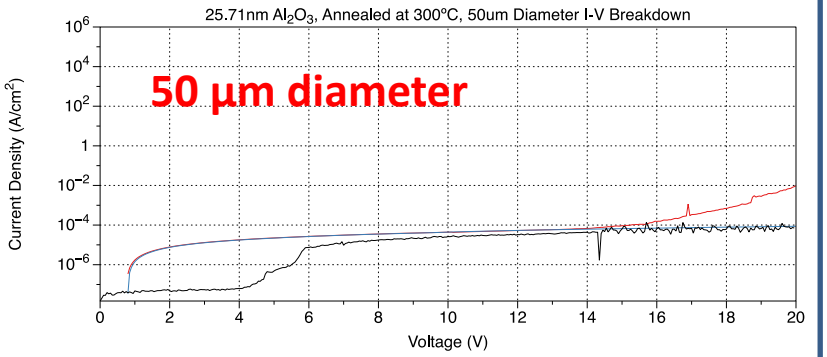
10.7 nm

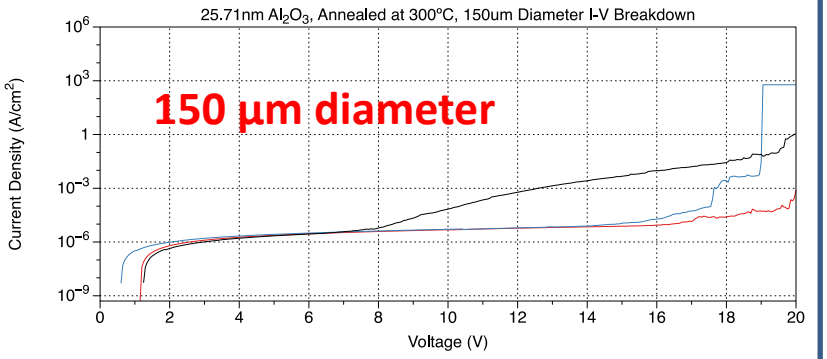


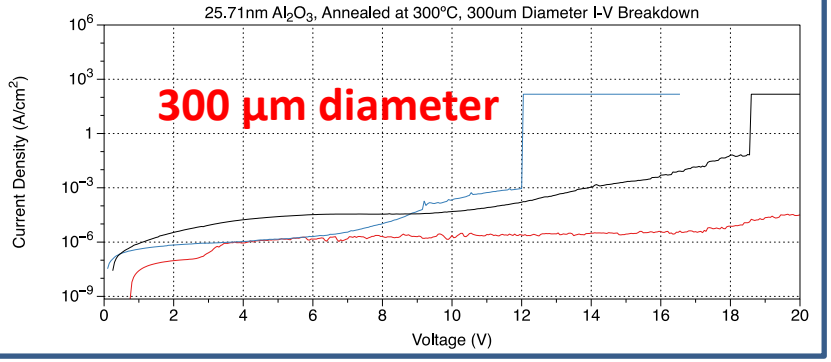




25.7 nm







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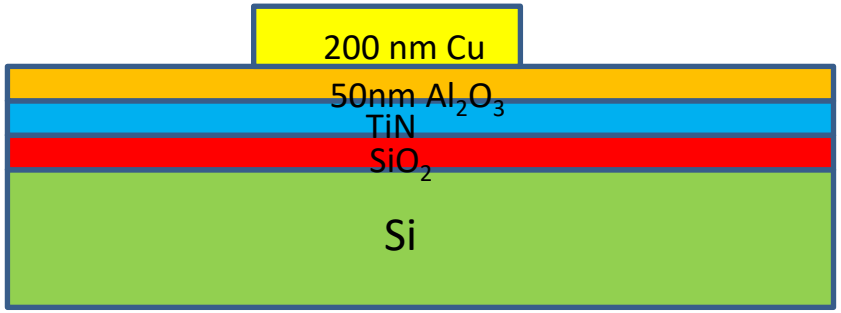
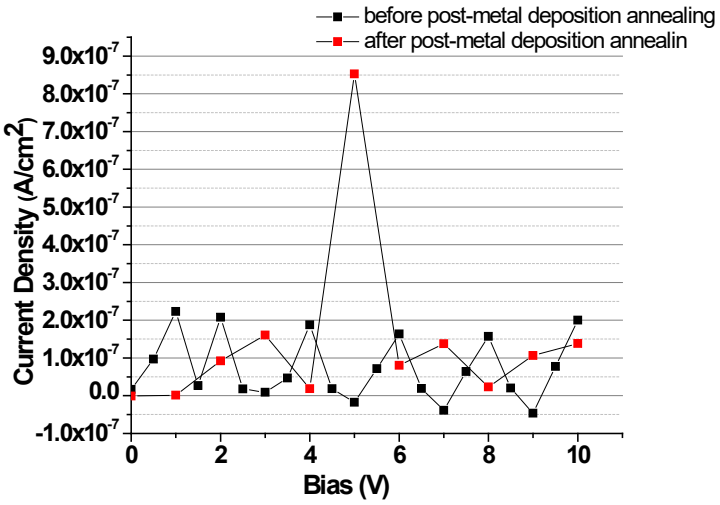
Barrier Properties of thin film ALD Al_2O_3

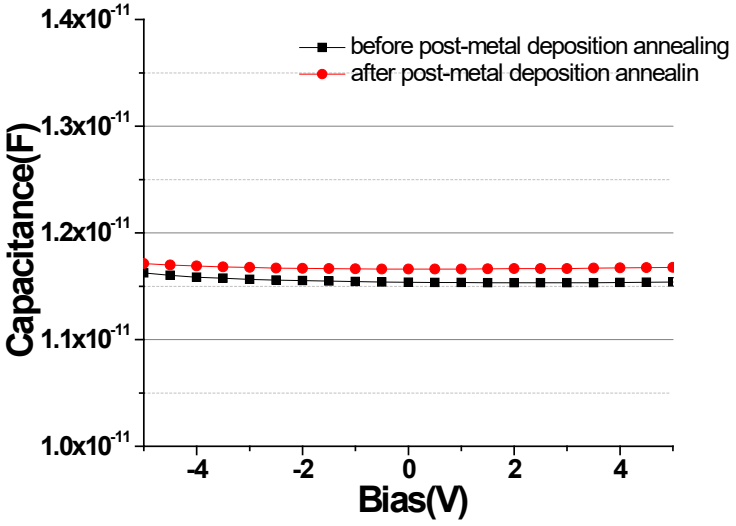


- 200°C for 30 min. on 50 nm Al_2O_3
- Next experiments
  - Thinner films (10 – 25 nm)
  - Higher temperatures (300°C - 400°C)
  - Longer times

No change in leakage current



No change in capacitance



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Temperature controlled time dependent dielectric breakdown system

Operating characteristics

- National Instruments / Labview control
- 250 capacitor capacity
- Up to 600V breakdown measurement
- Up to 200°C measurement temperature

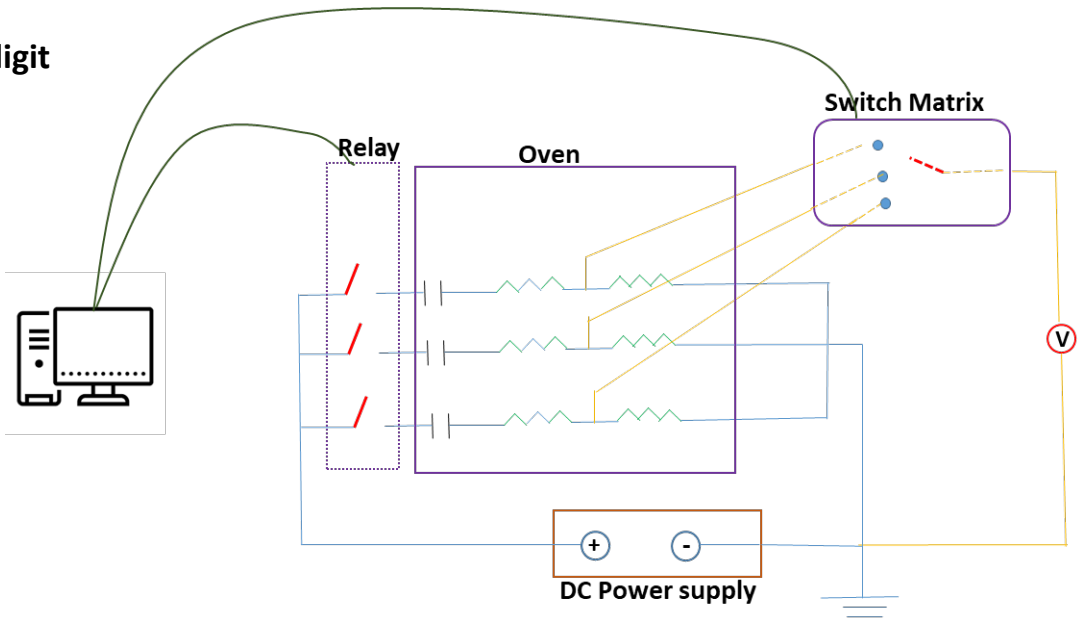
Relay: National Instruments PXI-2567 64-Channel Relay x4

Oven: Despatch Industrial Oven, Model LAC1-38, Max. Temp 260°C

Switch Matrix: National Instruments NITB-2633 4x64 Matrix Terminal Block

DC Power supply: National Instruments RMX-4217, 0-650V / 7A 1500W

DMM: National Insrtuments PXI-4065 6½ digit



Summary

- ALD Al_2O_3 process demonstrated
- 10 nm – 25 nm thick films provide good breakdown and leakage current characteristics
- Initial diffusion barrier results look encouraging

Upcoming work - 2019

- Determine diffusion coefficient of copper in thin-film Al_2O_3 at 175^oC
- Determine the impact of thin-film Al_2O_3 deposited on $BaTiO_3$ on the electrical characteristics of thick film $BaTiO_3$ capacitors

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Thank you!