Additive Manufacturing of Energy Harvesting Material System for Active Wireless Microelectromechanical Systems (MEMS) Sensors

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Award: DE-FE0027502

Outline

- Motivation
- Project Description
- Objectives
- Previous Results
- Updates and ongoing work
- Conclusion
- Future Work
- Acknowledgements

Motivation

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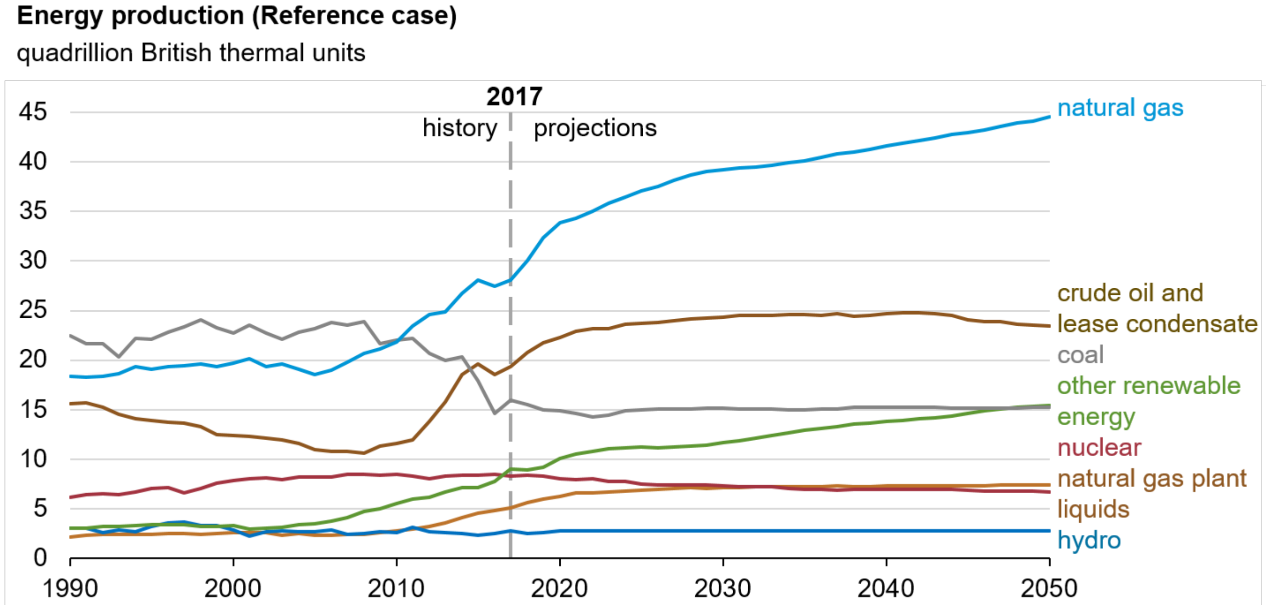
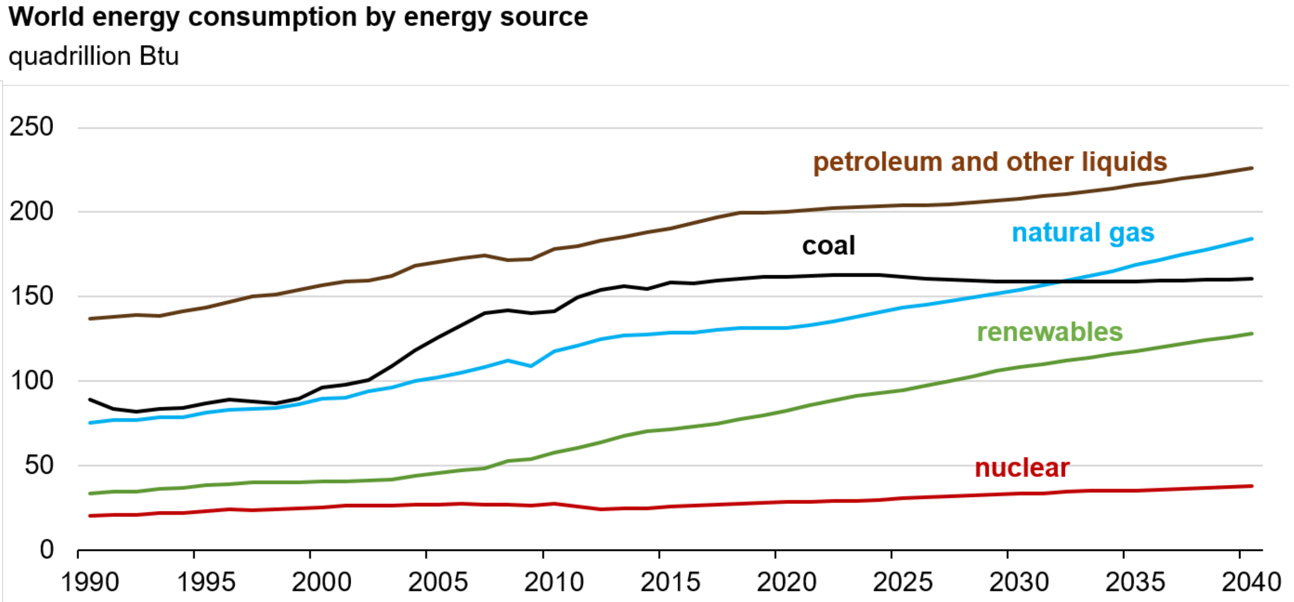
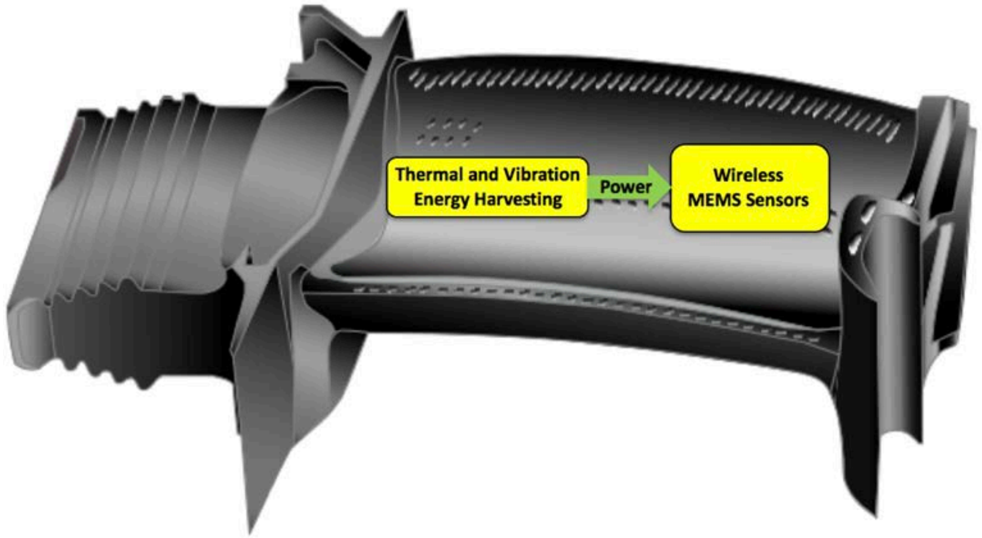
- Highly efficient and environmentally benign power and fuel systems require:
  - Critical sensing in modern power plants and energy systems
  - Higher efficiencies in energy conversion
  - Lower emission for near-zero emission power plants





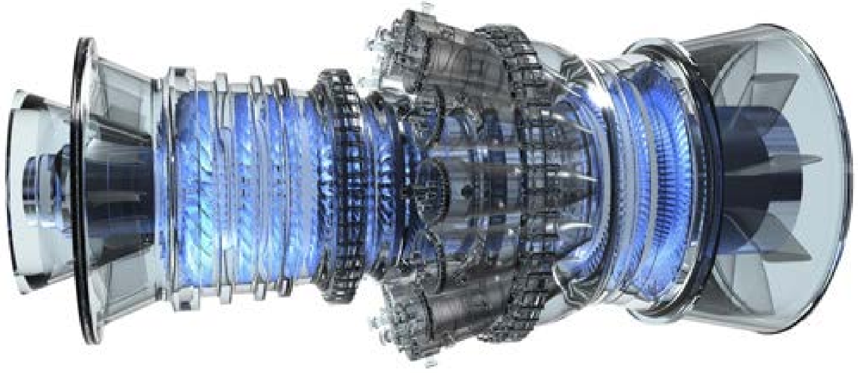
Project Description

- Monitoring/estimating operating conditions in real time is needed for high system performance and reliability, lower emission, higher efficiency
- Energy harvesting and direct sensing using additively manufactured piezoelectric ceramics



Indirect Sensing by Energy Harvesting

Turbines and Gasifiers
- Up to 1200 °C
- Up to 1000 psi
- Oxidative, corrosive, highly reducing

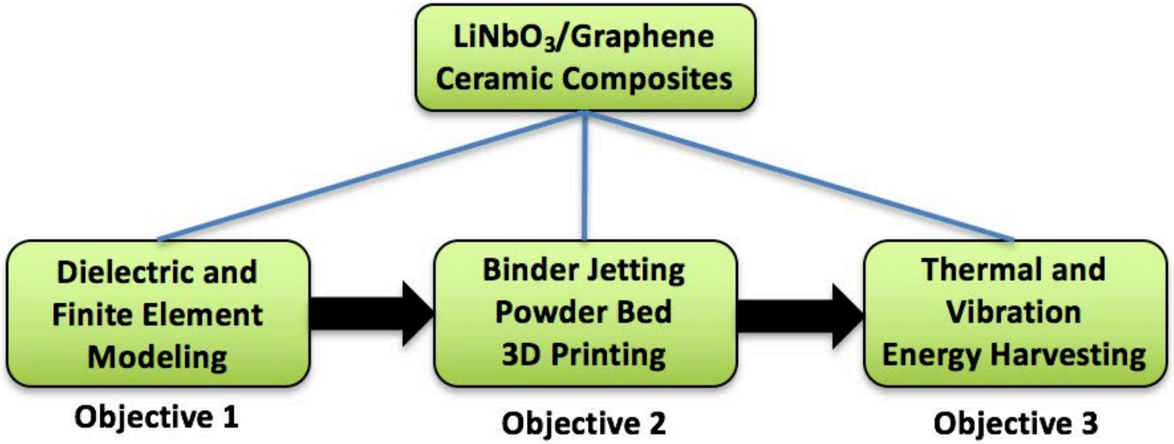


Direct Sensing of Temperature and Pressure

Objectives

$LiNbO_3$/Graphene Ceramic Composites

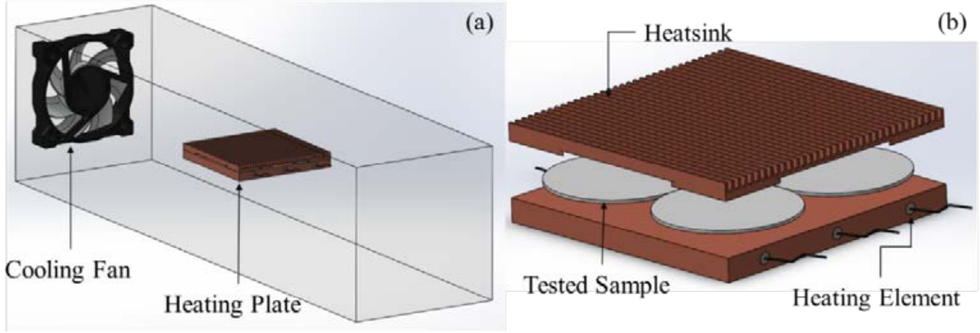
- Dielectric and Finite Element Modeling
  - Completed by end of year one
- Binder Jetting Powder Bed 3D printing
  - Ongoing effort to understand fabrication impact in material properties
- Thermal and Vibration Energy Harvesting
  - Testing set-ups already developed
  - Characterization of bulk piezoelectric ceramics completed

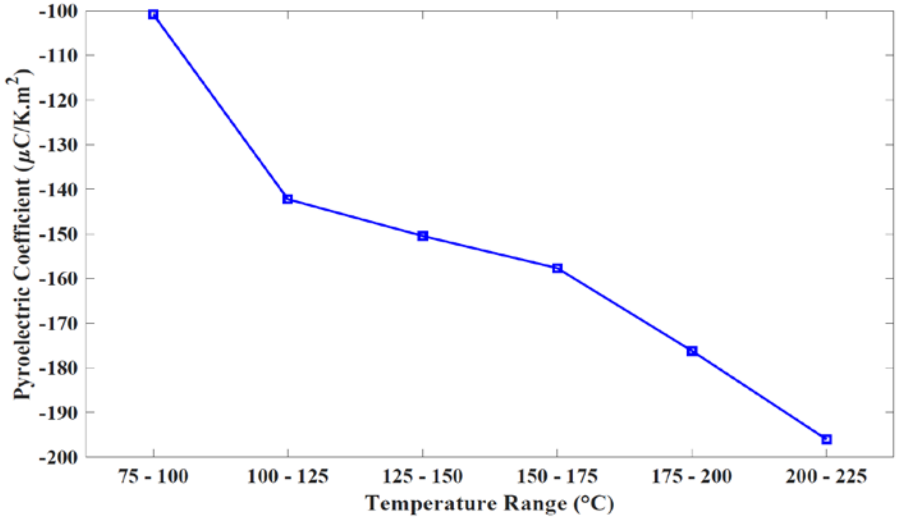


Previous Results

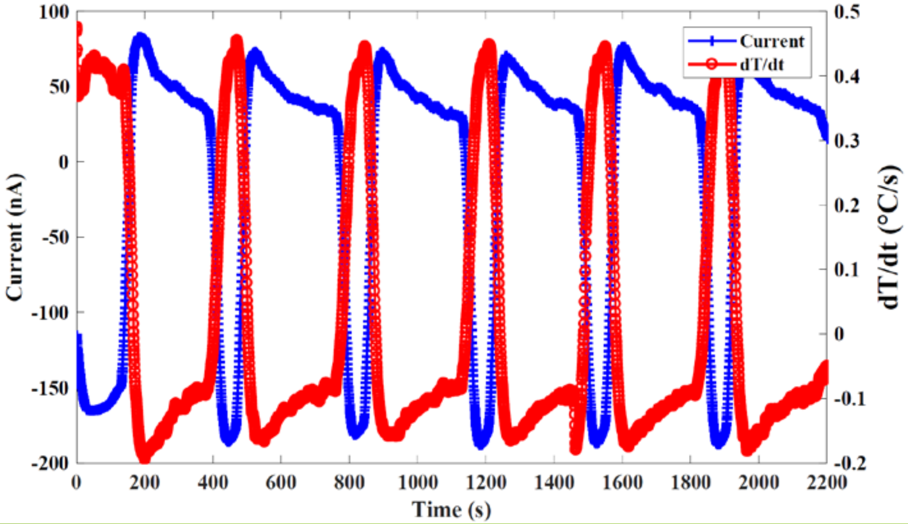
Thermal Energy Harvesting – $LiNbO_3$

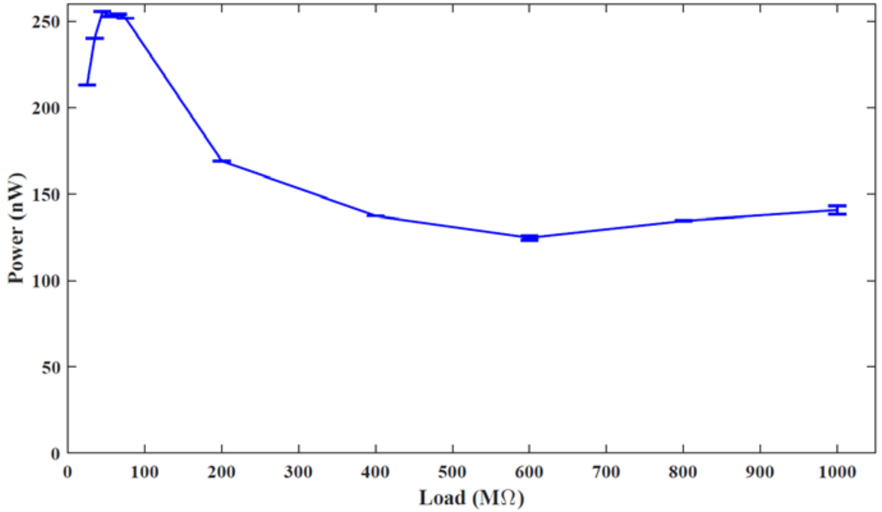
- Characterize pyroelectric properties of the material
- Perform energy harvesting at different temperature ranges





$$i_p = \frac{dQ}{dt} = Ap\frac{dT}{dt}$$

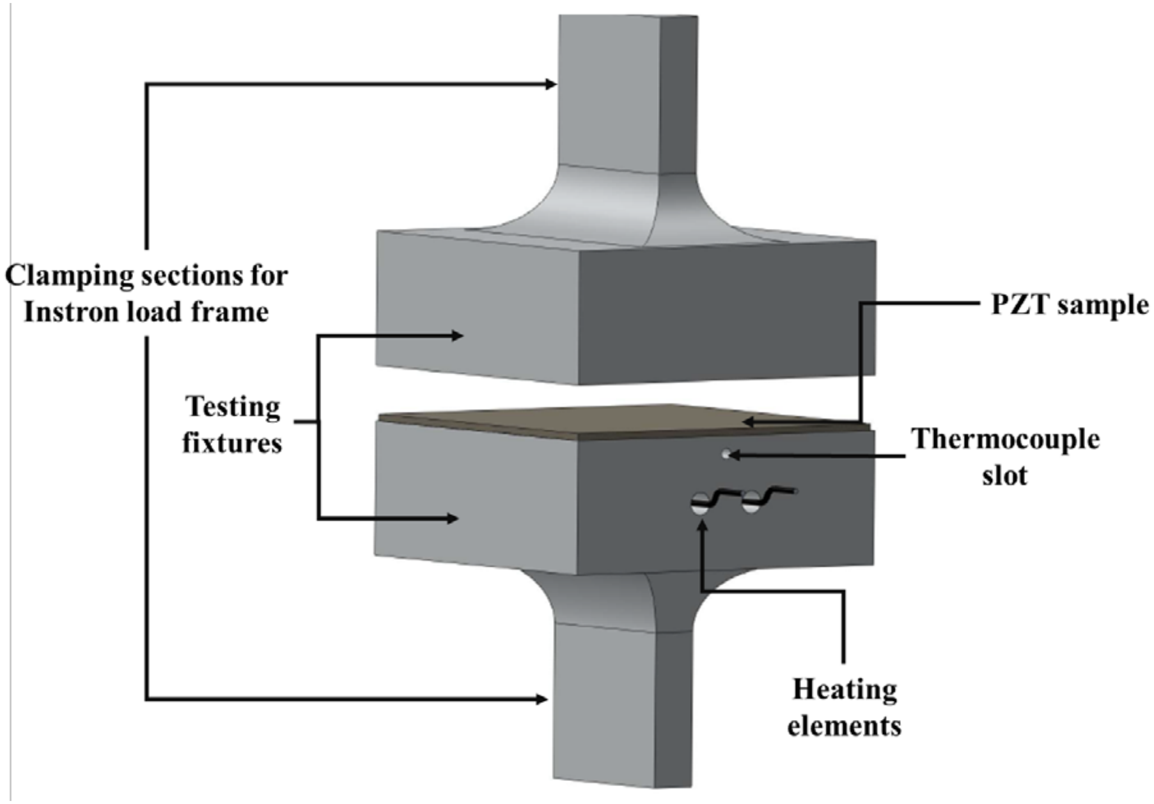


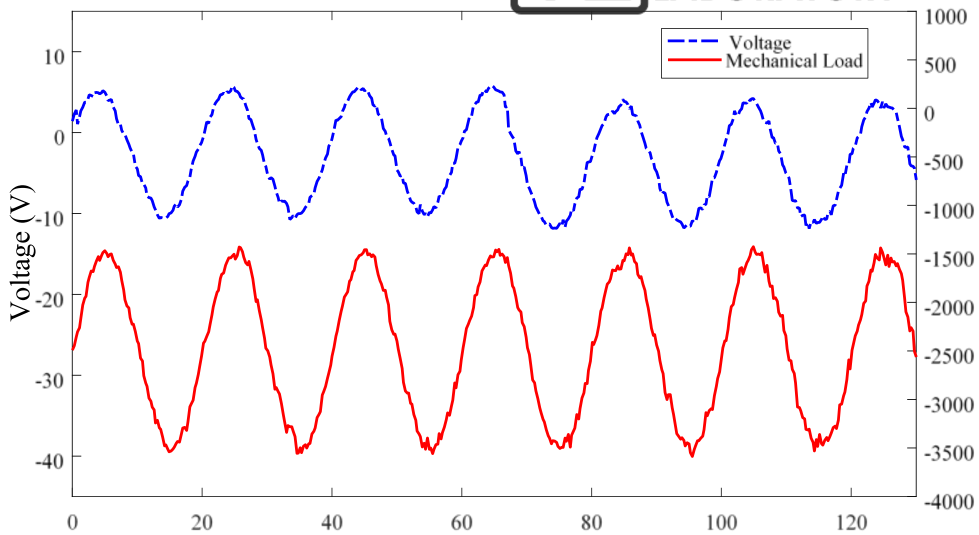


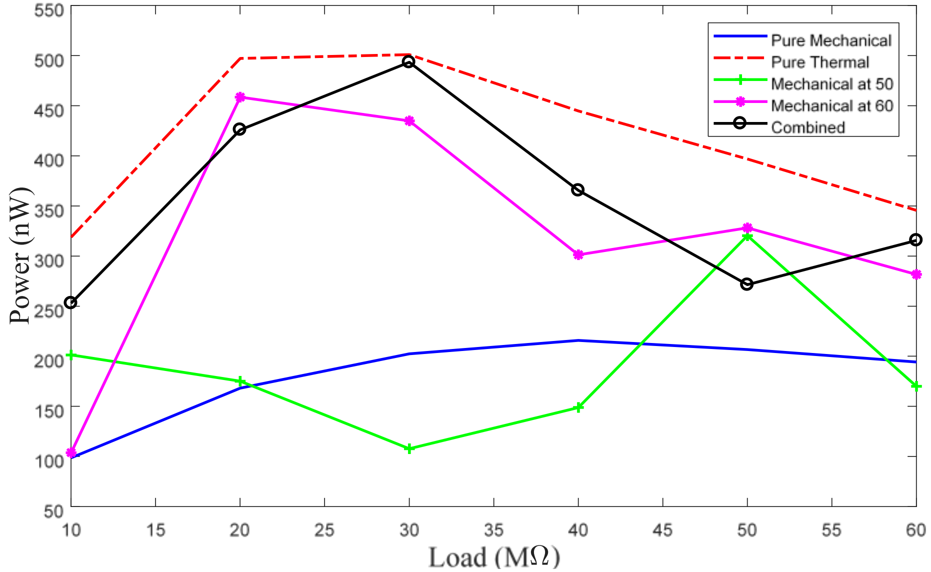
Previous Results

Hybrid Energy Harvesting – PZT

- Thermal and mechanical loads were applied
- Study harvester behavior under simultaneous loads

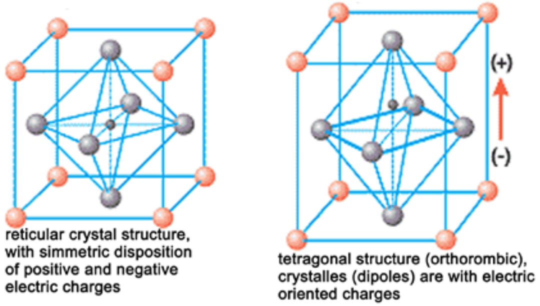






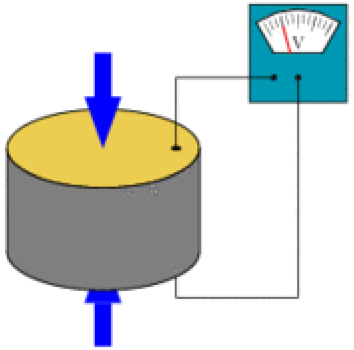
Additive Manufacturing of Ceramics

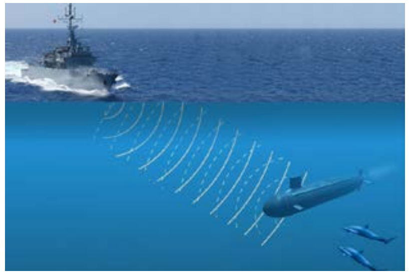
- ✓ Lead zirconate titanate (PZT), $BaTiO_3$ (BTO), Potassium niobate, ZnO, etc.
- ✓ High piezoelectric coefficient (PZT: 650 pC/N; BTO: 180 pC/N)
- ✗ Brittle; Design limitation for large scale; Thin plate based; non customizable
- ✗ Complicated fabrication process; Limited geometry freedom

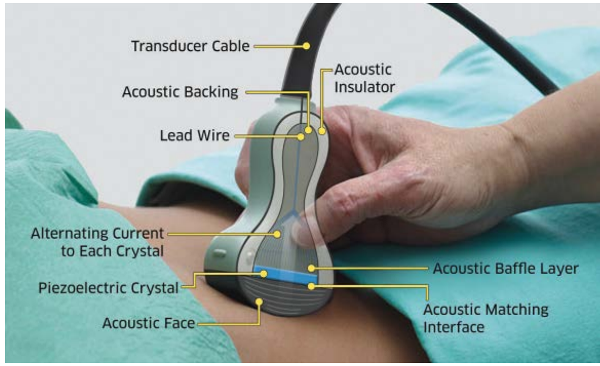


Tc < T
Cubic
a=b=c

Tc > T
Tetragonal
a=b≠c

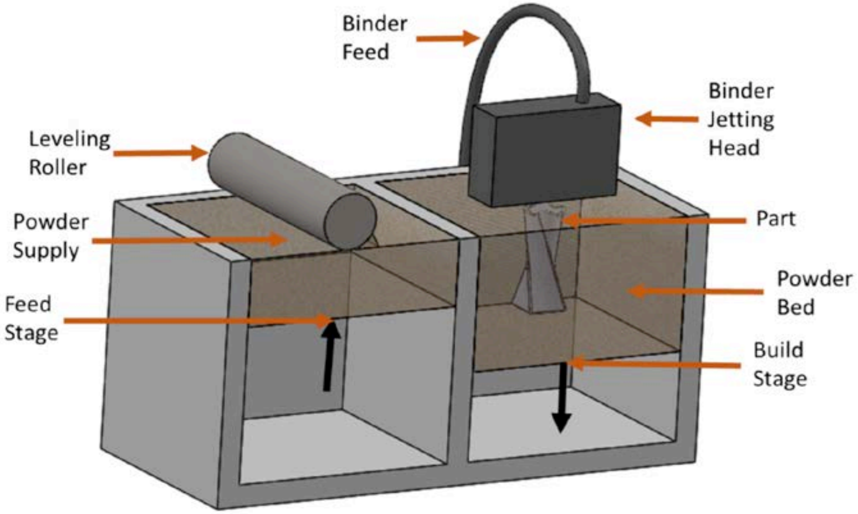






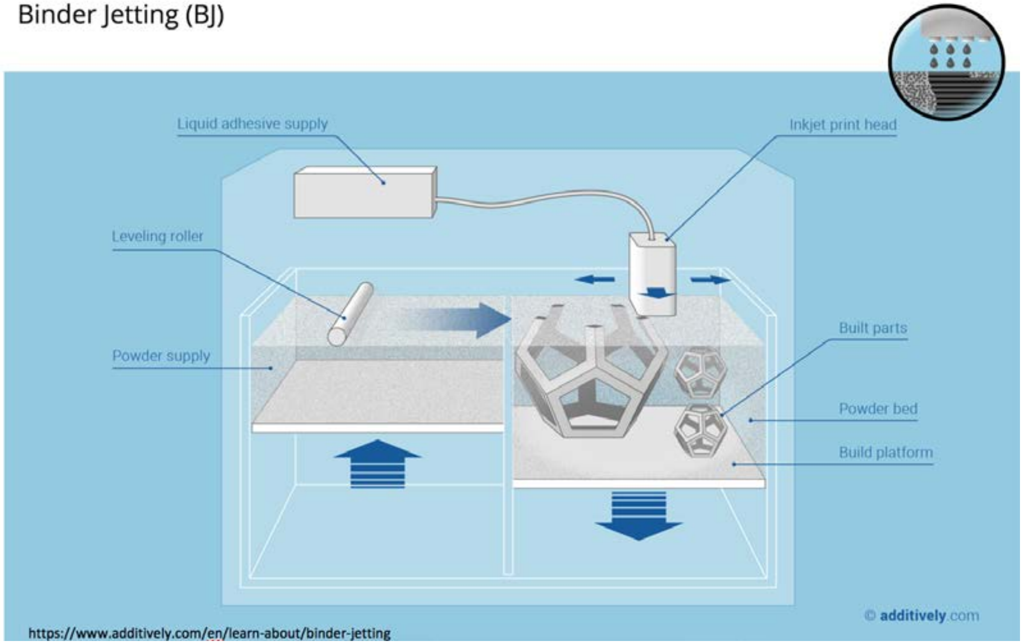
Binder Jetting

- Powder bed binder jetting technique
- Binder jetting layer by layer fabrication
- Process of ceramics, metals, polymers, and composites
- Geometry design freedom



Schematic representation of binder jetting additive manufacturing technology.

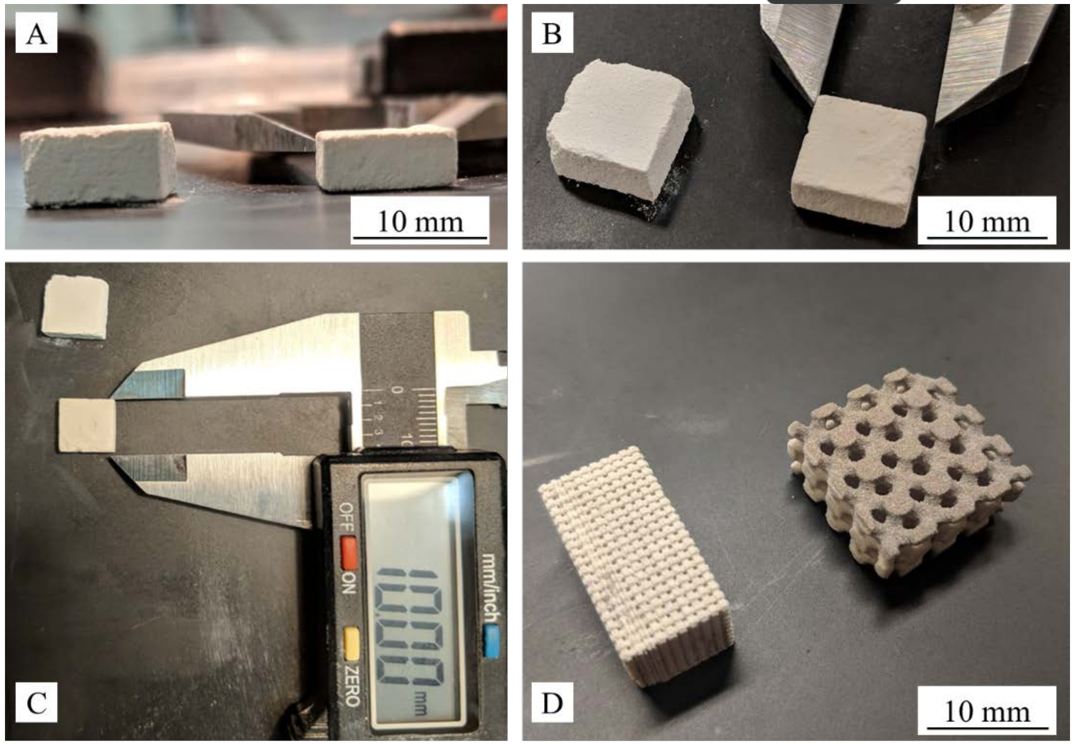
Binder Jetting (BJ)



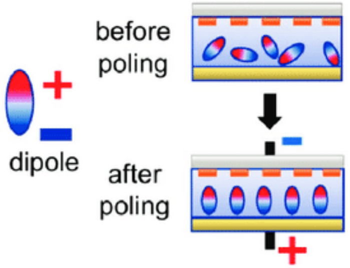
Additive Manufacturing of Piezoelectric Ceramics

Barium Titanate Printing

- Excellent geometry resolution
- Lattice, size, design freedom
- Printing, sintering, poling, testing



$$C = \varepsilon_o \varepsilon_r \frac{A}{t}$$



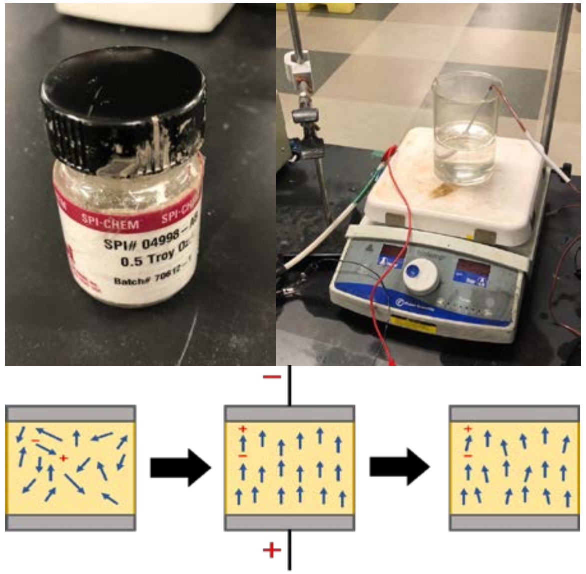
Fabrication Process

Binder Jetting Printing

- Layer thickness: 100 µm
- Feed to build ratio: 1.75
- Saturation level: 100%

Sintering Process

- 1200 °C
- 2 hours dwell
- No atmosphere control



Poling Process

- Silicone oil bath
- 1 kV/mm
- 60 °C for 1 hour

Additive Manufacturing of Piezoelectric Ceramics

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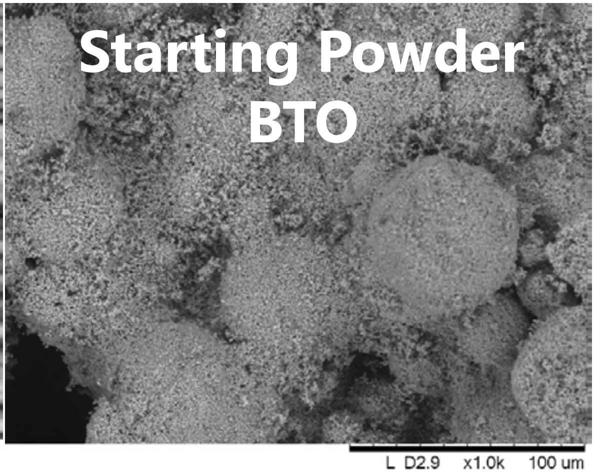
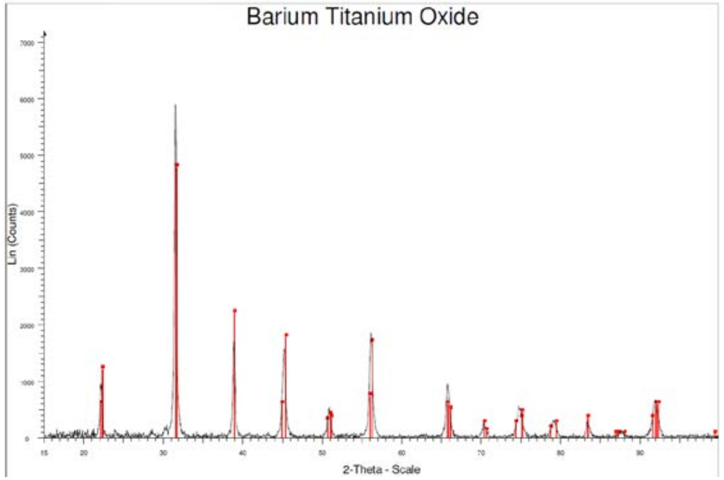
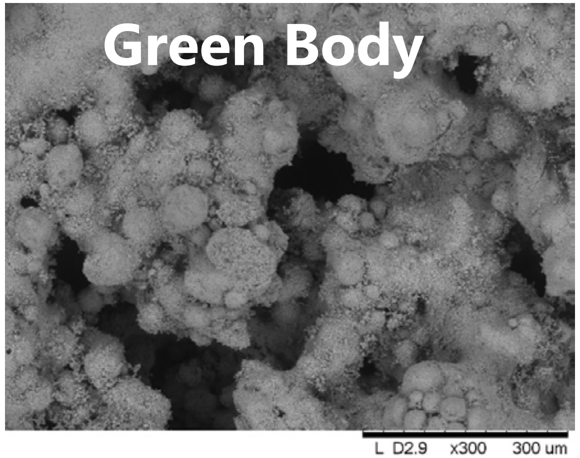
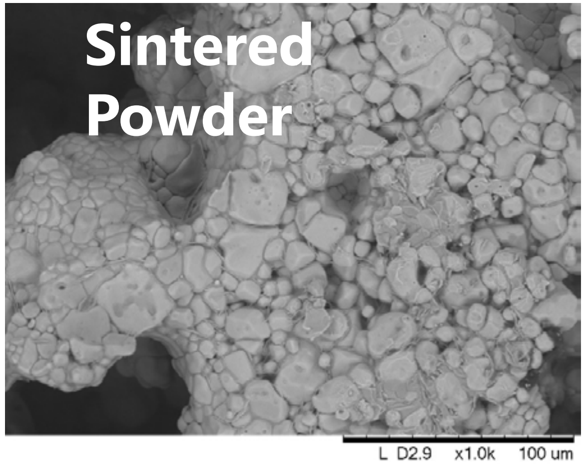
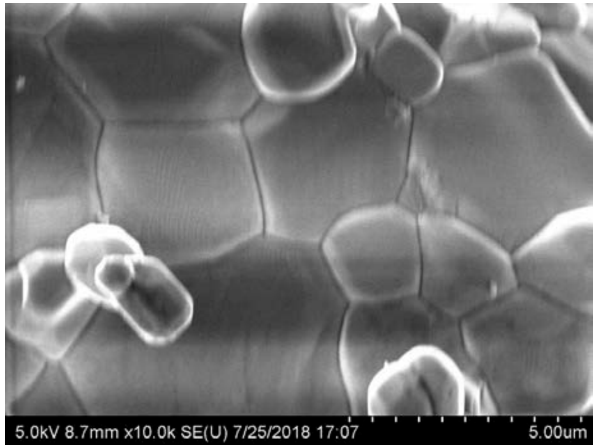
SEM and XRD











- 45 µm powder used
- Sintering induced grain growth
- Still porous in the final ceramic parts
- Crystal structure match with standards

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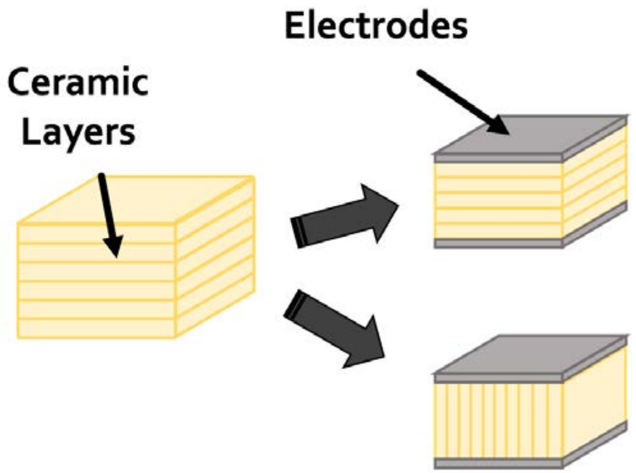
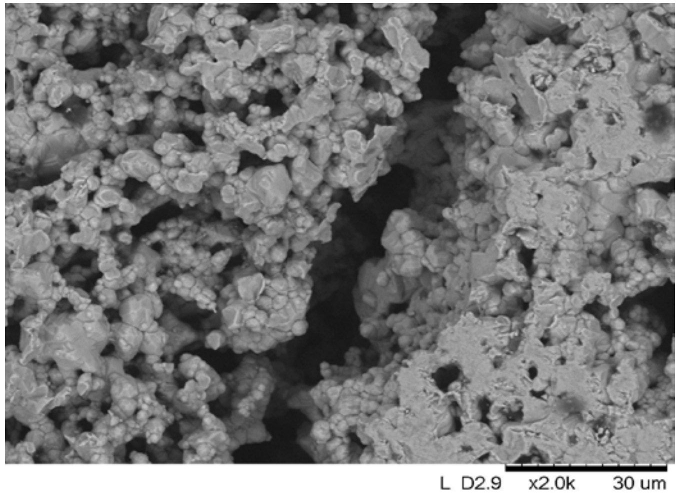
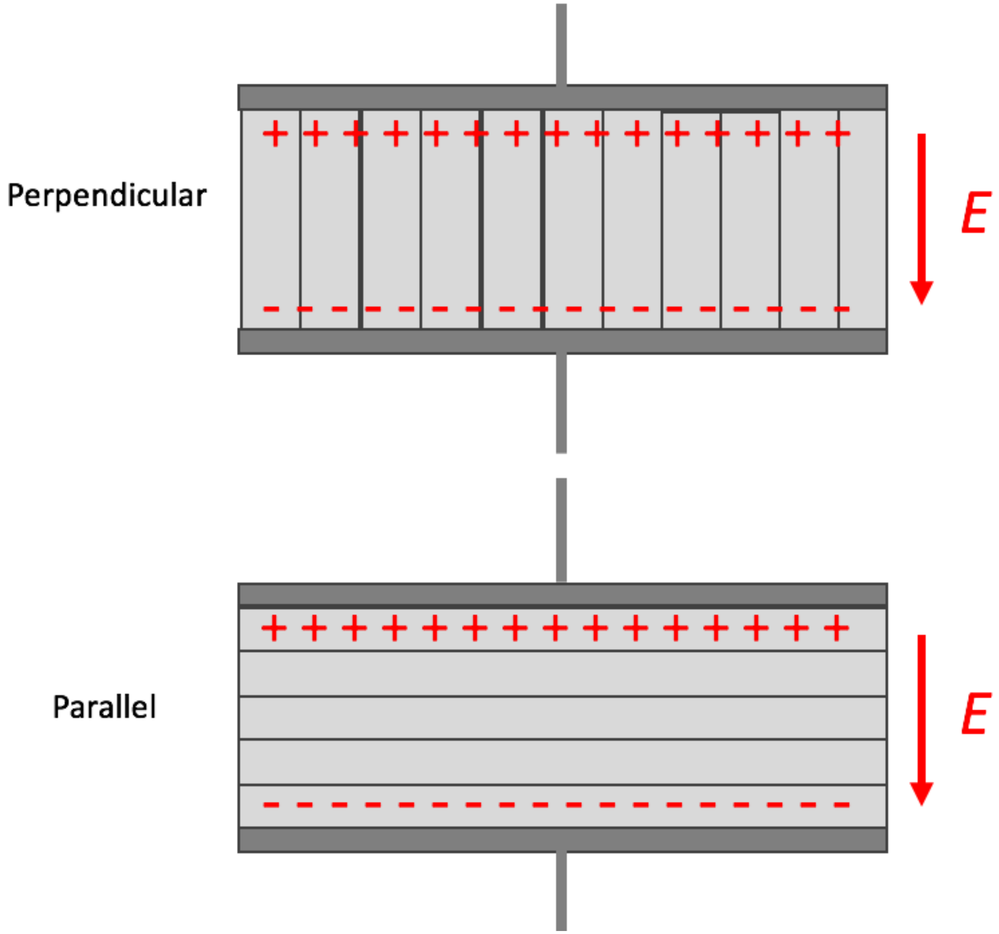
Printing Induced Orthotropic Properties



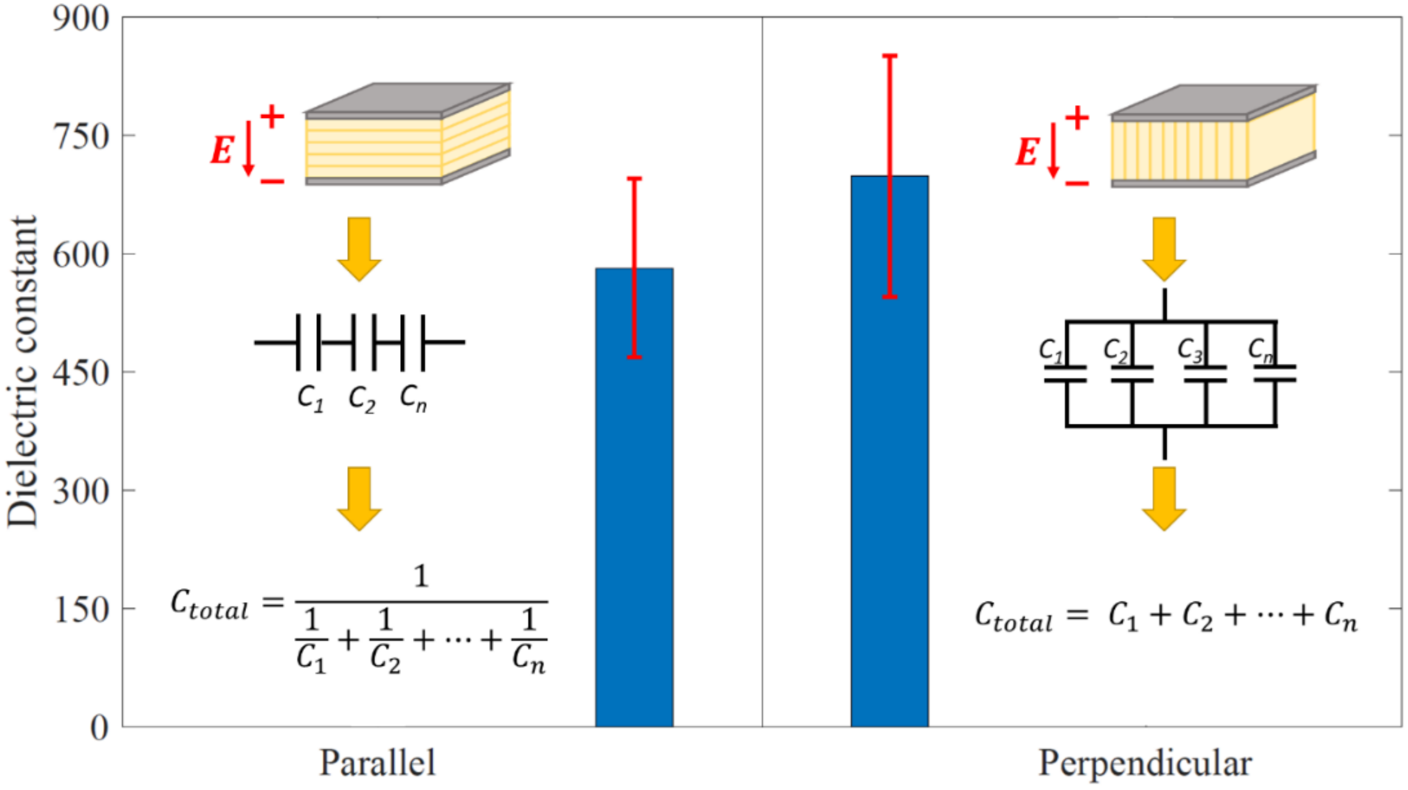




- All BTO samples were polished to have same thickness about 3.45 mm
- Both perpendicular and parallel orientation were tested
- Layer lines might be induced by powder bed roughness and lack of binder saturation

Dielectric Properties

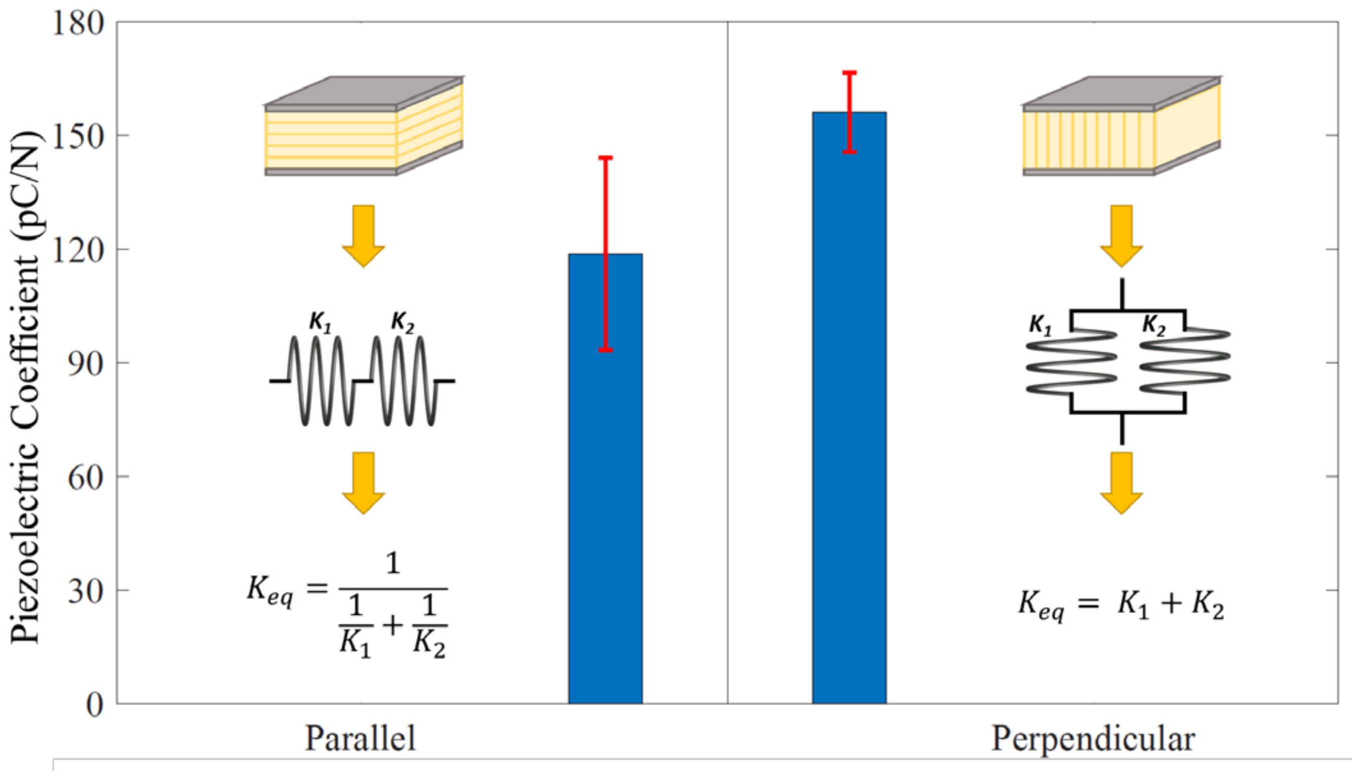
- Dielectric constant showed orientation dependency
- Capacitance connectivity in parallel or series caused dielectric orthotropic property



Piezoelectric Properties

- Piezoelectric constant also showed orientation dependency

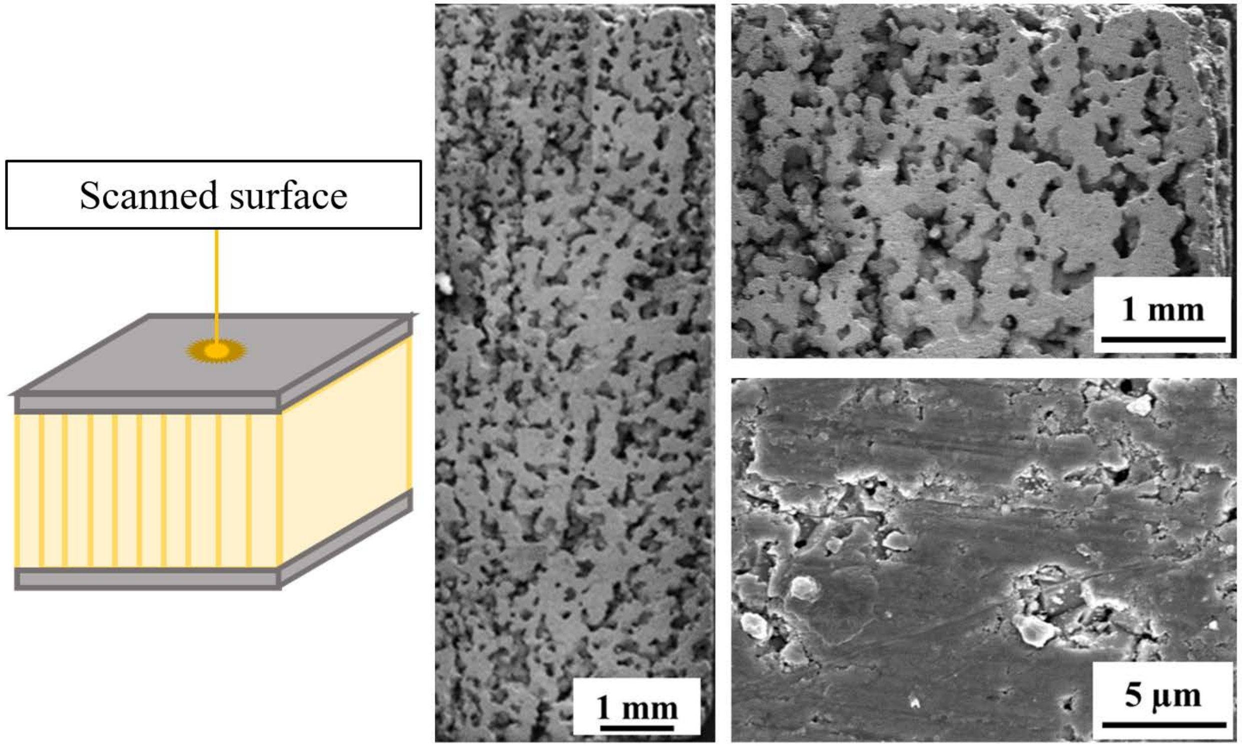
- Defects along the layers absorb applied mechanical loading thus lowering d_{33}

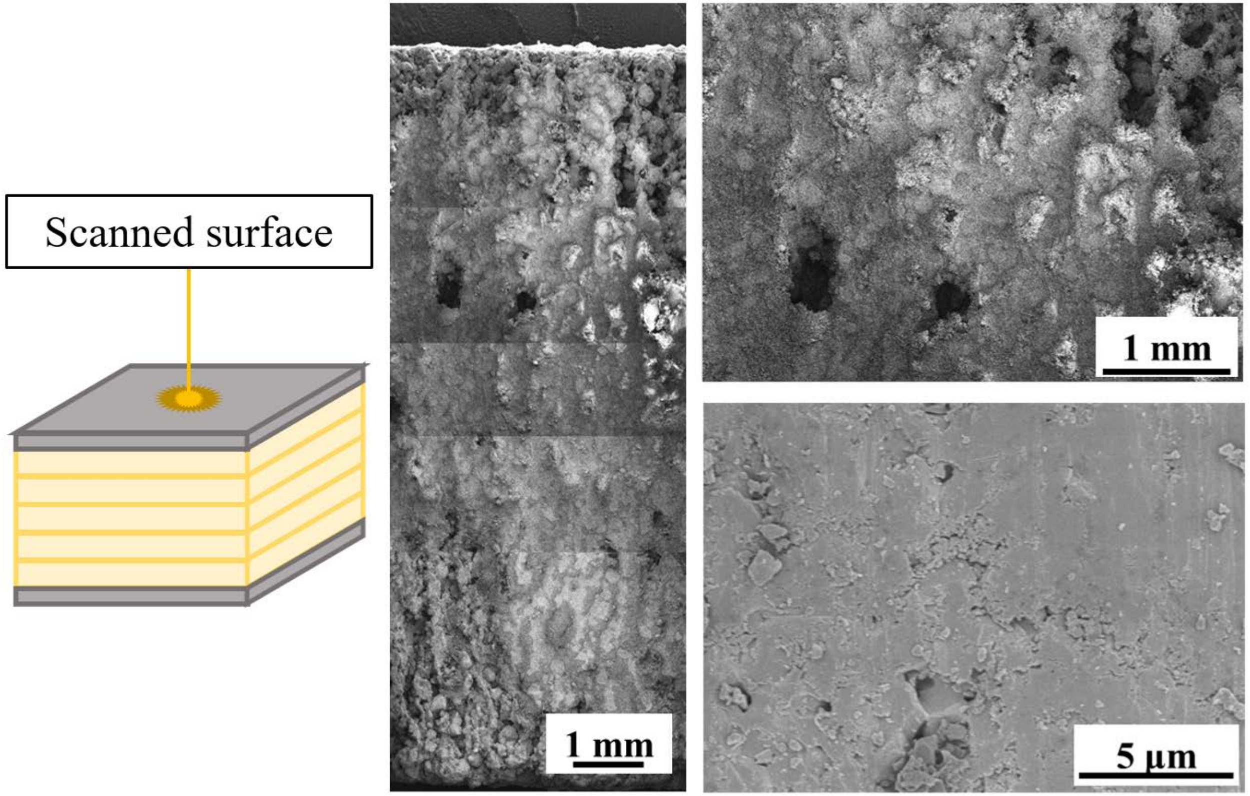


Additive Manufacturing of Piezoelectric Ceramics

SEM

- Different viewing orientations showed different defect patterns

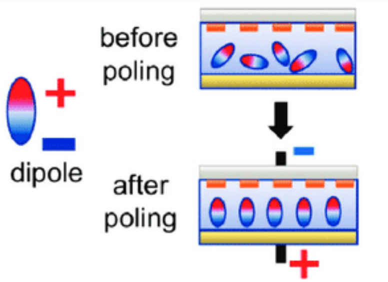


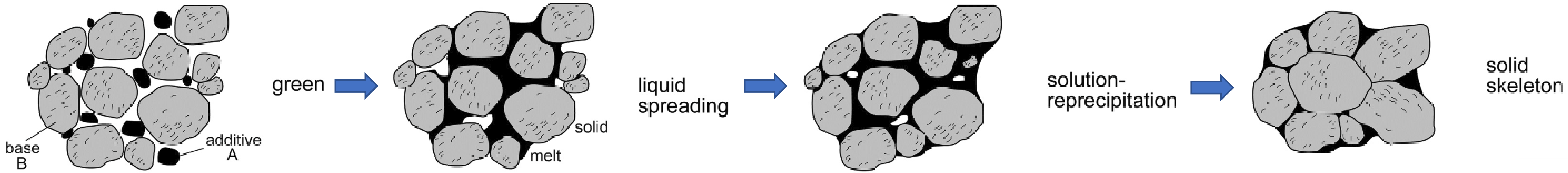


Additive Manufacturing of Piezoelectric Ceramics

Property Optimization

$$C = \varepsilon_o \varepsilon_r \frac{A}{t}$$

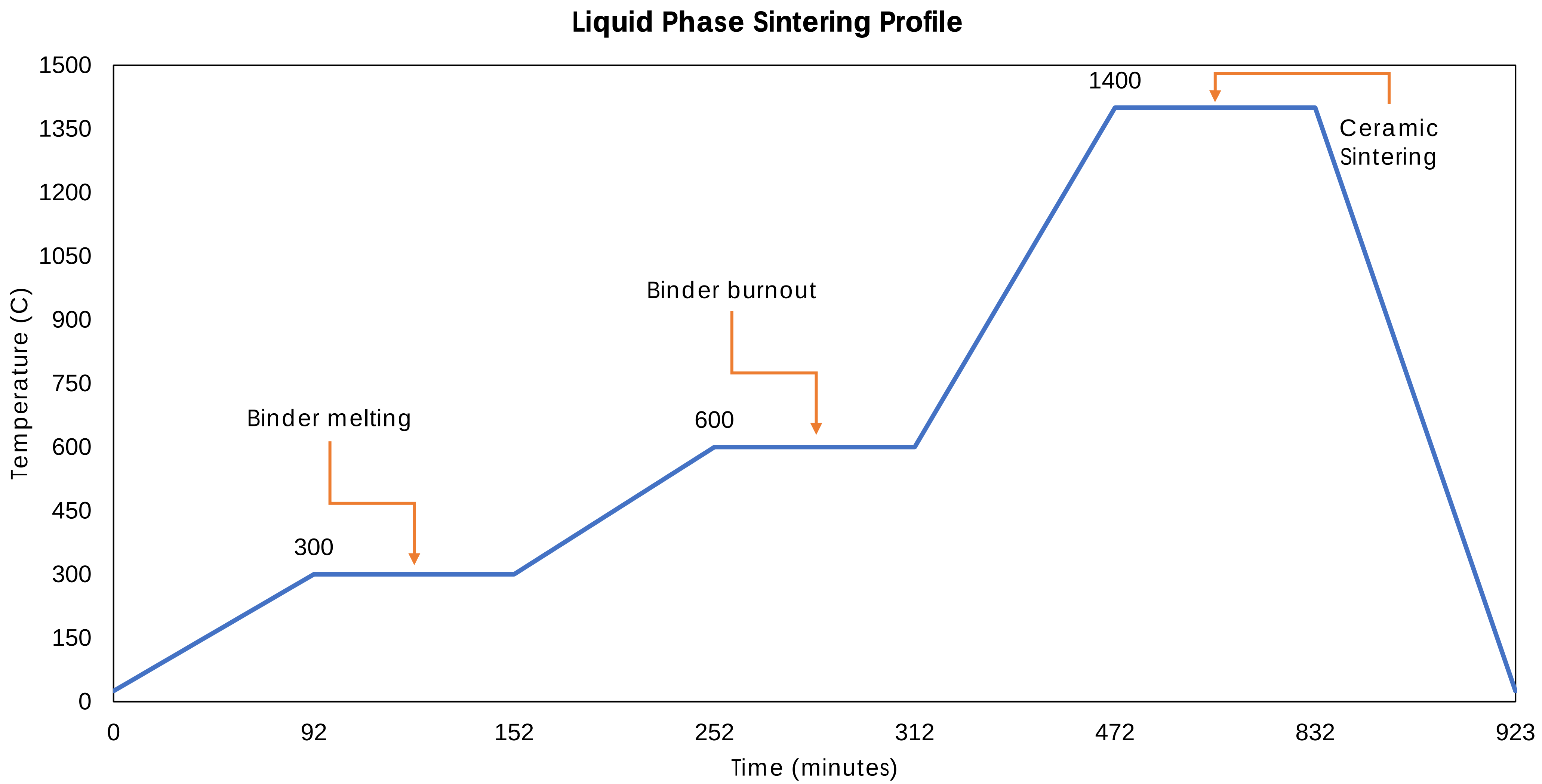




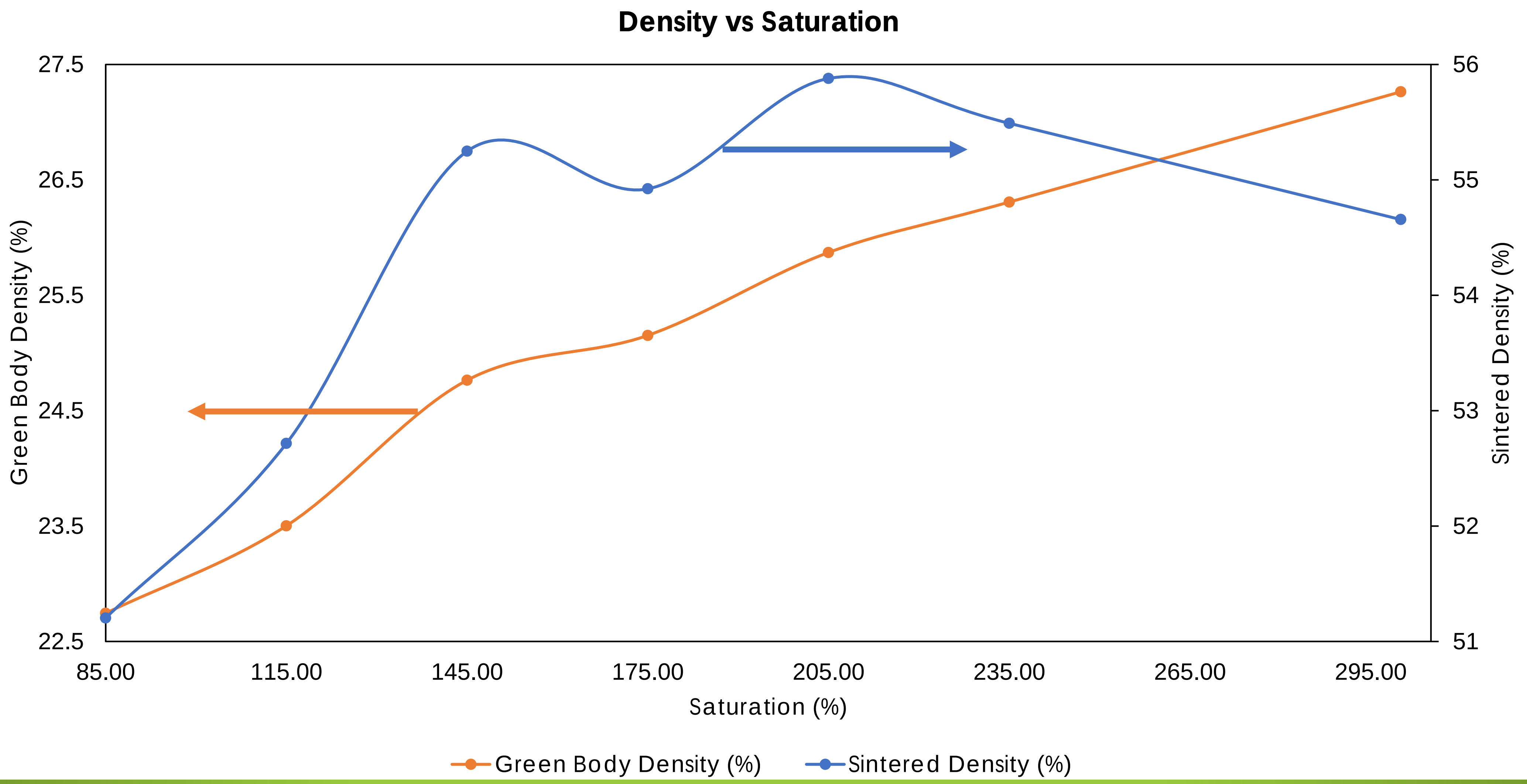
Sintering: From Empirical Observations to Scientific Principles, R. German, 2014

Additive Manufacturing of Piezoelectric Ceramics

Liquid Phase Sintering

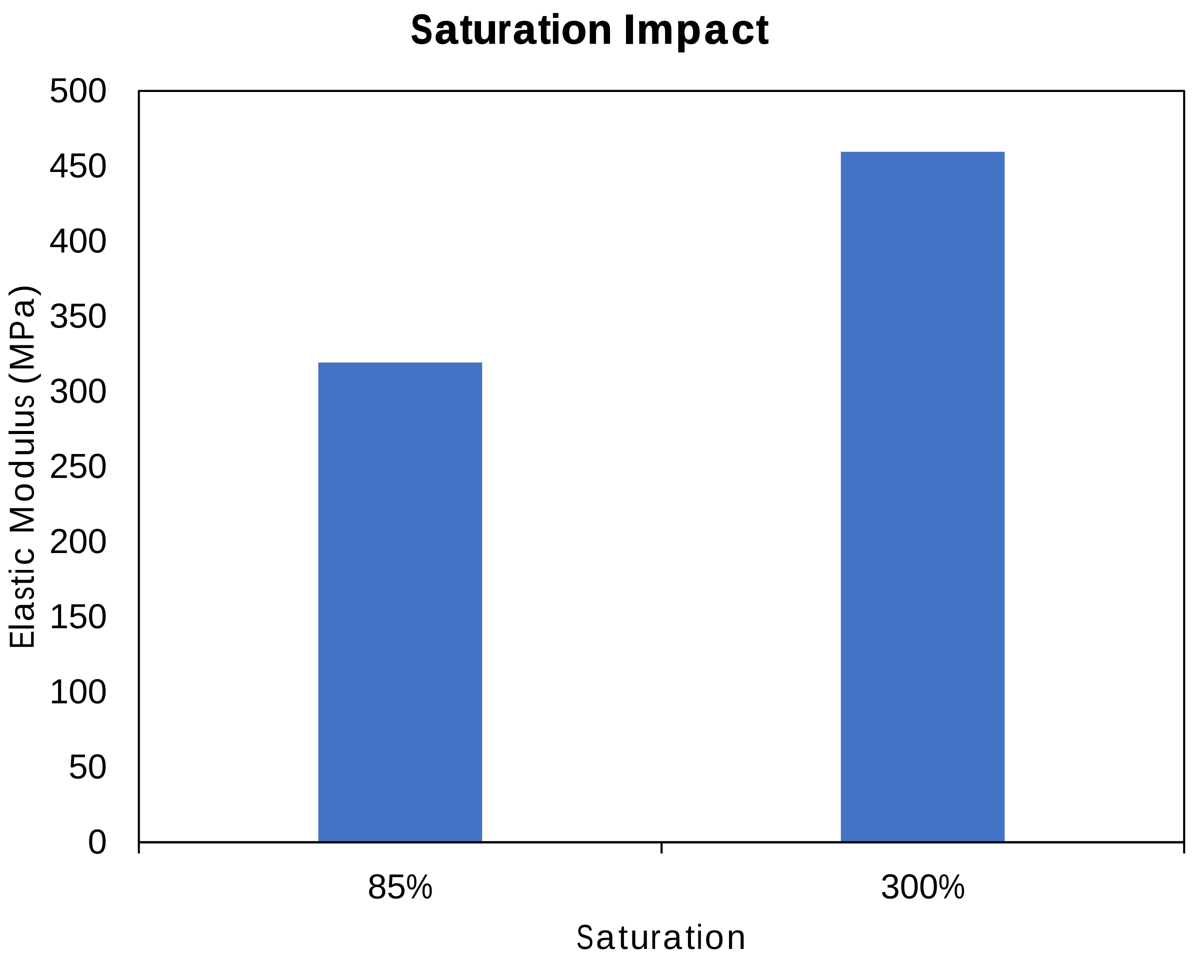


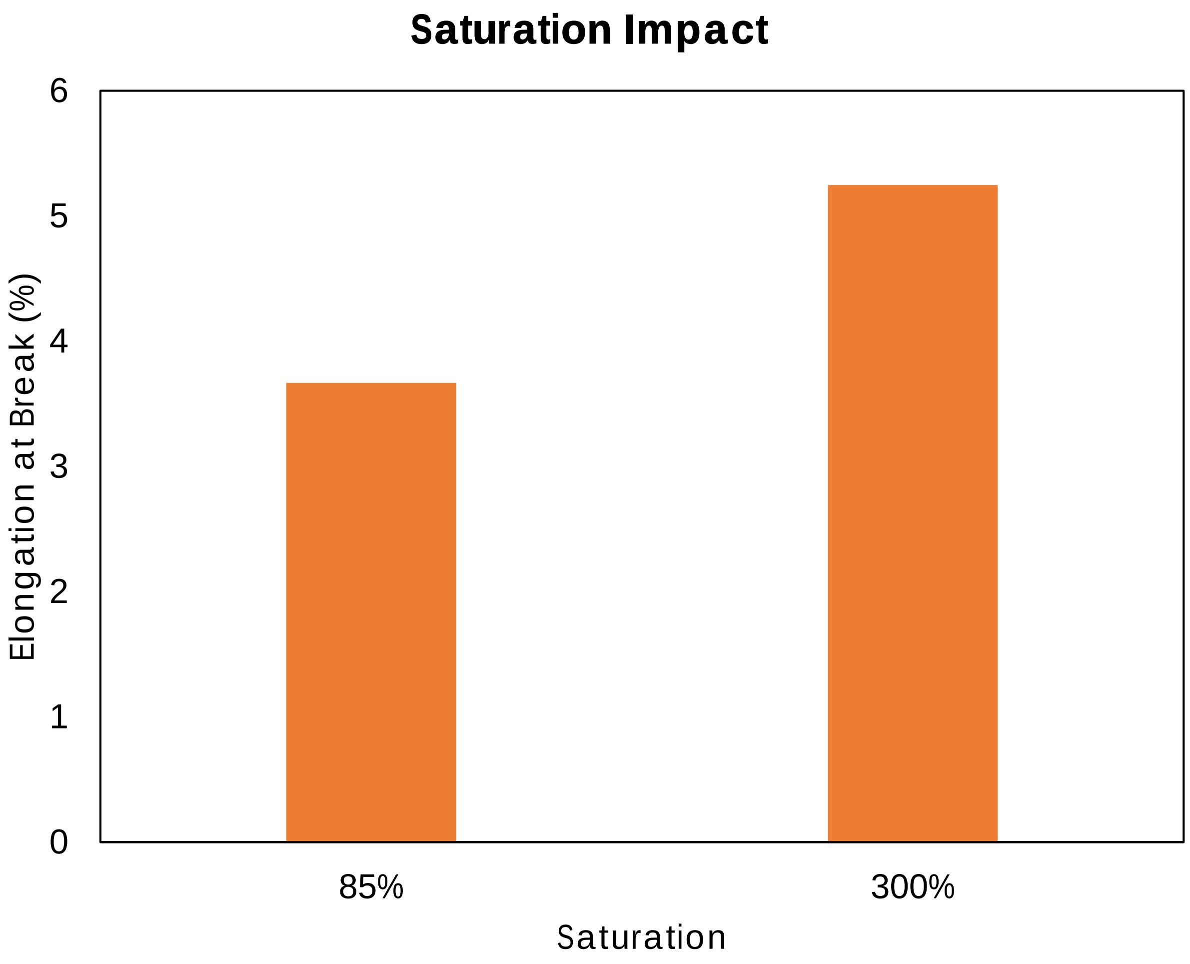
Binder Saturation Influence



Additive Manufacturing of Piezoelectric Ceramics

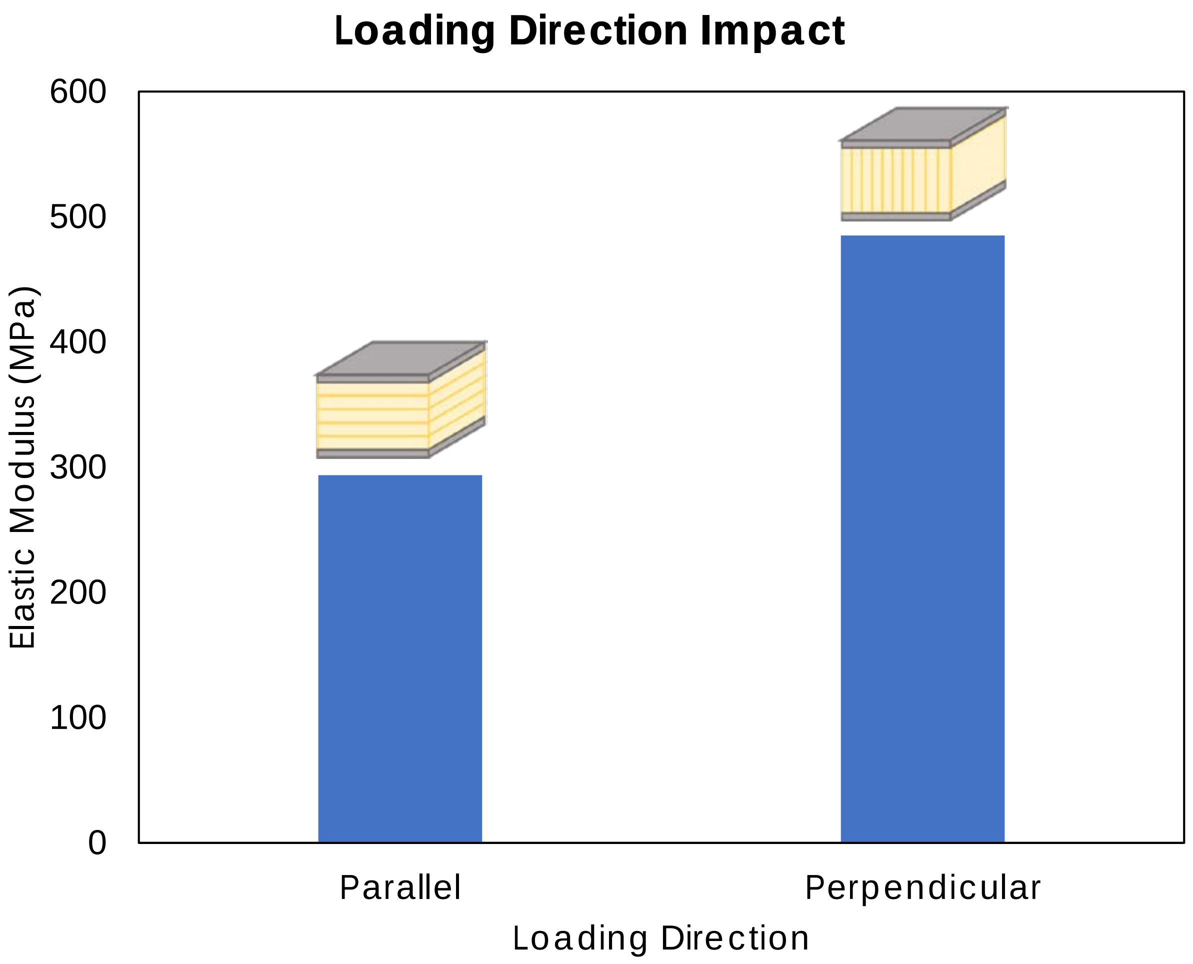
Saturation Influence

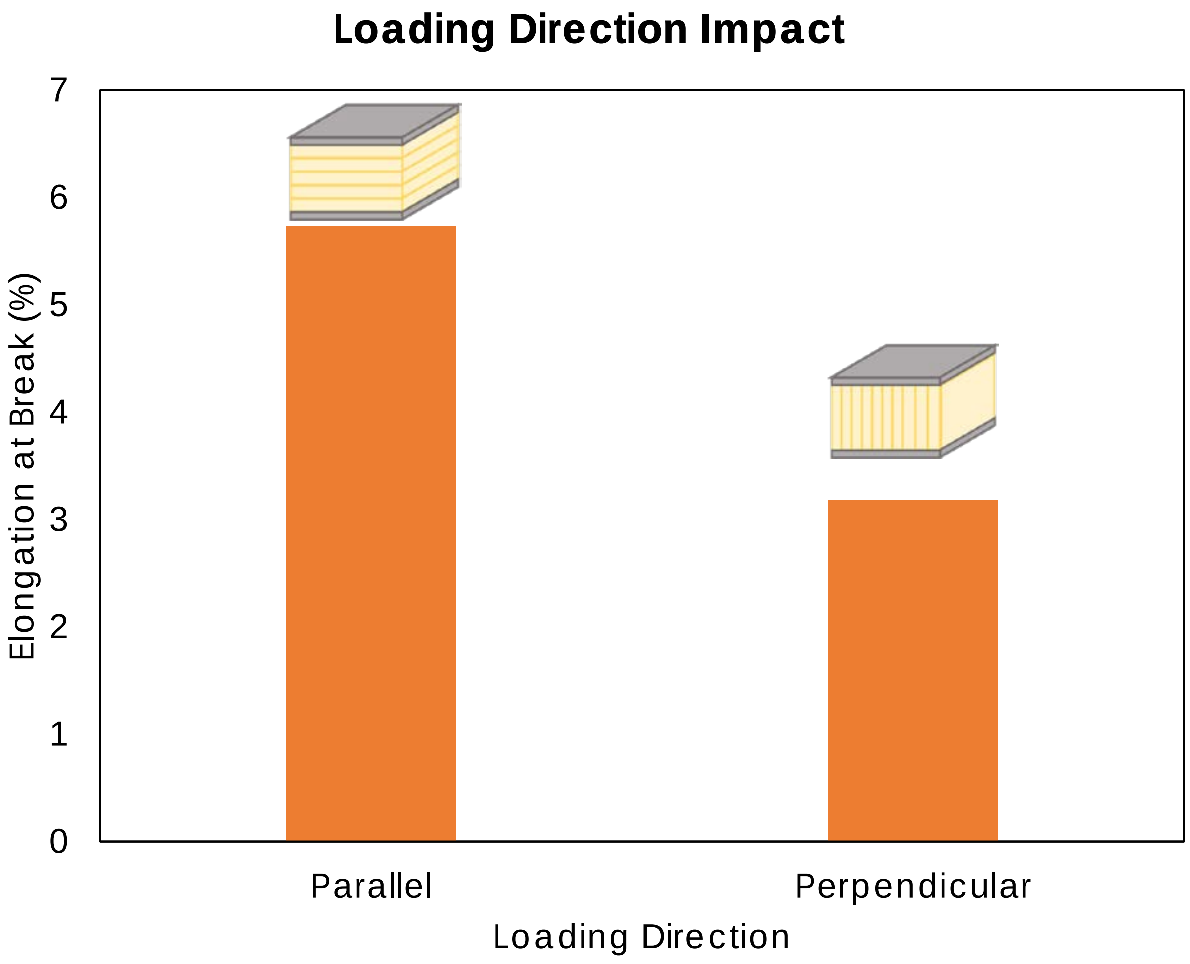




Additive Manufacturing of Piezoelectric Ceramics

Loading Direction Influence

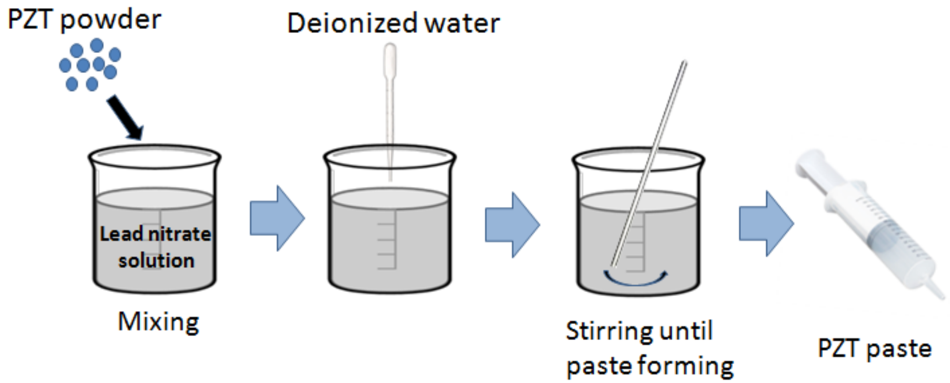


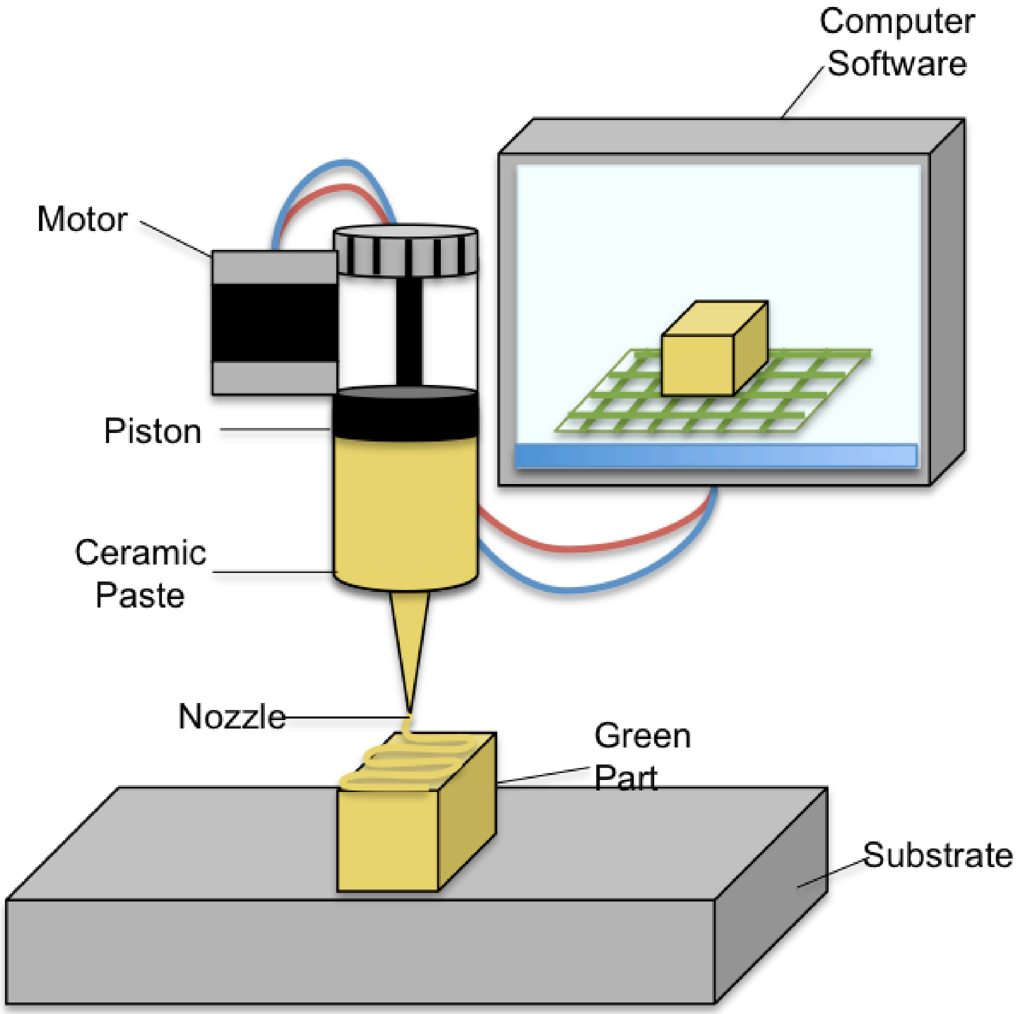


Additive Manufacturing of Piezoelectric Ceramics

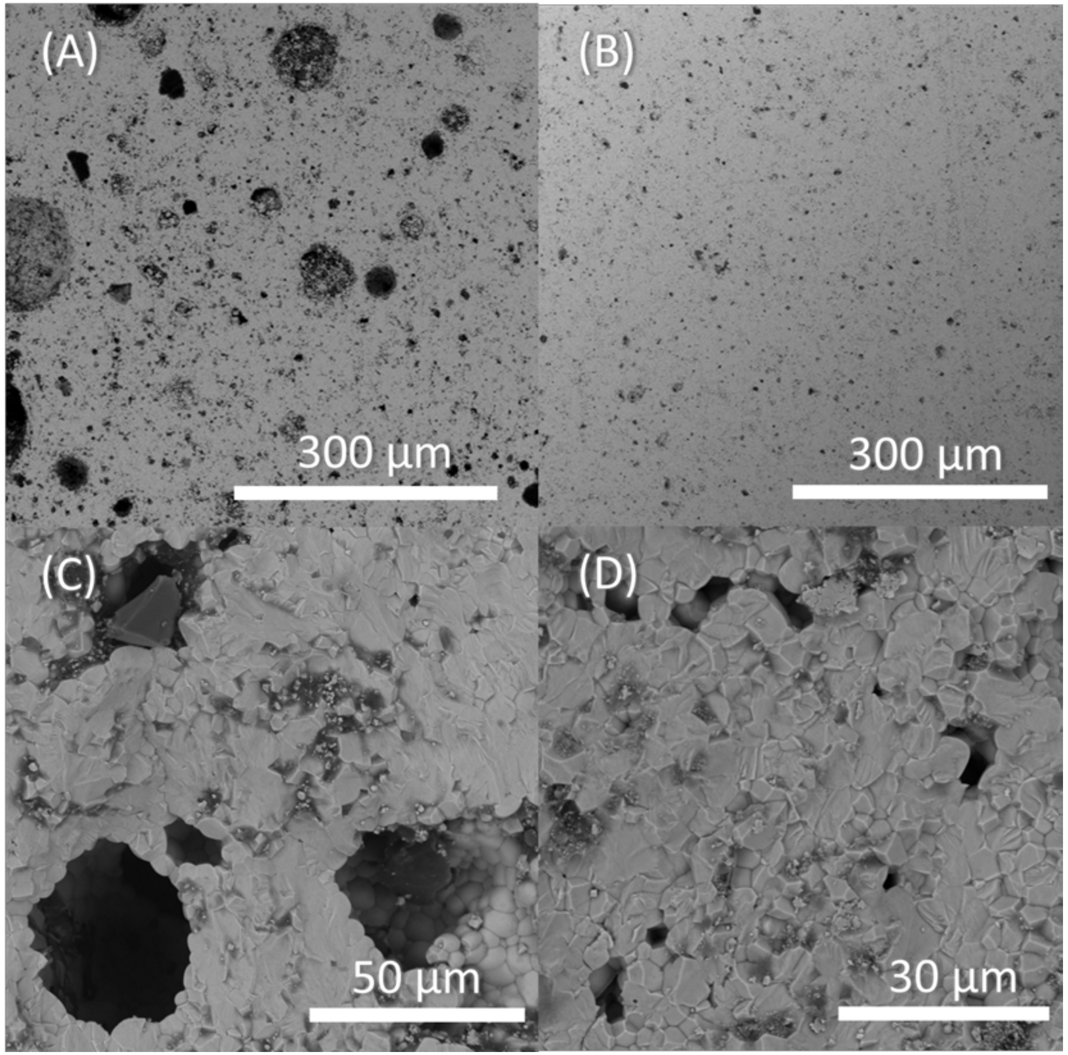
Other Printing Techniques

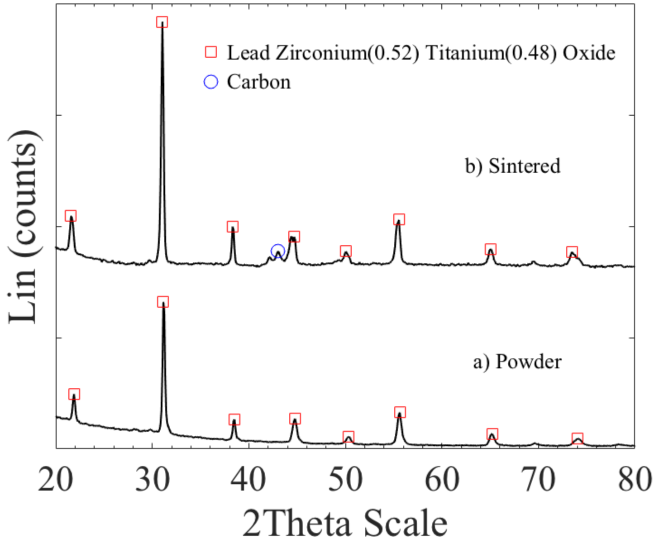
- Paste Extrusion of PZT
  - High density
  - High functional properties
  - Shape retention and resolution

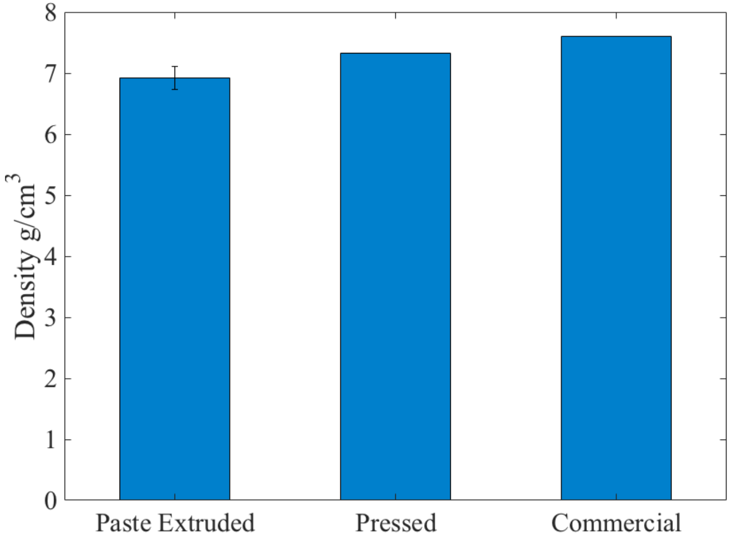




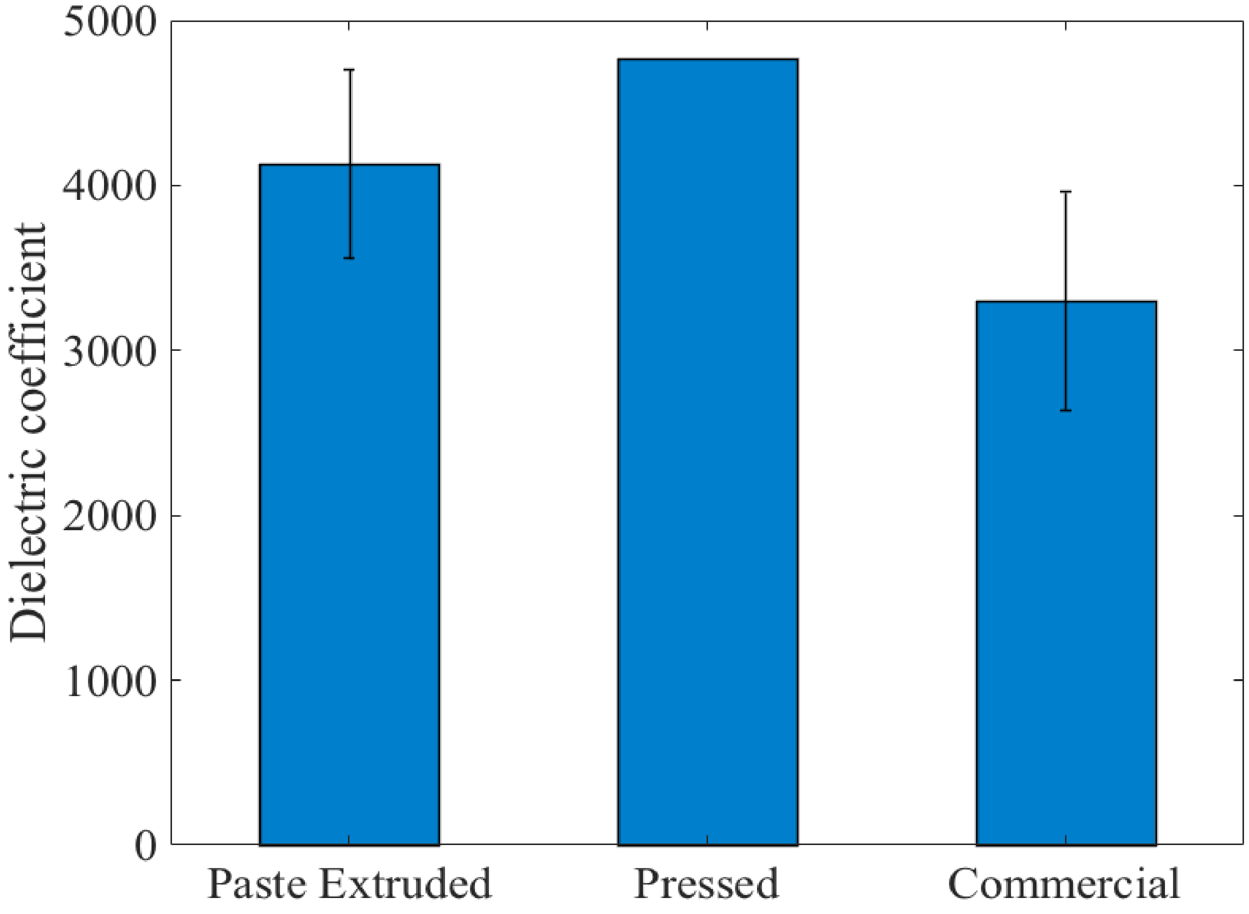
Paste Extrusion of PZT

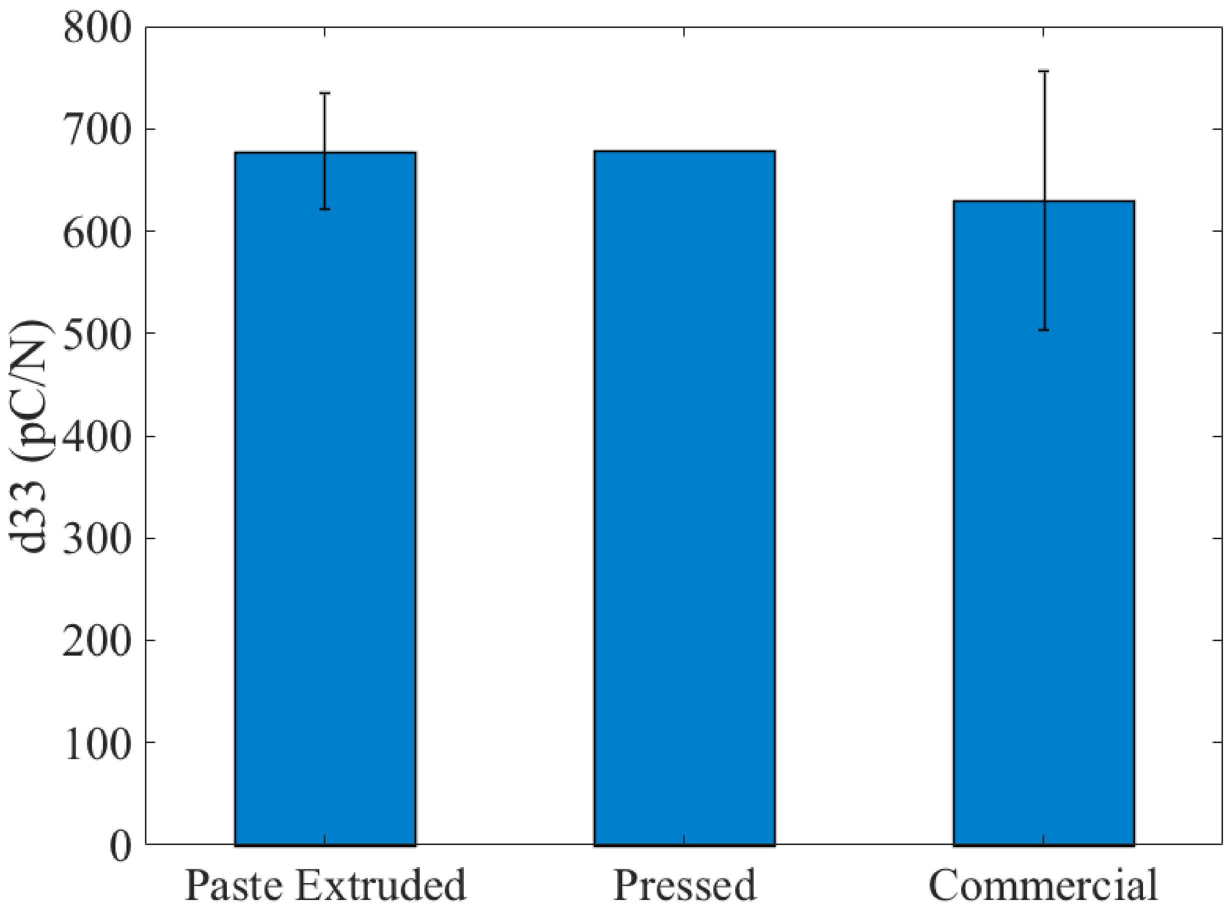






Paste Extrusion of PZT

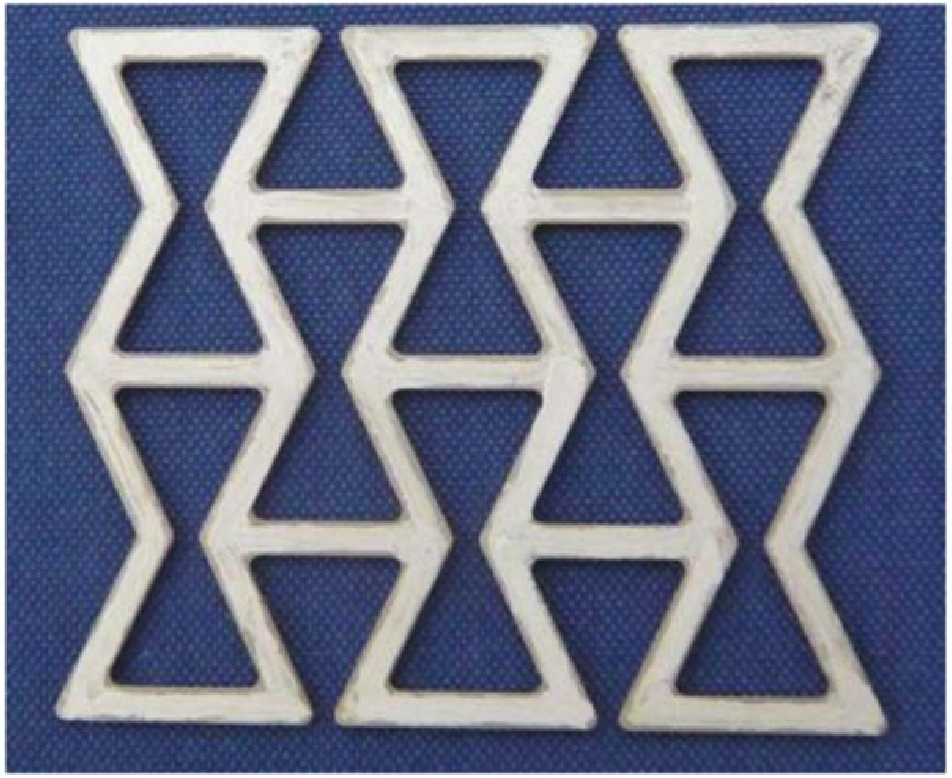




Ongoing Work

Mechanical Energy Harvesting Optimization

- Enhancing piezoelectric response through geometry



Mechanical and electrical strain response of a piezoelectric auxetic PZT lattice structure

Tobias Fey[1], Franziska Eichhorn[1], Guifang Han[1], Kathrin Ebert[1], Moritz Wegener[1], Andreas Roosen[1], Ken-ichi Kakimoto[2] and Peter Greil[1]

Mechanical response ($\sigma^{al}_{22} = -1.62$ MPa)	Poisson's ratio	Strain amplification factor		Stiffness coefficients (GPa)		
	ν_{21}	$\varepsilon^{al}_1/\varepsilon^b$	$\varepsilon^{al}_2/\varepsilon^b$	C^{al}_{11}	C^{al}_{22}	
Measured	−2.05	−70	34	0.385[a]	1.62	
Calculated						
—rib flexure	−2.29	−173	33	0.317	1.67	
—rib stretching	+0.5	2.2	4.4	24.6	12.3	
Piezoelectrical response ($E_3 = -566$ V mm^{-1})	Strain amplification factor		Coupling coefficient (pm V^{-1})			
	$d^{al}_{31}/d^b_{31} = \varepsilon^{al}_1/\varepsilon^b$	$d^{al}_{32}/d^b_{32} = \varepsilon^{al}_2/\varepsilon^b$	d^{al}_{31}	d^{al}_{32}	d^{al}_{33}	d^{al}_h
Bulk PZT			−140	−140	400	120
Auxetic lattice	30.3	29.0	−4240	−4060	400	−7900

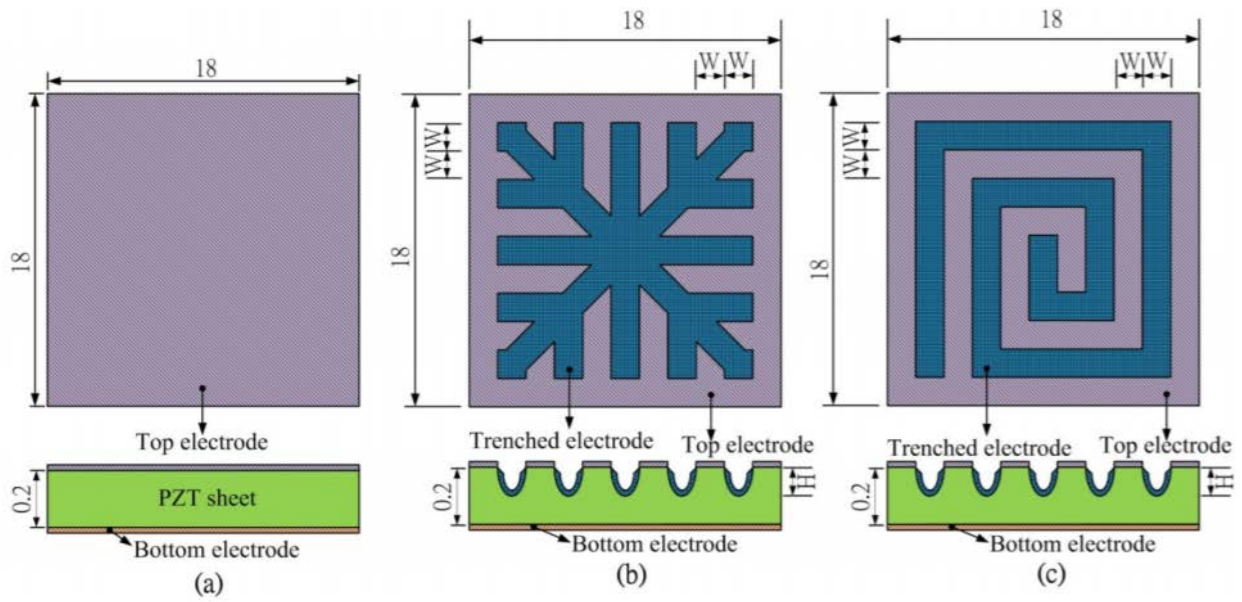
Ongoing Work

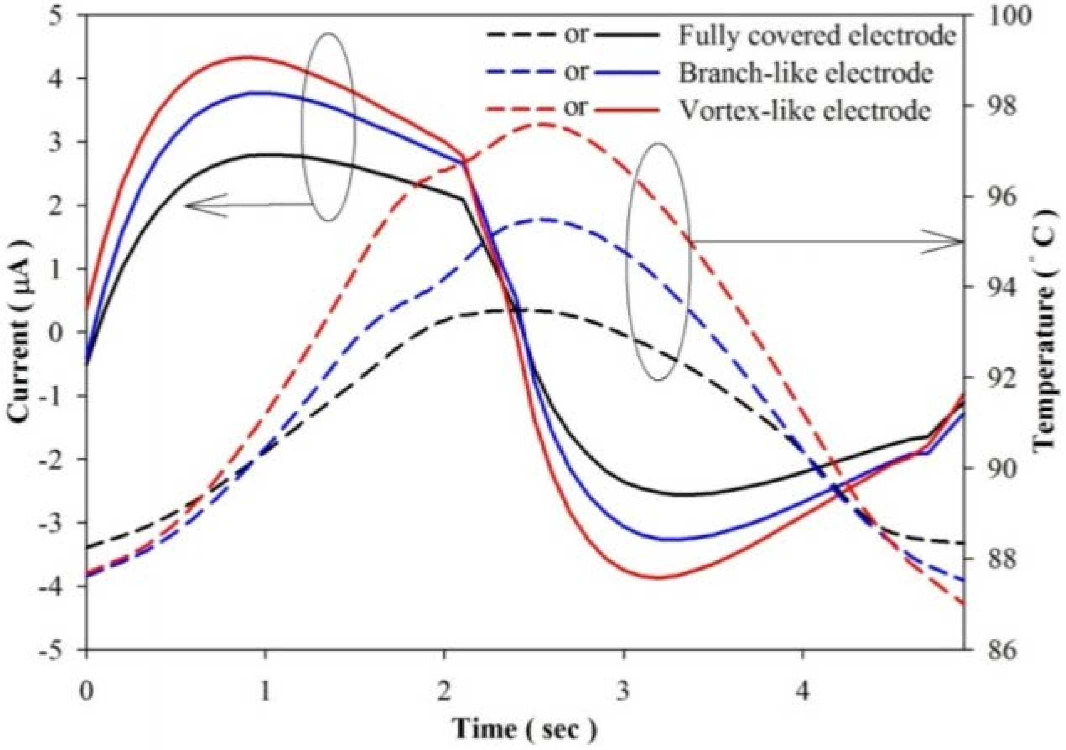
Thermal Energy Harvesting Optimization

- Pyroelectric response enhancement through geometry

Improving Pyroelectric Energy Harvesting Using a Sandblast Etching Technique

Chun-Ching Hsiao * and An-Shen Siao





Preparing Project for Next Steps

Market Benefits

- Efficiency improvement through continuous sensing
- Reduced down-time by eliminating need to replace thermocouples
- Increase wireless sensing adoptability by industry

Technology-to-Market Path

- Industry partner: ExOne, development of printing parameters for ceramics
- Develop a “packaged system”
- Need for stronger collaborations with industry for testing of 3D printed ceramics in real life settings

Concluding Remarks

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Results Summary

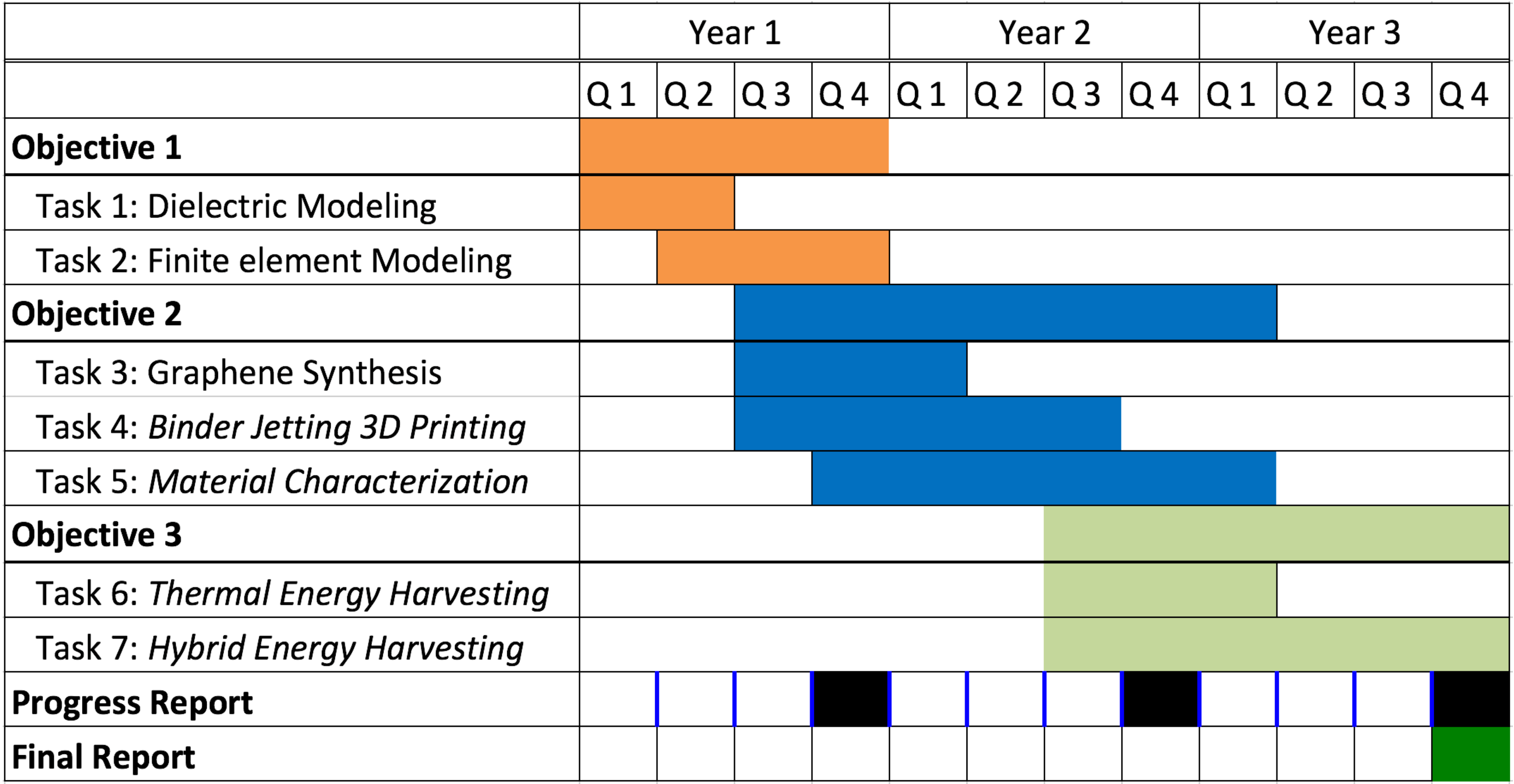
- Pyroelectric energy harvesting using a lead free material was demonstrated
- Current and pyroelectric power were characterized at elevated temperatures
- Hybrid energy harvesting was also performed
- It’s possible to improve the amount of energy harvested by improving the harvesting circuit design and circuit elements
- Low density ceramics with high piezoelectric response were successfully 3D printed
- Demonstrated testing orientation influence in properties of these ceramics

Concluding Remarks

Future Work

- Further optimize properties of 3D printed piezoelectric ceramics
  - Saturation level and sintering profile optimization
- Characterize energy harvesting capabilities of 3D printed ceramics
  - Influence of testing direction in response
- Perform direct sensing using 3D printed ceramics
- Additive manufacture complex structures to tune piezoelectric and pyroelectric responses
  - Lattice structures

Project Schedule



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- Program Manager: **Barbara Carney**, NETL

Student Involvement

Carleigh Simmons: Lockheed Martin

Paulina Ibave: Microsoft, Intern

Sebastian Vargas: Honeywell, Intern

Bethany Wilburn: Lockheed Martin, Intern

Samuel Hall: Starting PhD

Luis Chavez: LANL, Intern

Thank you!

Questions?