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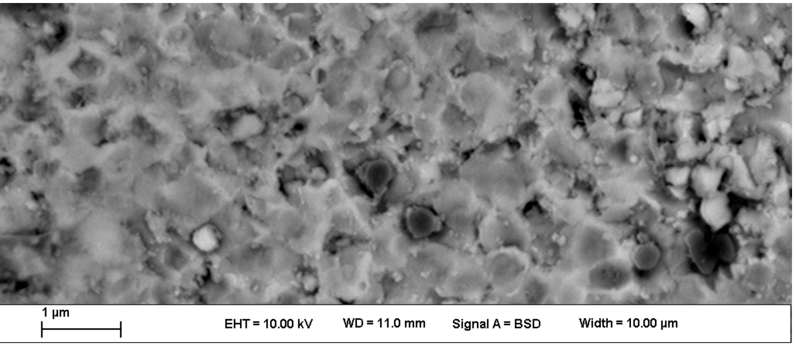

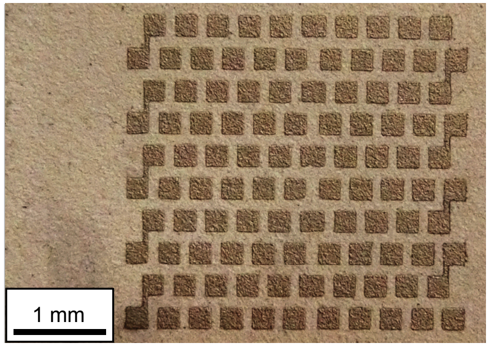

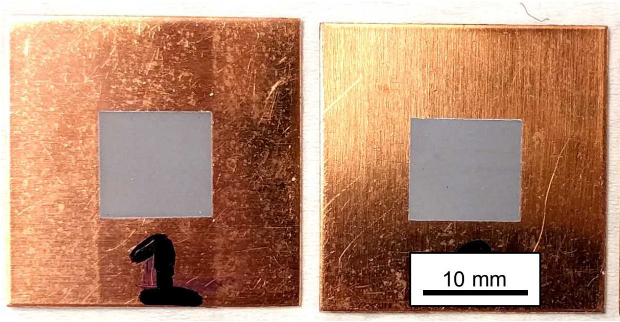

Aerosol Deposition as a Method of Room Temperature Thick-Film Deposition

Jesse Adamczyk, Pylin Sarobol, Andrew Vackel, Tom Holmes, Paul Fuierer

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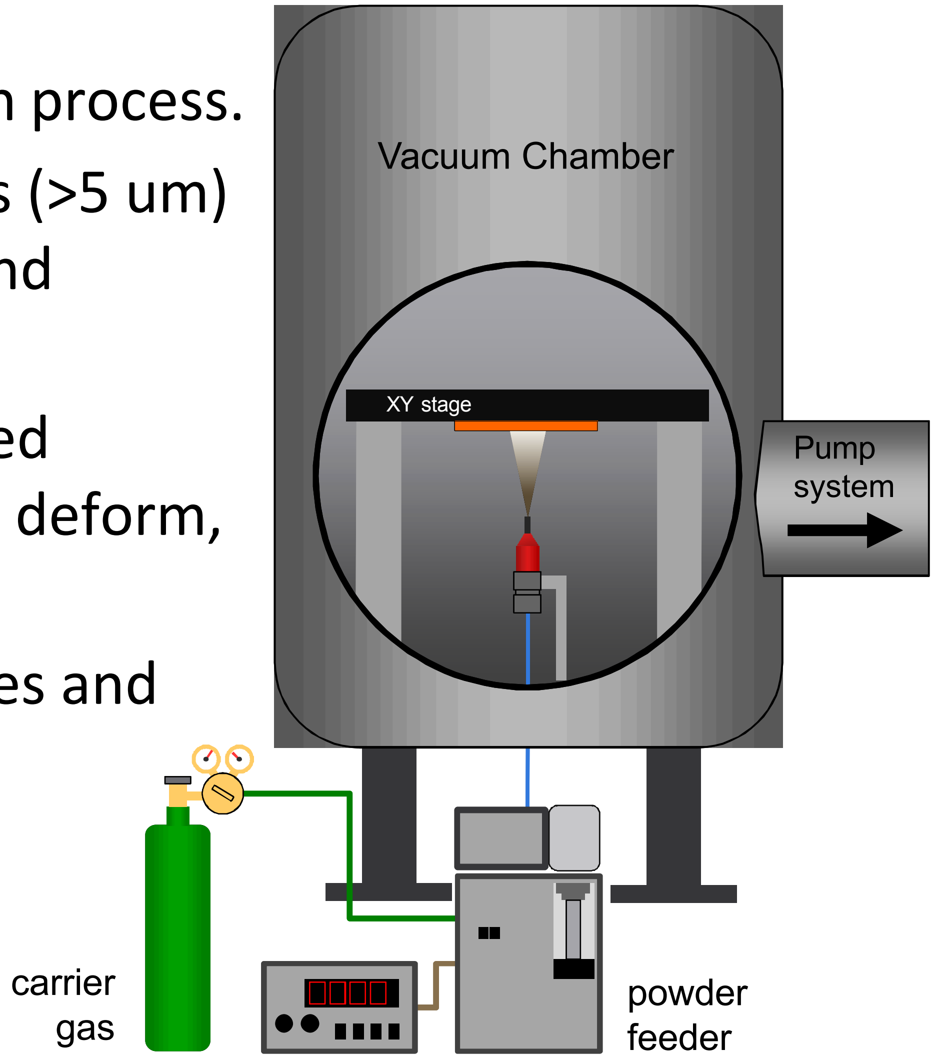
Aerosol Deposition (AD) Process

- Room temperature deposition process.
- Deposits thick and dense films (>5 um) of metal, ceramic, polymer, and composites.
- Utilizes micron-submicron sized powders to impact, plastically deform, and bond to the substrate.
- Vacuum environment increases and maintains particle velocity.



Aerosol Deposition (AD) Process

- Deposition methods

Characteristics of various deposition processes

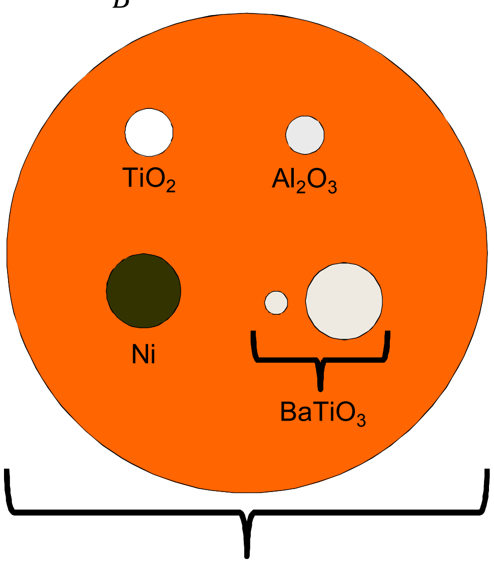
Process Parameters	PVD [1]	Aerosol Deposition	Thermal Spray
Temperature	>500 °C	20 °C	>1000 °C
Pressure	<10^{-2} torr	<10 torr	760 torr (1 atm)
Max Film Thickness	1 µm	100 µm	1 mm
Feedstock	Granule	Micropowder	Powder
Substrate prep	Clean/smooth	None	Grit blasting
Transport phase	Vapor	Solid	Solid/Liquid
Particle Size	Molecular	<5 um	40 um
Deposition rate	µm/hr	µm/min	µm/s
Gas consumption	none	10 SLPM	50 SLPM

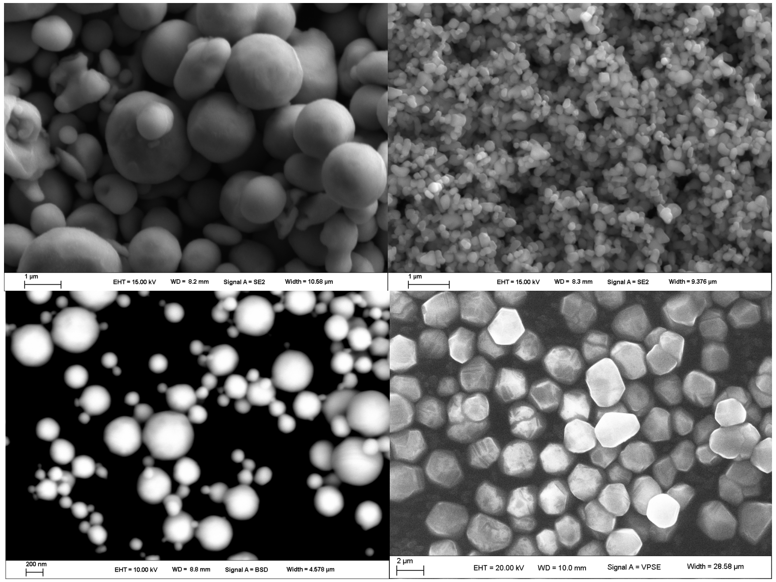
AD Powders Characteristics

- Utilizes micron to submicron powders
- Not intuitive whether a powder will deposit well
  - Agglomeration
  - Compressibility index [2]

$$CI = 100 \cdot \frac{V_B - VT}{V_B}$$

Relative particle sizes of AD powders



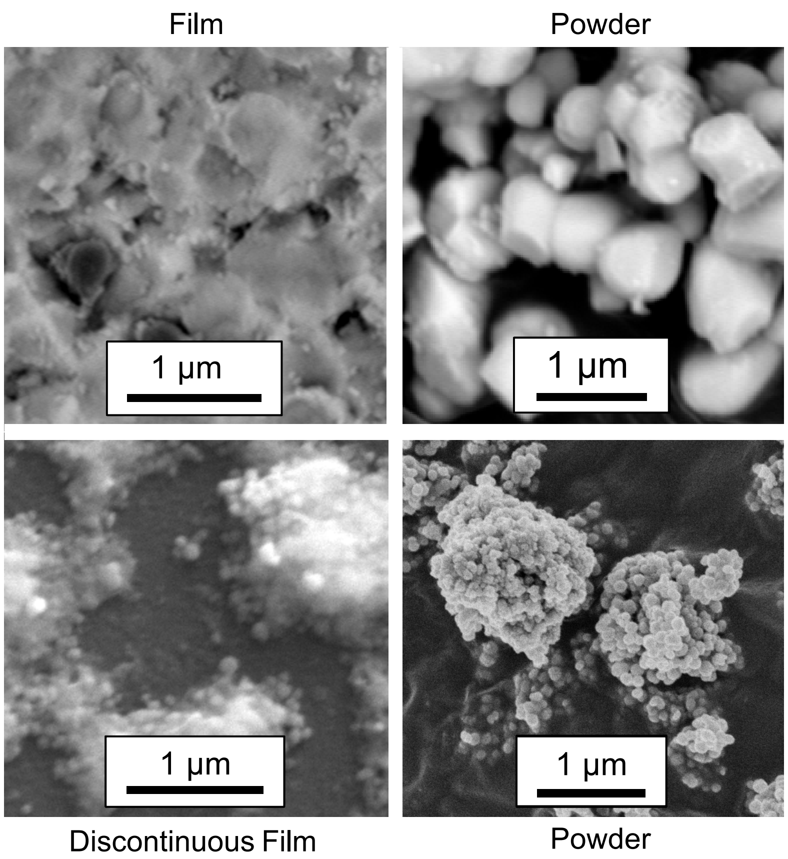


SEM images of aerosol deposited powders

AD Powders

- Larger Particles (>400 nm)
  - Show evidence of plastic deformation in the form of “pancake” structure.
  - Can damage the substrate if highly agglomerated.
- Small particles (<200 nm)
  - Adhere to the substrate poorly
  - Retain their initial structure

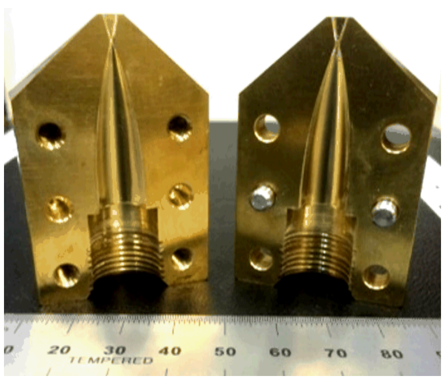
Submicron $BaTiO_3$



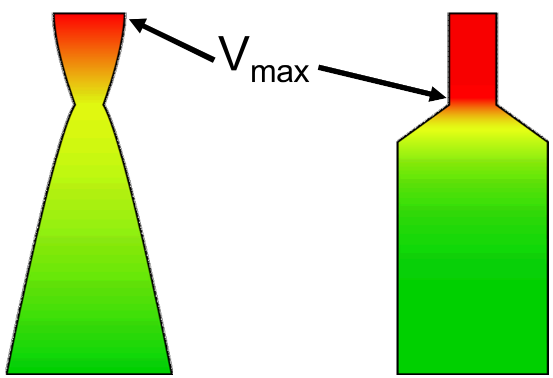
120 nm $BaTiO_3$

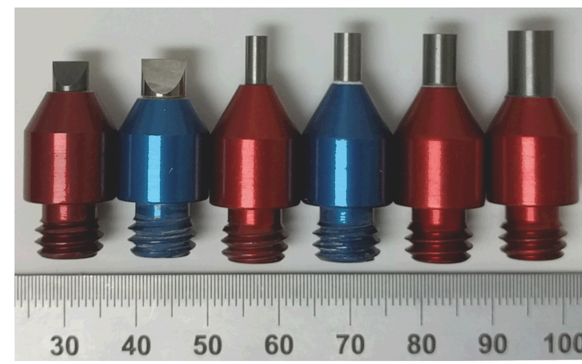
Velocity of Gas & Particles

- Different Nozzles
  - Choked flow
  - Gas expansion
- "Critical velocity"
- Particle size and density



Converging-Diverging
De Laval Nozzle





Different cross sections of converging tungsten carbide nozzles (mm)

Kinetic Theory of Gases

- Approximations of drag on particles
- Neglect change in gas viscosity
- Molecular weight of gas

Drag force	$F_D = 3\pi\eta v d_p$
Slip corrected drag force equation for particles <1 μm	$F_D = \frac{3\pi\eta v d_p}{C_c}$
Cunningham (Slip) Correction factor	$C_c = 1 + \frac{2.5\lambda}{d_p}$
Mean free path of a gas	$\lambda = \frac{1}{\sqrt{2}\pi n (d_m)^2}$

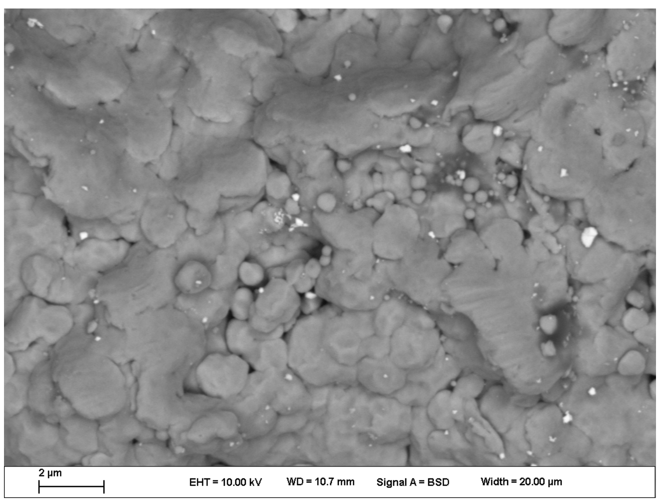
Equations for approximating effects of gases on particles [3]

	760 torr	10 torr
F_D	$2.03 \cdot 10^{-8}$ N	$4.05 \cdot 10^{-9}$ N
λ	61 nm	4.65 μm

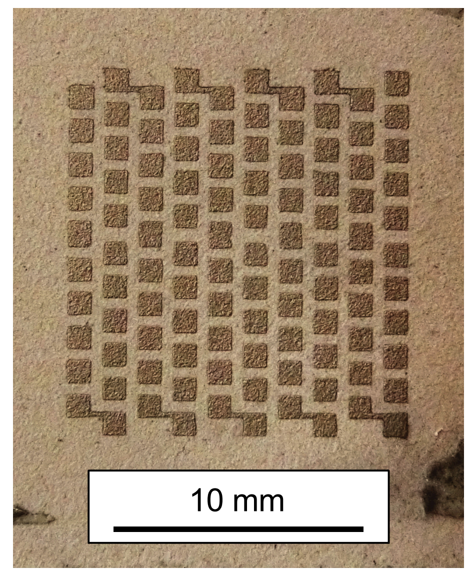
Parameters for a 1 um particle at 300 m/s

Metallic Electrical Interconnects

- Easy to deposit metals
  - High plasticity of particles
  - Films over 100 um
- Patterned by direct applied masks



SEM image of Copper deposited by AD



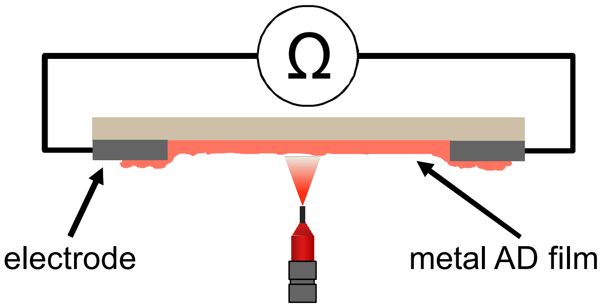
Patterned Nickel interconnects deposited through a mask

Metallic Electrical Interconnects

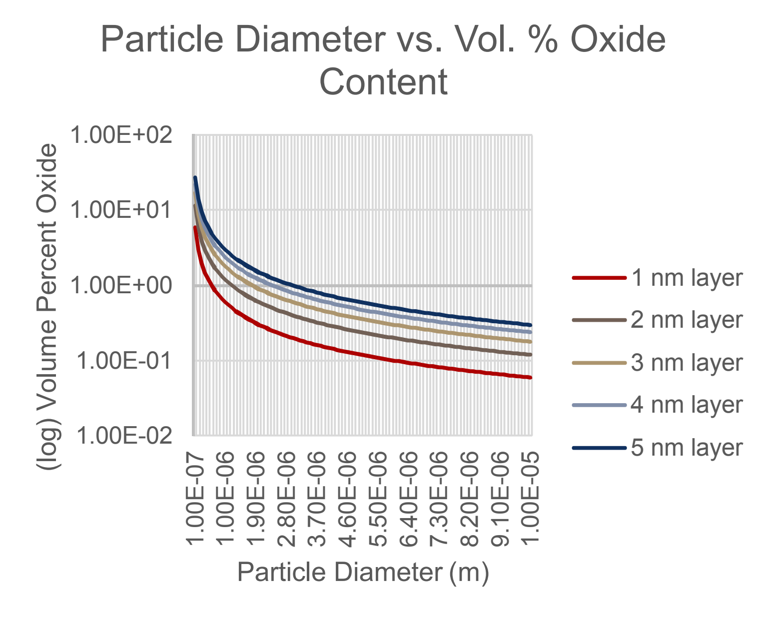
- Oxide content approximation (EDX images of Cu/Ni)
- Resistivity approximations
  - Nordheim's equation (mixing rule)
  - Grain boundary scattering

$$\rho_{eff} = \rho_c \frac{1 + \frac{1}{2}\chi_d}{1 - \chi_d}$$

- Resistivity measurements
  - Four point probe method
  - In-situ measurement

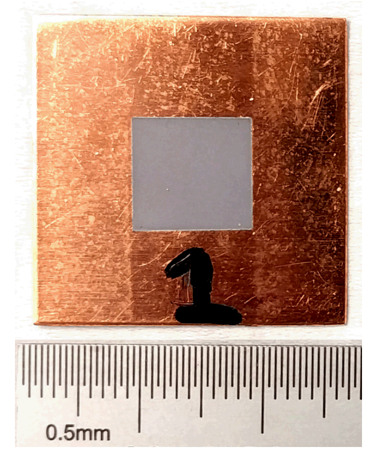


Apparatus for In-Situ resistivity Measurements

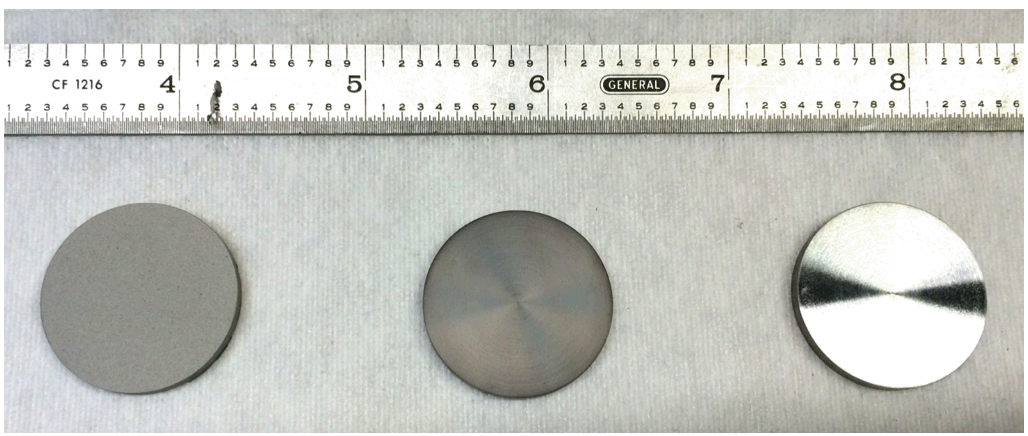


Thermal & Electrical Barriers

- Limits thermal damage
  - Maintain room temperature phases
  - Phonon scattering on grain boundaries
- Prevent conduction between surfaces
- Allow high temperature circuitry



Insulating ceramic layer deposited on copper

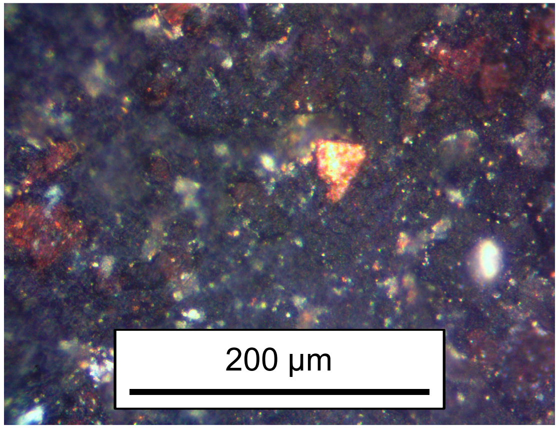


Thermal Spray YSZ

Aerosol Deposited TiO_2

Uncoated

Hiperco Substrates



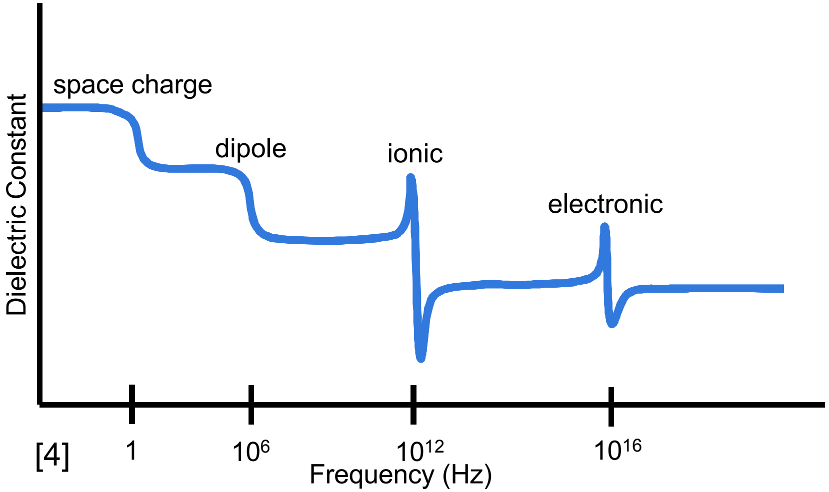
Pinholes through insulating ceramic layers

Dielectric Materials

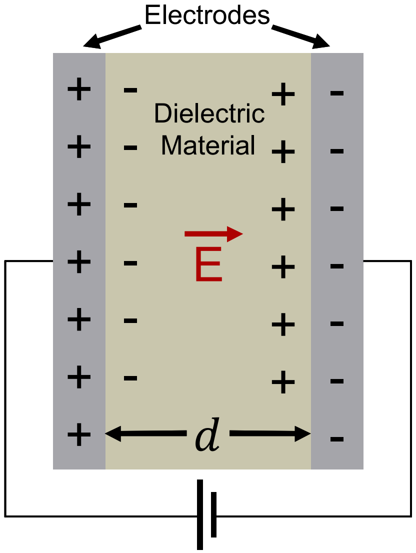
- Dielectric Constant
- Barium Titanate
  - Ferroelectric property
- Polarization mechanisms
  - Frequency dependence
  - Dependence on grain size

$$C = \frac{\varepsilon_0 k A}{d}$$

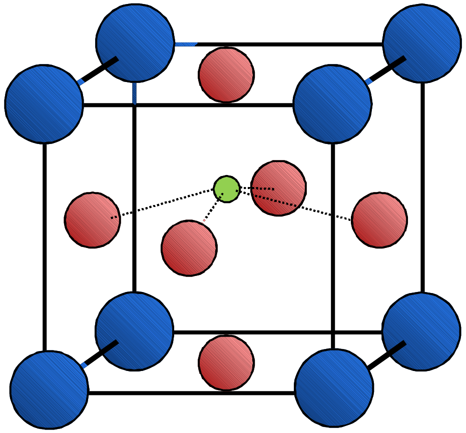
Capacitance equation



[4]



Simple Capacitor



Ferroelectric Phase Perovskite Structure ($BaTiO_3$)

Multilayered Ceramic Capacitors

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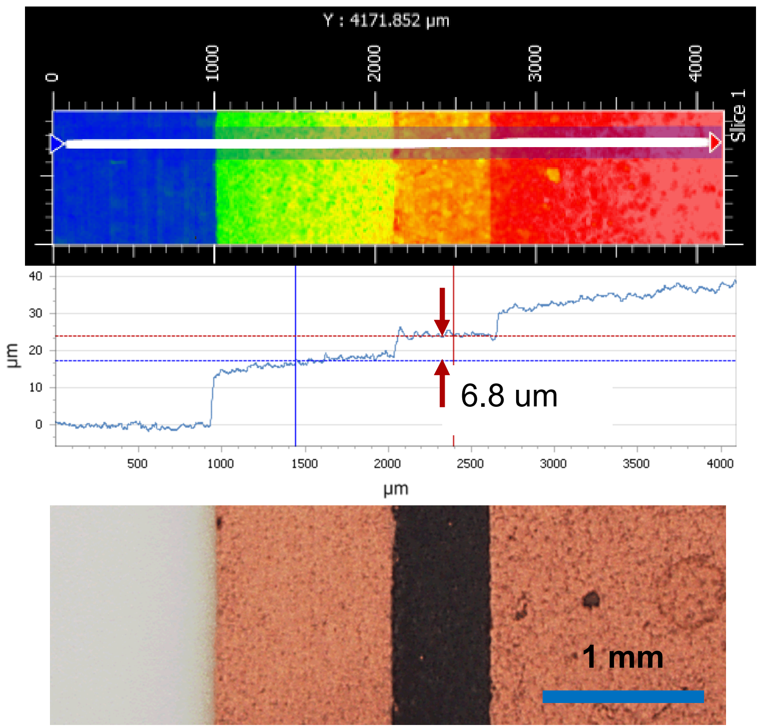
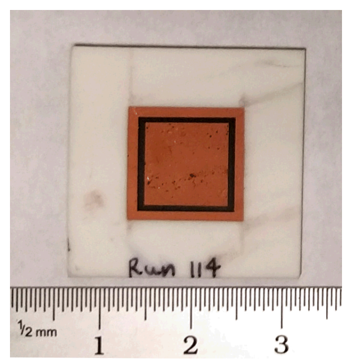
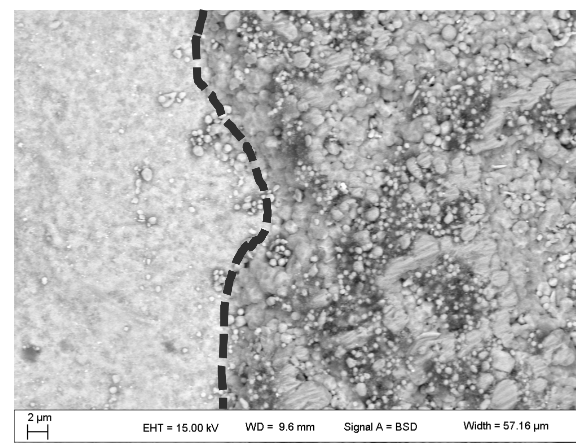
- Combines electrical interconnects and insulating barriers
- Directly applied electronic components



Cu-BaTiO$_3$-Cu Capacitor



- Increase grain size
  - Flash lamp annealing
  - Laser annealing



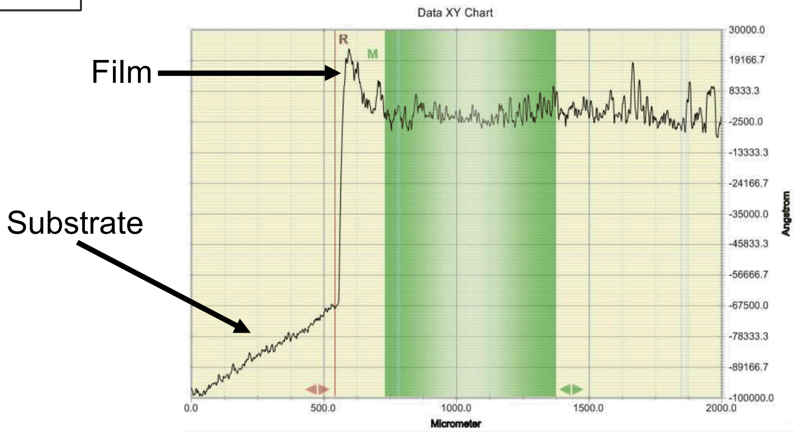
BaTiO$_3$ Cu

Stress in AD Films

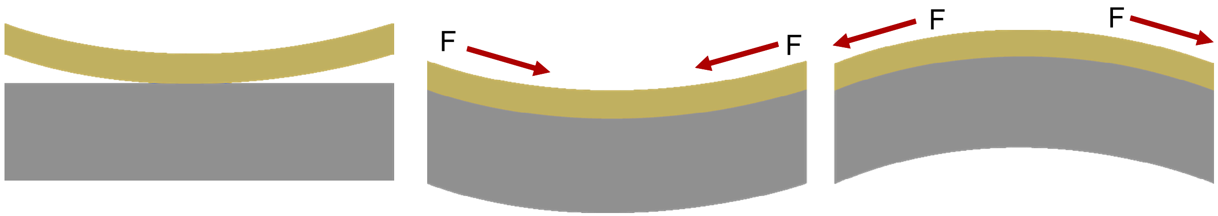
- High film stress
  - Substrate bending
- Film delamination
  - Poor anchoring layer
  - Stress higher than adhesion force
- Mitigation
  - Annealing
  - Energetic milling

$$\sigma = \frac{E_s {h_s}^2}{6h_f(1 - v_s)R}$$

Stoney formula



Substrate bending shown by contact profilometer



Film Delamination (compressive)

Compressive Stress

Tensile Stress

Conclusion

- Uniqueness of AD Process
  - Room temperature
  - Multi-material
  - Nanocrystalline structure
- Future Work
  - Develop process for higher deposition efficiency
  - Property measurements
  - Explore materials for AD

References

[1] D. M. Mattox, *Handbook of Physical Vapor Deposition (PVD) Processing*. Park Ridge, N.J.: Noyes Publications, 1998.

[2] J. Exner et al., “Powder requirements for aerosol deposition of alumina films”, Adv. Powder Technol., vol. 26, no. 4, pp. 1143-1151, Jul. 2015.

[3] W.C. Hinds, *Aerosol Technology: Properties, Behavior, and Measurement of Airborne Particles.* New York: Wiley, 1999.

[4] S. Kasap, *Principles of electronic materials and devices*. Boston: McGraw-Hill, 2006.

End

Questions?