Dry Aerosol Deposition (DAD) of Nanostructured Ceramics

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New Mexico Tech Research Colloquium
March 1, 2024

ABSTRACT

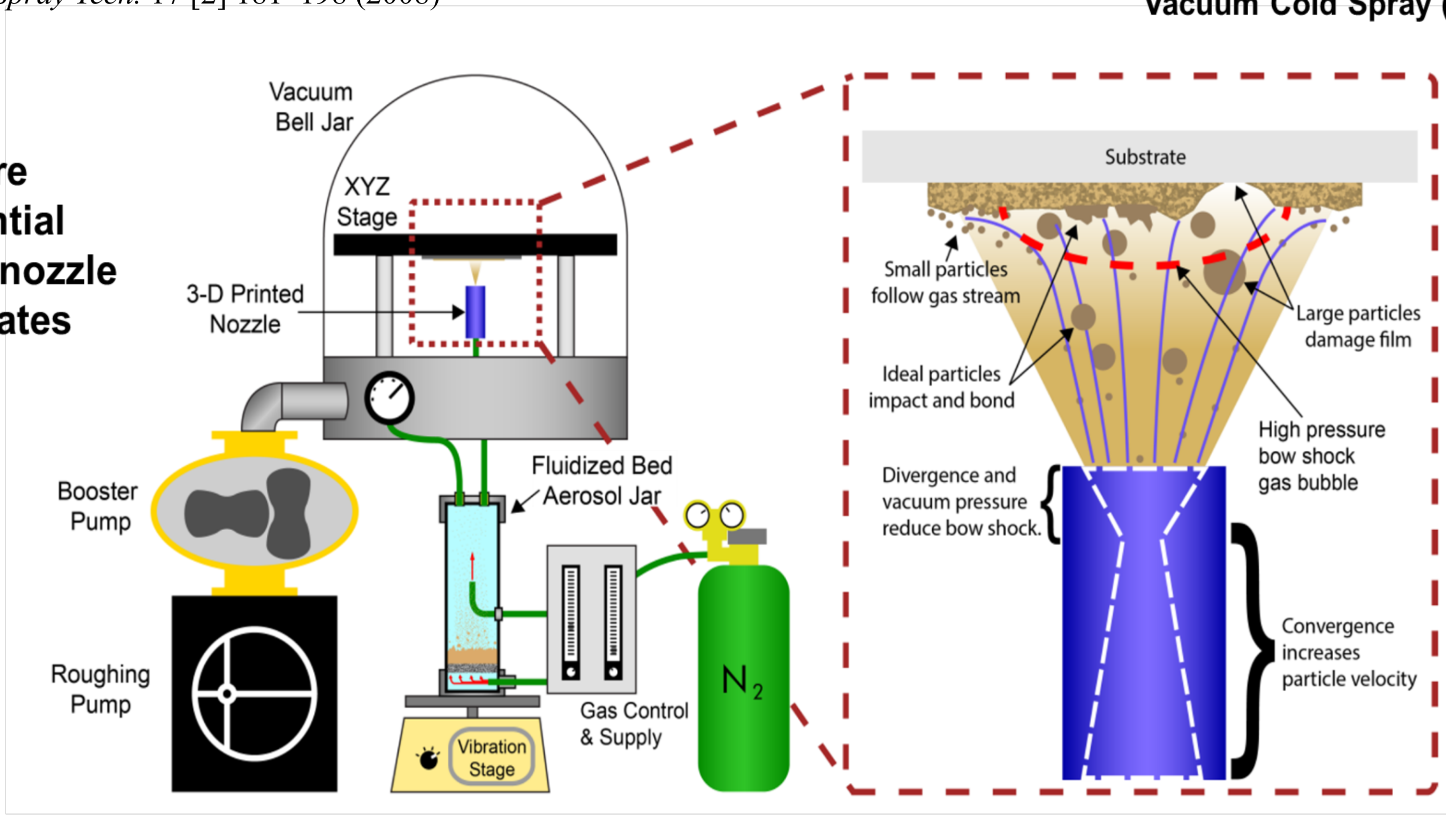
Dry Aerosol Deposition (DAD) is an emerging additive manufacturing spray process for building fully dense, nanostructured ceramic coatings and low profile 3D structures directly from dry powder without the need for binder or fluid medium. Because DAD relies on kinetic energy of impact rather than heat for densification, functional ceramics can be deposited directly on polymeric as well as ceramic and metallic substrates. This presentation will describe some of our results concerning two vastly different ceramic feedstock powders used in our custom built deposition systems: 1. Barium neodymium titanate, a high-*K* microwave dielectric of interest in RF/microwave communications, and 2. Simulated lunar regolith, of interest for *in situ resource utilization* (ISRU) and in-space manufacturing.

Introduction to Aerosol Deposition

J. Akedo,, *J. Am. Ceram. Soc.* 89 [6] 1834–1839 (2006); *ASM International, J. Thermal Spray Tech.* 17 [2] 181–198 (2008)

AKA: Aerosol Deposition Method (ADM)
Vacuum Kinetic Spray (VKS)
Vacuum Cold Spray (VCS)

Pressure Differential across nozzle accelerates aerosol

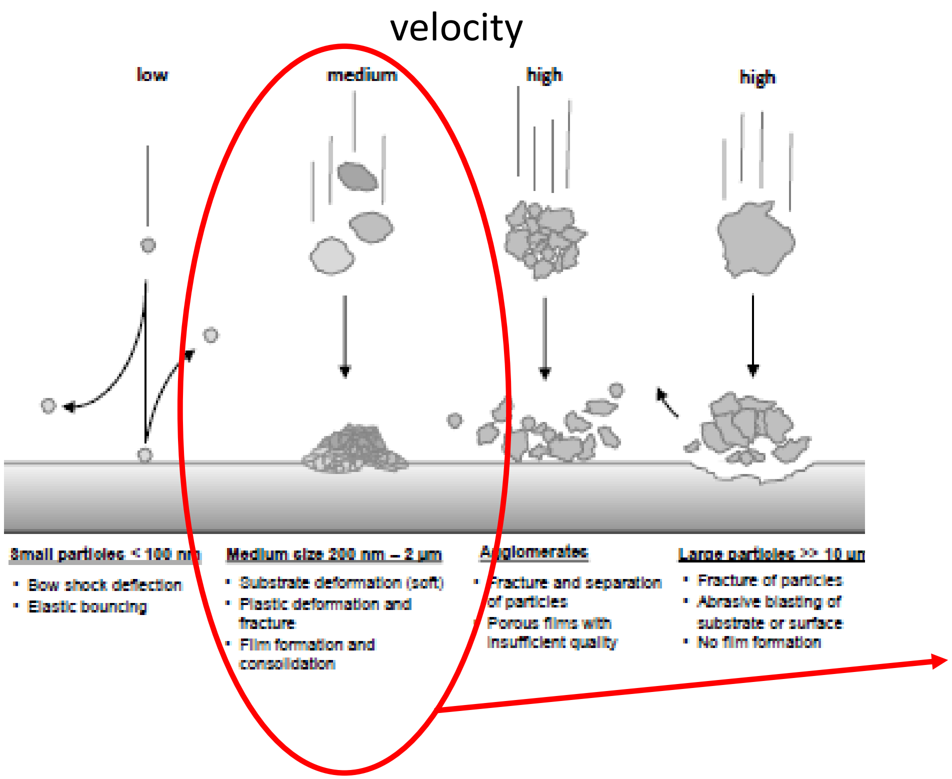


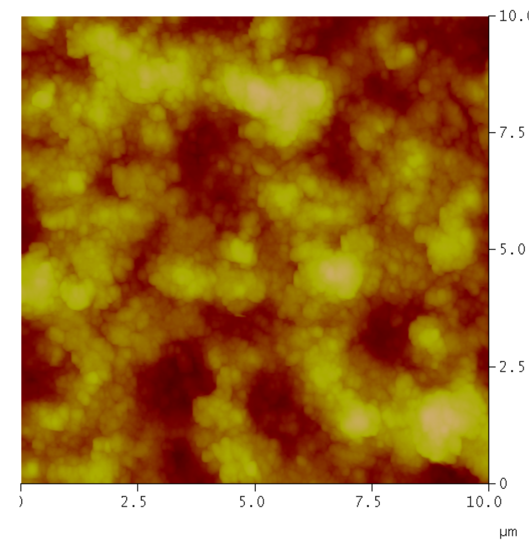
J. Adamczyk, P. Fuierer, Compressive stress in nano-crystalline titanium dioxide films by aerosol deposition, Surface and Coatings Technology 350 (2018) 542-549.

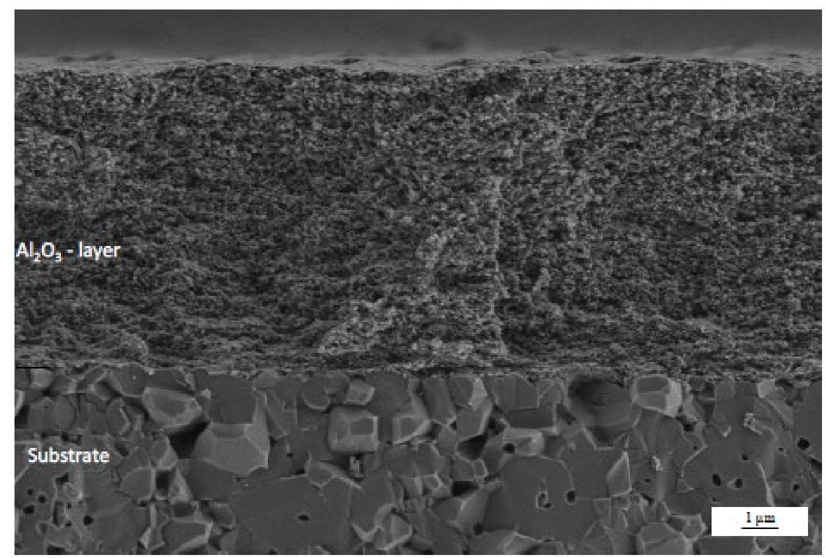
Room Temperature Impact Consolidation

NOTE: Ceramic Densification occurs via KINETIC ENERGY not THERMAL ENERGY!

Particle size and velocity key for "Impact Consolidation"







When particle size and velocity is just right, ceramic particles fracture and re-bond, resulting in growth of robust films.

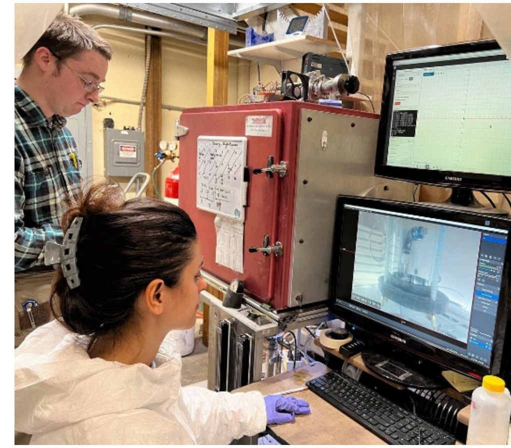
- Thin - thick ceramic films
- High adhesion/cohesion
- Theoretically dense
- Nano-crystalline

J. Exner, M. Hahn, M. Schubert, D. Hanft, P. Fuierer, R. Moos, "Powder requirements for aerosol deposition of alumina films", *Adv. Powder Tech* 26 1143-1151 (2015).

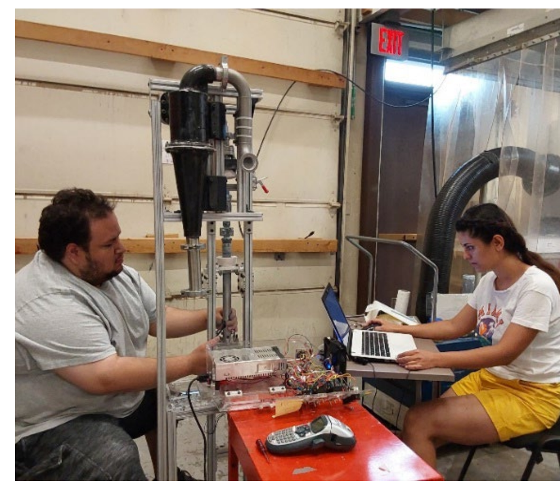
Fuierer DAD Lab @ NMT

DAD team (2021-2022)

Flat substrates, masked or un-masked



Inside pipe coating tech



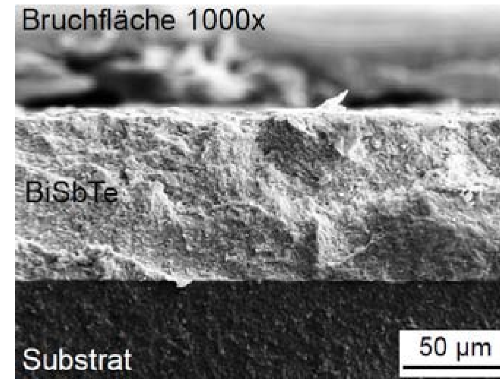
Fuierer group is the only USA university laboratory with DAD know-how, operating with three custom-built systems.

P. Fuierer, M. Hinton, "AEROSOL METHOD FOR COATING", US Patent #10792703B2 (2020)
P. Fuierer, M. Hinton, R. Calvo "SOLID PARTICLE AEROSOL GENERATOR", EP under review, serial # 62/834.764, Filed April 10, 2019

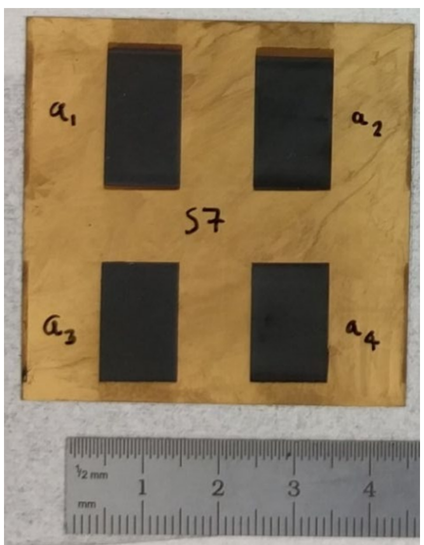
Application Areas for DAD Ceramics

- Scalable additive manufacturing (AM)
- Thin to thick films & coatings
- High dep rates, 10^4 $\mu m \cdot mm^2/min$
- Room temperature process
- Metal, ceramic, glass & polymer substrates possible

- Thermoelectrics

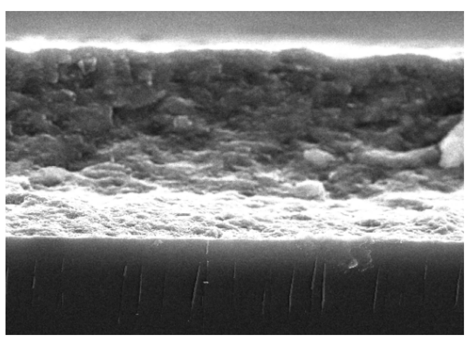


- Electronics
- Fuel Cells
- Catalytic surfaces
- Optical Coatings
- Tribology coatings
- Protective coatings



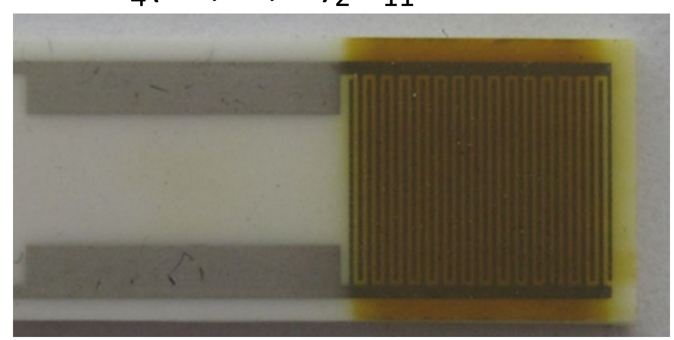
- Batteries

($LiCoO_2$ cathode)



- Sensors

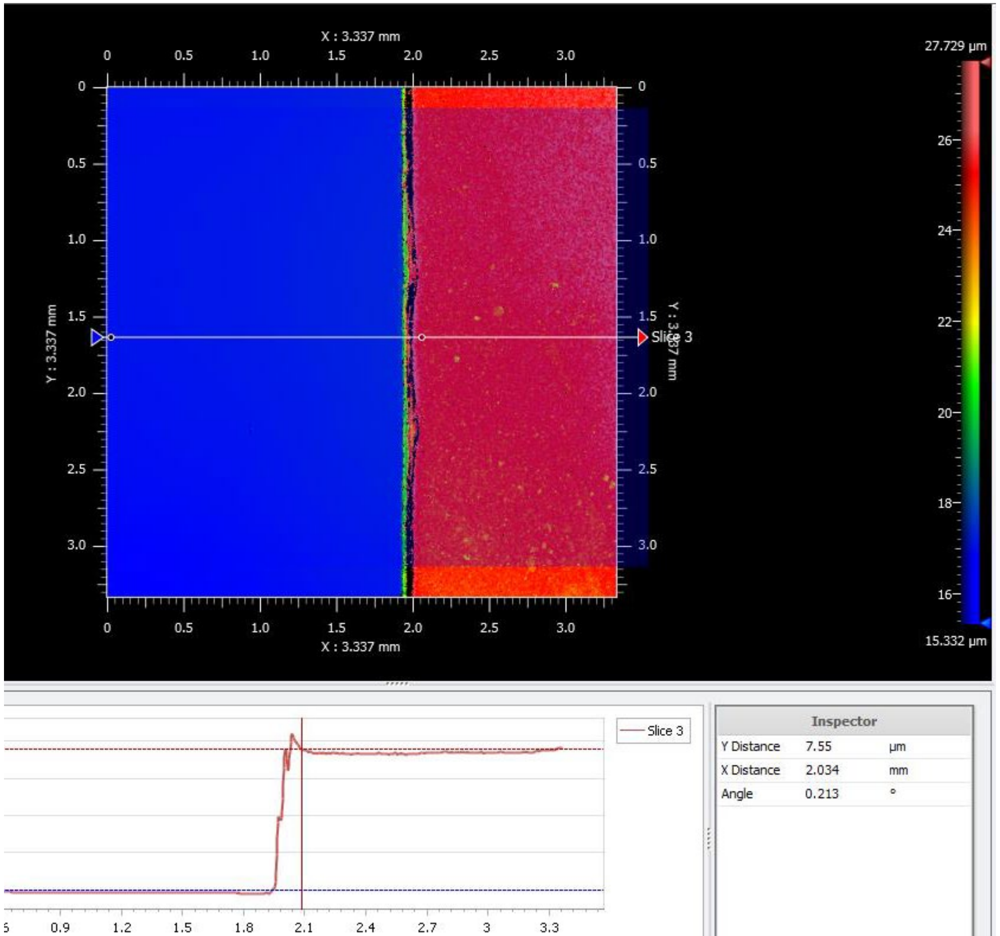
$Bi_4(Cu, Ti, V)_2O_{11}$ over IDE



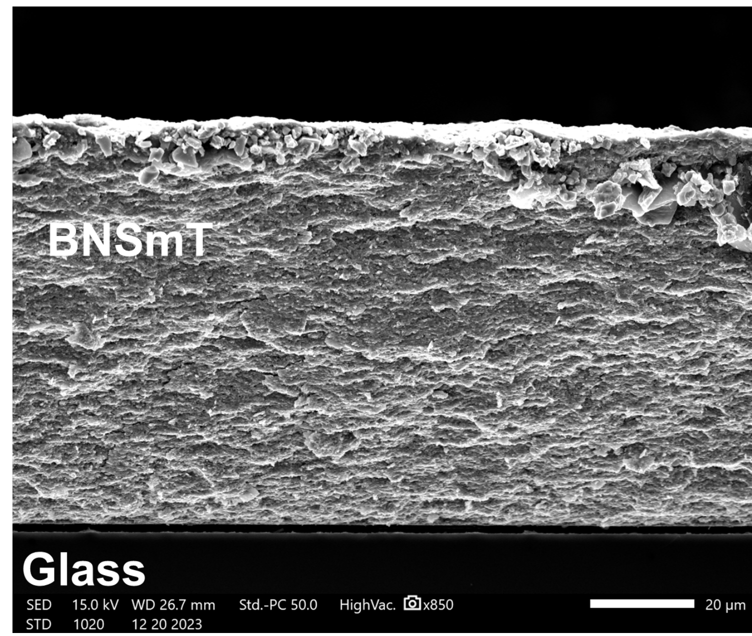
Hanft, Exner, Schubert, Stöcker, Fuierer, Moos, "A Review of the AD Method", *J Ceram Sci & Tech*, 6 [3] 147 (2015)
J. Exner, P. Fuierer, R. Moos, Aerosol deposition of (Cu,Ti) substituted bismuth vanadate films," Thin Solid Films, 573 185-190 (2014).

Microwave Dielectric Ceramic on Glass

BNSmT = $Ba(Nd,Sm)_2Ti_{4+x}O_{12+y}$



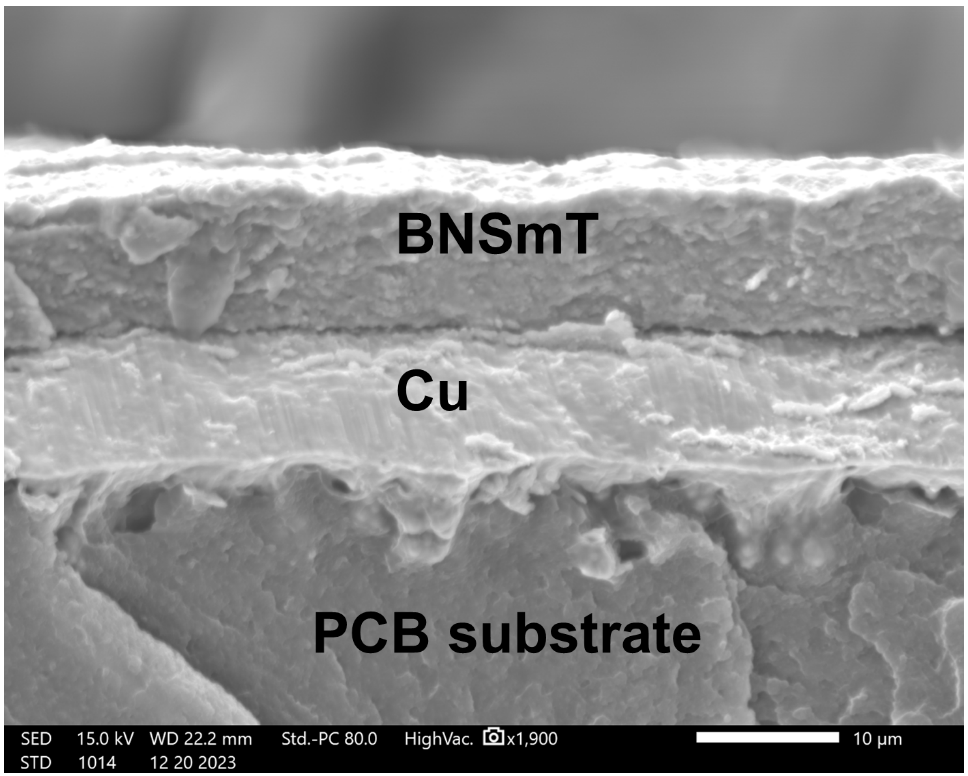
h = 7.6 µm, S_A = 0.390 µm

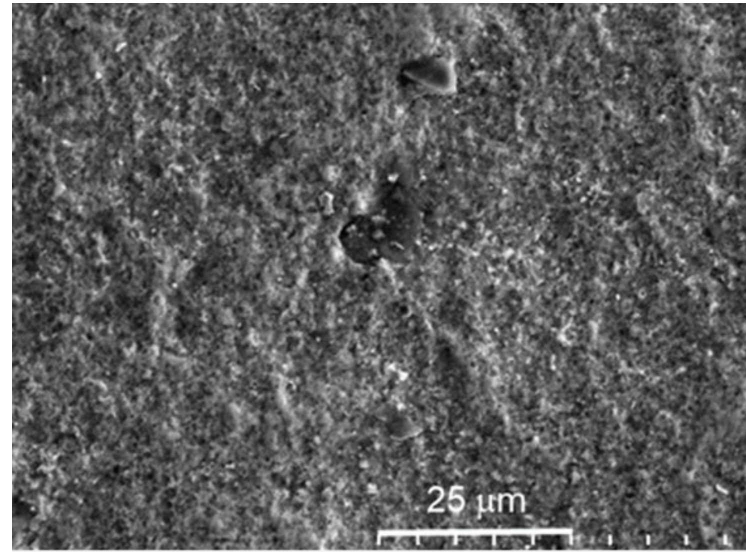


A.Valdez, "DAD of Barium rare-earth titanate dielectric and copper conductor for microwave devices", *MS Thesis (in progress).*

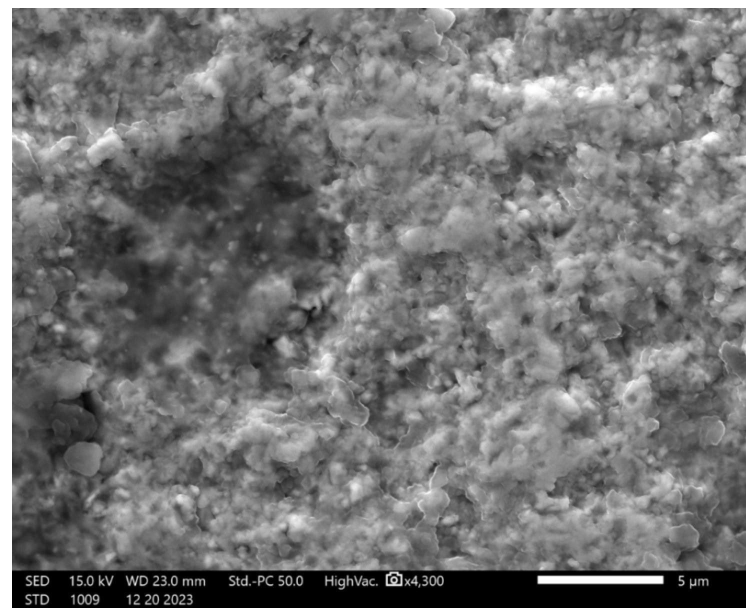
DAD BNSmT on PCB substrate

Cross-section view of fracture surface



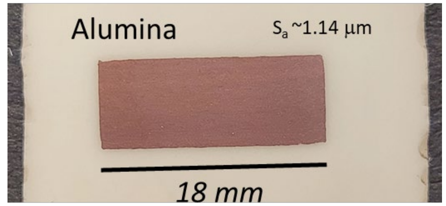


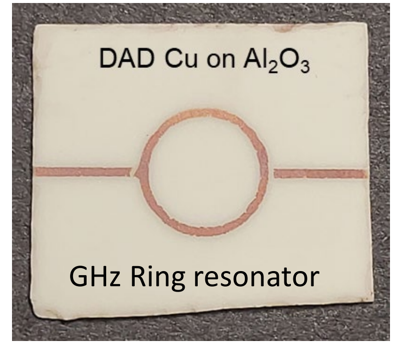
Planar surface view

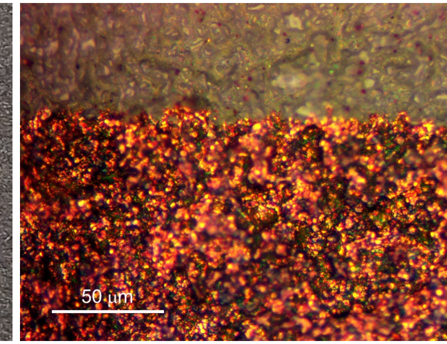


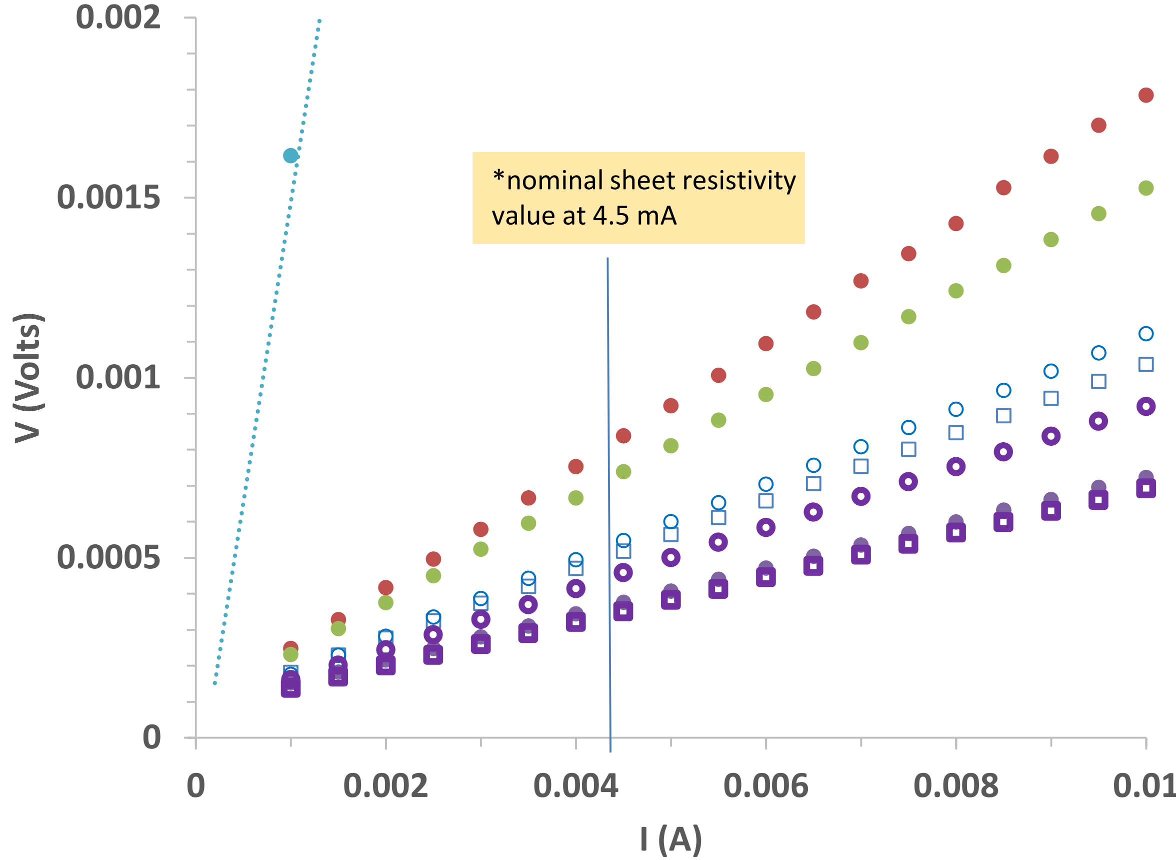
Copper conductor

DAD can do metallization too!









Commercial, *h* ~ 25-100 μm

	Sheet resistivity ρs (Ω/sq)
Sprayed Cu/Ag, 1 mil	7.32
Sprayed Cu/Ag, 2 mil	0.85
sprayed Cu/Ag, 3 mil	0.74
sprayed Cu/Ag, 4 mil	0.38
DAD Cu on alumina 1.0	0.51
DAD Cu on alumina 2.0	0.55
DAD Cu on sint BNSmT 1.0	0.46
DAD Cu on sint BNSmT 2.0	0.35
Linear (Sprayed Cu/Ag, 1 mil)	

DAD, *h* ~ 1 μm

$$R = \frac{\rho L}{hw} = \frac{\rho_s L}{w}$$

Result for DAD Copper:

$\rho = 0.5\Omega/\text{sq} * 1\text{x}10^{-6}\ \text{m} = \boldsymbol{\rho = 5x10^{-7}\ \Omega m}$

Compare to:

- bulk Cu (crystal) $\rho = 0.17x10^{-7}\ \Omega m$

or

- Dupont CB200 PCB copper conductor

With ρ_s = 20-30 mΩ/□ at t=1mil

$\rho = 6.25\ x10^{-7}\ \Omega m$

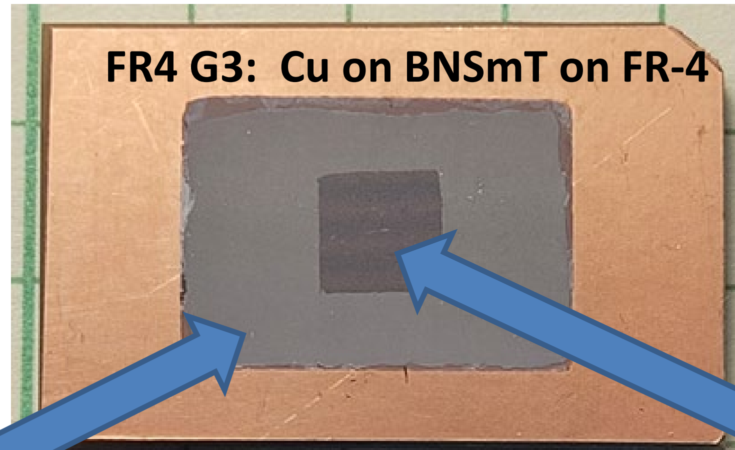
NOTE: V-I data obtained using Signatone 4 pt probe with Keithley 2400 SMU

A.Valdez, "DAD of Barium rare-earth titanate dielectric and copper conductor for microwave devices", *MS Thesis (in progress).*

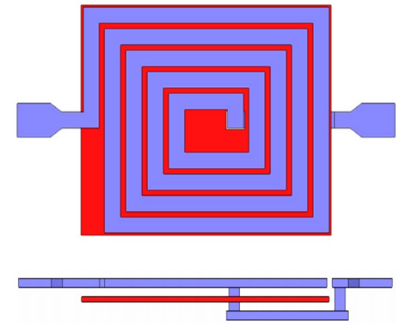
DAD Printed Passive Electronics

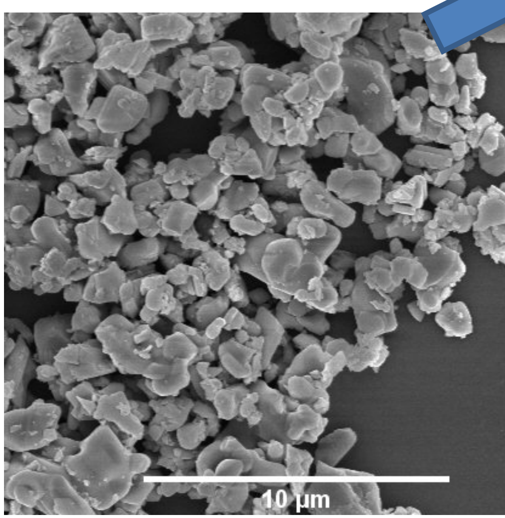
R

C

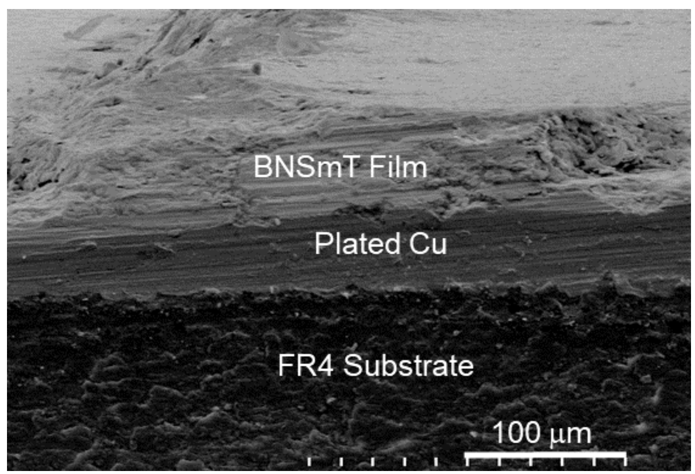


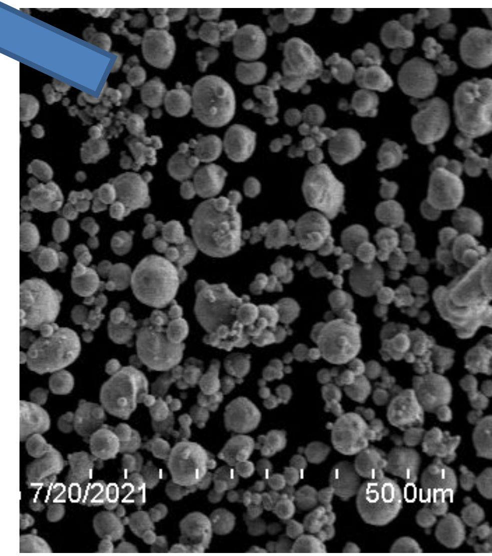
L





Commercial BNSmT

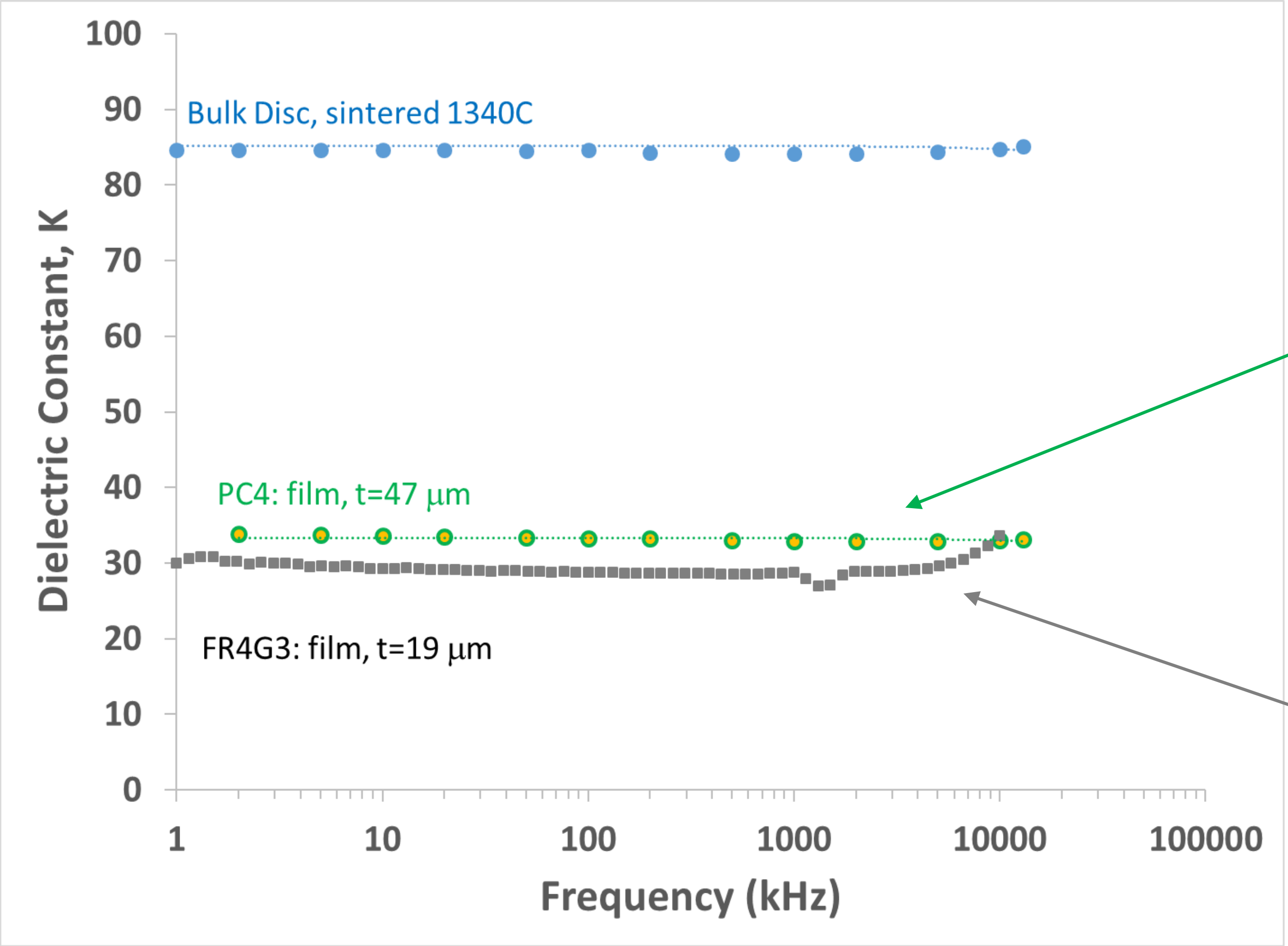


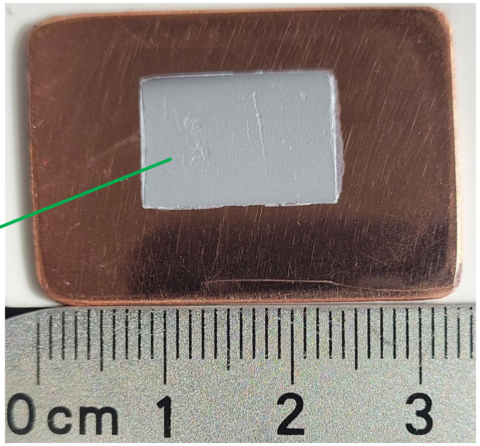


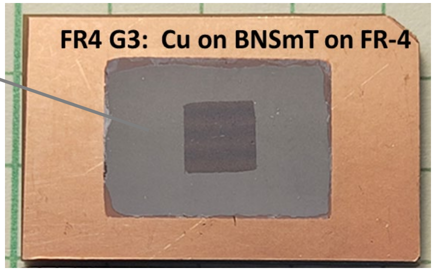
Gas-atomized copper

P. Fuierer, A. Valdez, "DAD to build microwave dielectric ceramics with metallization", *Thermal Spray & Surface Eng. Forum*, IMAT, Sept, 2022.

Dielectric Response of DAD BNSmT







* *K* value for DAD films is 1/2 that of bulk.
DAD FILMS ARE NOT SINTERED or ANNEALED!

A.Valdez & P. Fuierer, "DAD of Barium Neodymium Titanate Dielectric Ceramic", *Solid Free-Form Fabrication* (32nd Annual Conference), Aug, 2021

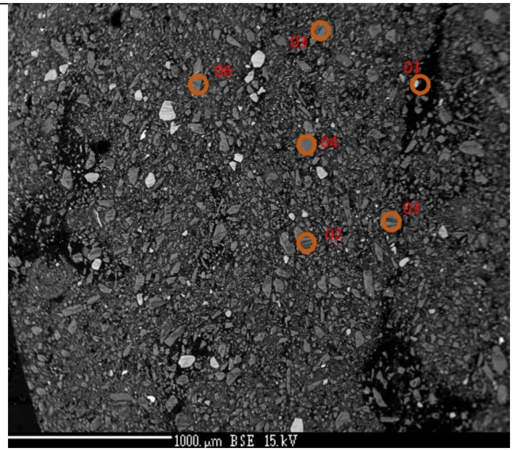
DAD Coatings from Lunar Mare Simulant

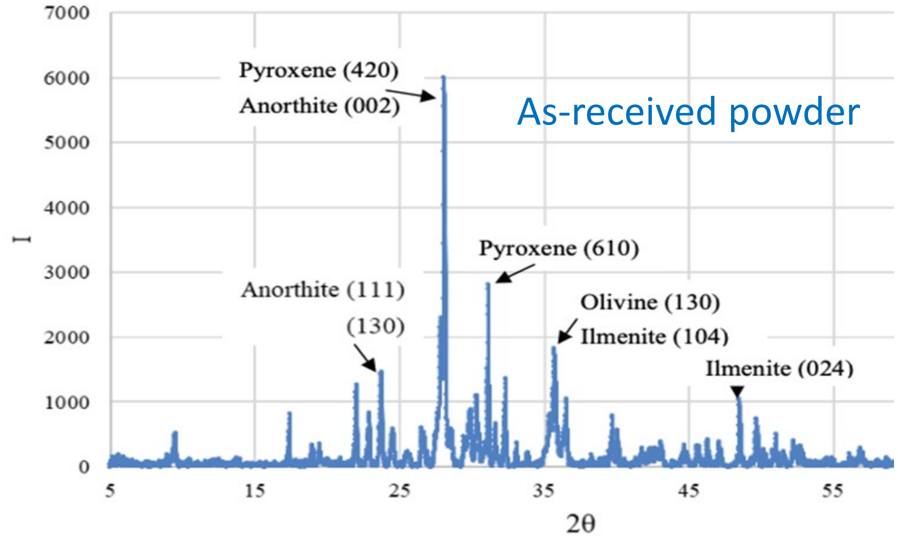
LMS-1 powder

Mineralogy

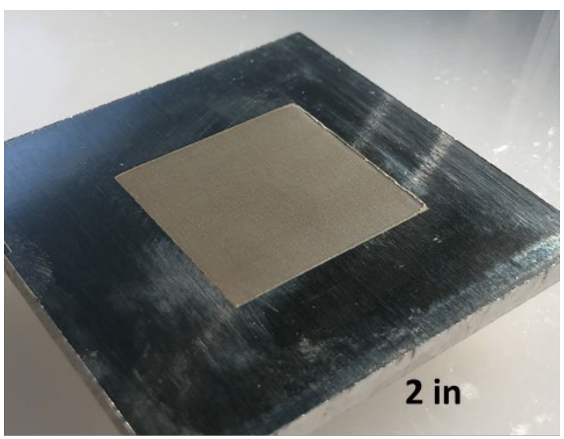
As mixed.

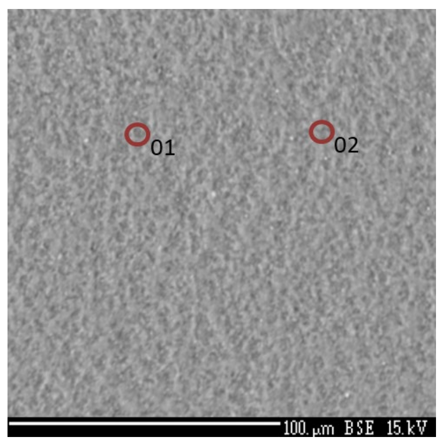
Component	Wt.%
Pyroxene	32.8
Glass-rich basalt	32.0
Anorthosite	19.8
Olivine	11.1
Ilmenite	4.3





DAD



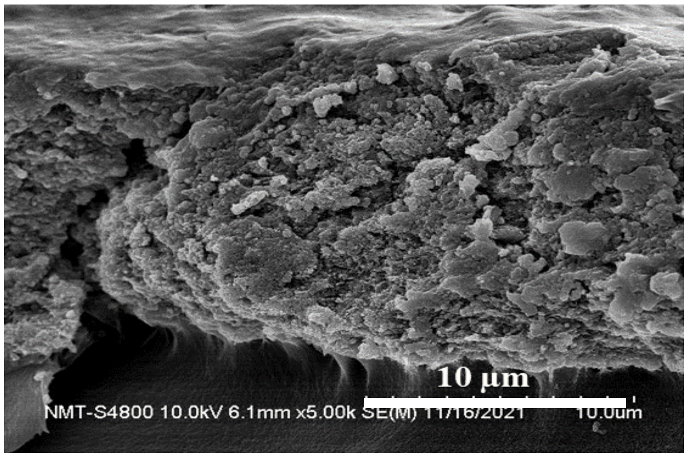


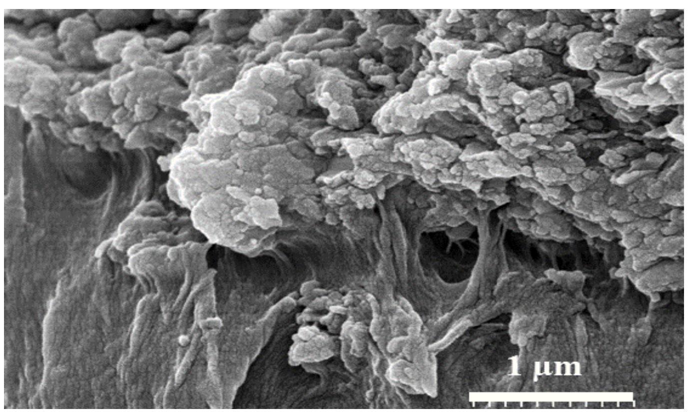
Result is a nano-structured coating with uniform chemical and phase composition

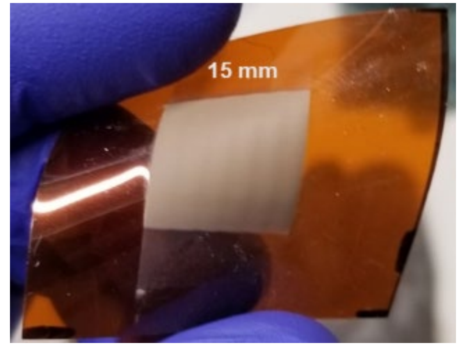
P. Fuierer, R. Calvo, G. Strobel, Dense, nano-grained, multi-phase ceramic coatings by DAD of lunar regolith simulant, ***J. Add. Manuf.*** 35 (2020).

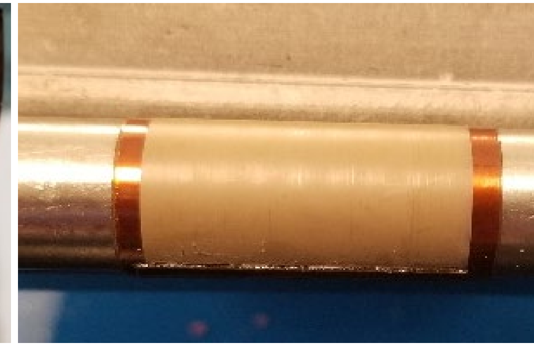
DAD LMS Protective Coatings for Space Materials

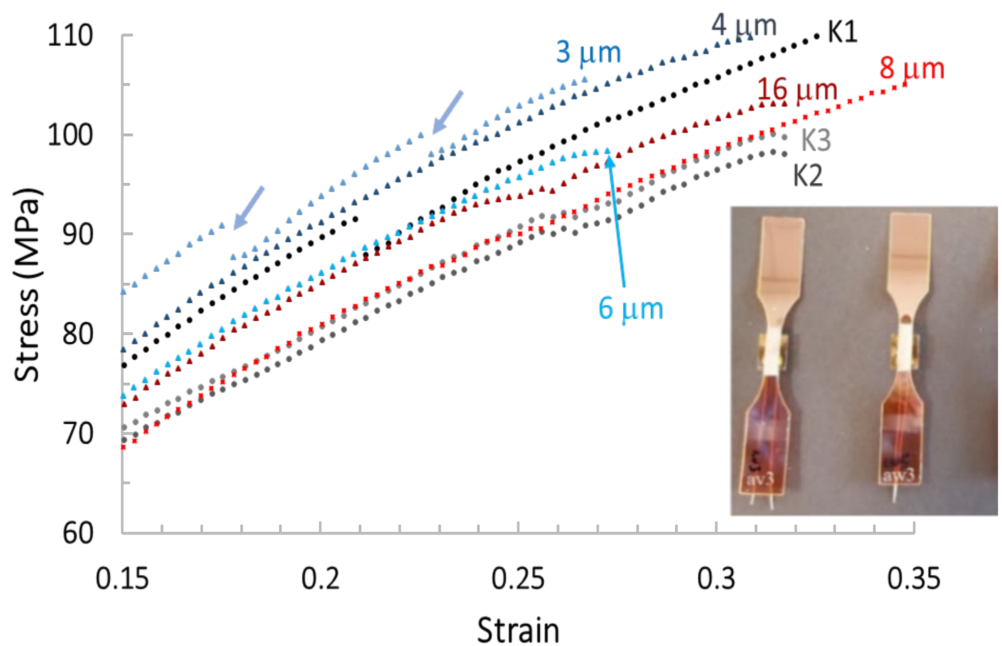
Objective: Demonstrate that DAD can apply ceramic coatings with high mechanical integrity to space-relevant substrates like ***Kapton*** using lunar regolith feedstock (for *ISRU*)





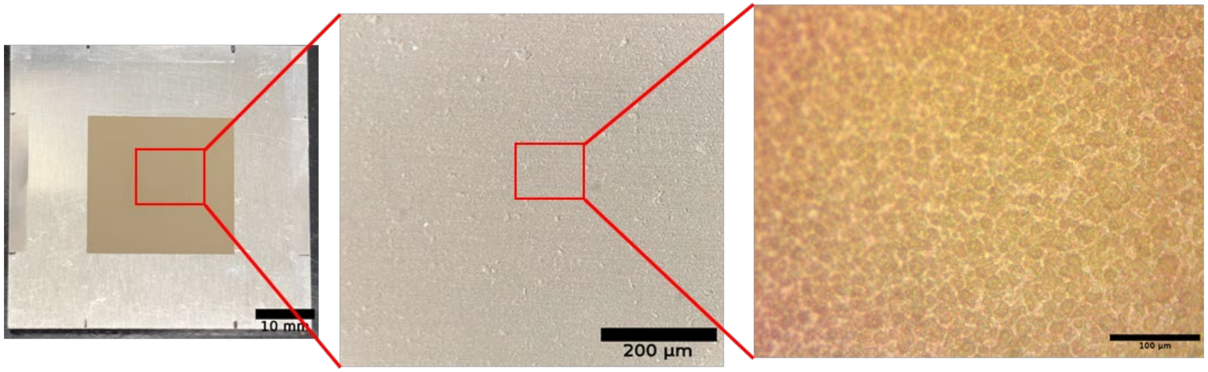


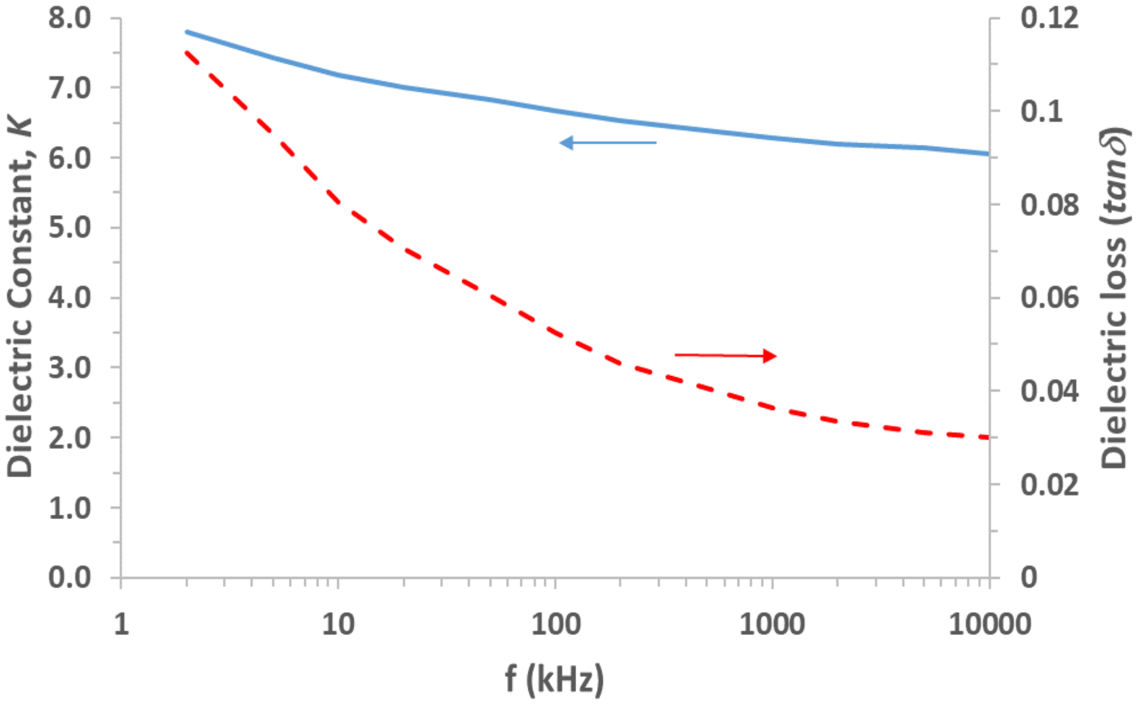




R. Calvo and P. Fuierer, "Mechanical integrity of ceramic coatings on Kapton made by a dry aerosol deposition of lunar mare simulant", *Int'l J Appl. Ceram. Technol.* 20 [1] 395-409 (2023) https://doi.org/10.1111/ijac.14235

On Demand Manufacturing of Electronics in Space (ODME –IS)





Result is a pinhole-free coating with a stable dielectric constant and low loss at high frequency

R. Borrego, *"Dielectric properties of lunar mare & highland simulant coatings produced by DAD"*, BS Thesis, NMT (2023)

Conclusions

- DAD is a unique and versatile method for producing fully dense, nanostructured ceramics with myriad (complex) compositions, on a variety of substrates.

- DAD shows promise as an on-demand, additive manufacturing method for electronics, combining dielectrics with metallization to produce functional components.

Acknowledgements:

Student Team: Robert Calvo, Robert Borrego, Alex Valdez, Arezou Karimian, Thomas Hands
New Mexico Space Grant Consortium (NMSGC), subawards QO2051 & Q02174
NASA Space Technology Research Fellowship, Federal award number 80NSSC19K1188
US Army ACC-APG-RTP, grant # W911NF2020190, Subproject: Hybrid Manufacturing of Electronic Materials