U.S. DEPARTMENT OF
ENERGY
Office of Electricity

Development of High Temperature Class II Ceramic Capacitors

TRAC Program Review

US Department of Energy, Office of Electricity

Presented at Oak Ridge National Laboratory

Oak Ridge, TN

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Project Overview

- Capacitors represent one of the top two sources of failure and volume in power electronic modules

- Advances in WBG semiconductor devices mean that operating temperature limitations are imposed on capacitors and packaging

  - Higher Power
  - Greater Efficiency

- Power electronics systems with reduced thermal management requirements are highly desirable

  - High Power Density
  - Reduced Complexity
  - Reduced cooling-related failures

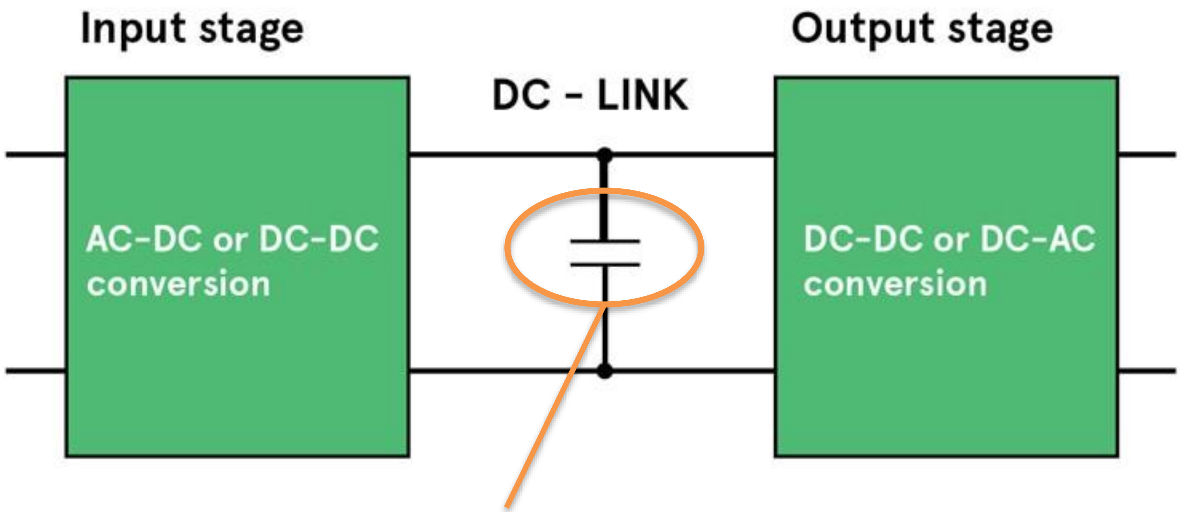
- Available high operating temperature capacitors fail to meet the criteria for desired performance and reliability

  - Severe Derating
  - Large Volume
  - Expensive

GOAL: Push forward reliable high temperature capacitor technology toward commercialization

- Budget: FY2020 – 480K, FY2021 – 480K

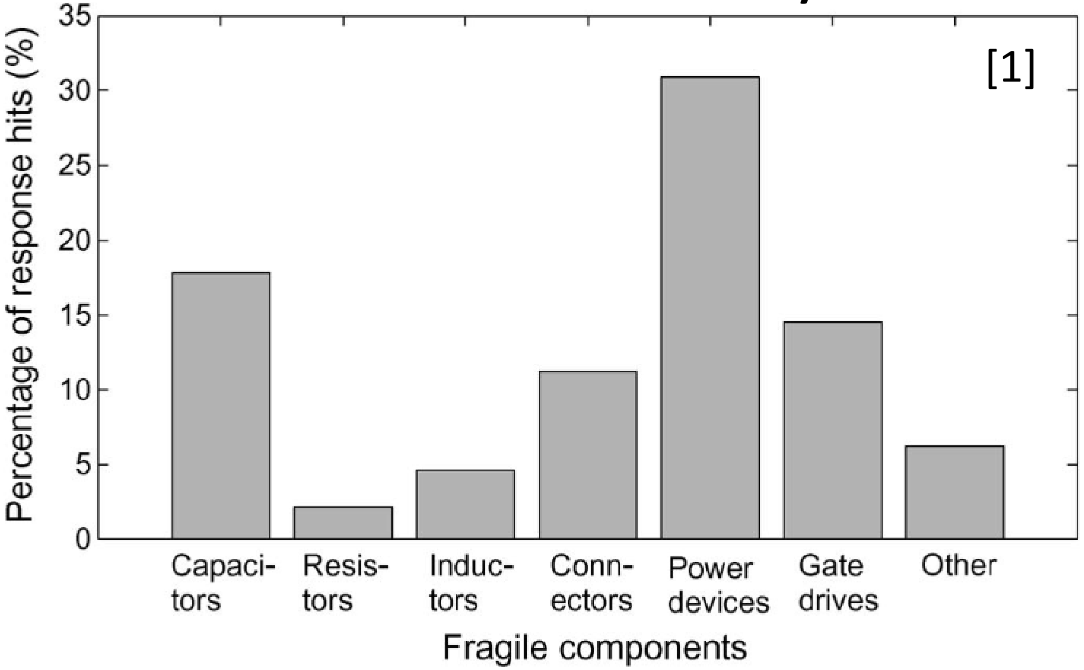
Challenges for DC Link Capacitors in Power Electronic Applications



<u>DC Link Capacitor Needs For Power Electronics:</u>

- High Ripple Current Capability
  - High Thermal Stability
  - Low Loss
  - Low ESR/ESL
- Long DC Lifetime
- High Voltage Capabilities (400V+)
- High Capacitance (10 to >100's uF)

Capacitors are a major reliability concern in Power Electronic Systems



To meet future needs capacitors require innovation in both baseline technology development as well as reliability

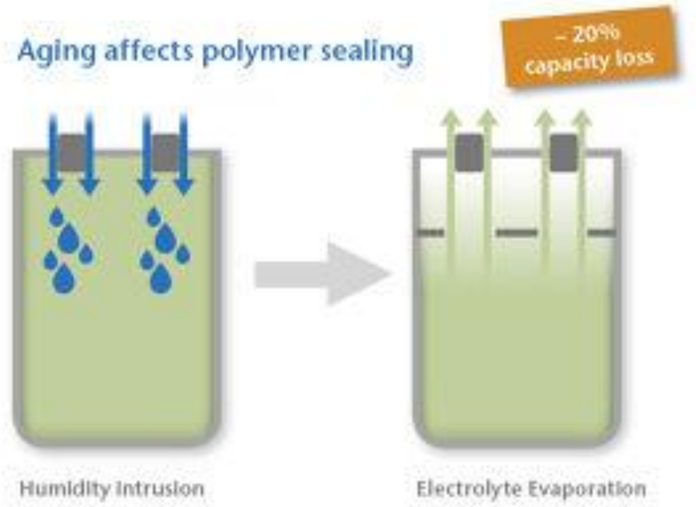
[1] S. Yang et al. IEE Trans. On Indus. App., 47 (3), 2001

Current State Of Capacitor Tech and Paths Forward

Aluminum Electrolytic

Challenges

- Short high-temperature lifetime due to electrolyte evaporation
- High ESR



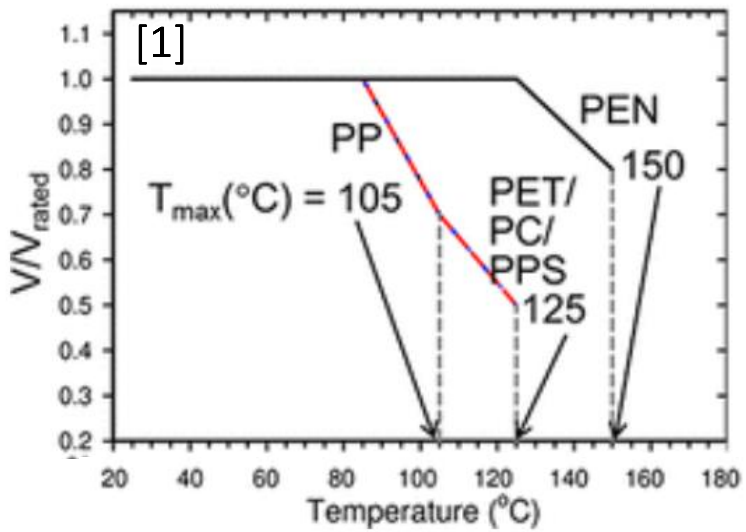
Strategies

- Development of polymer electrolytes
- Increased seal robustness and materials development
- High-Temp low-ESR electrolyte formulation

Polymer Film

Challenges

- Common films must be heavily derated >125°C (Polymer melts)
- High-temp polymers have low processability and poor self-healing behavior (inc. derating)



Strategies

- Materials development for new high-temp polymers/blends
- Decreasing minimum achievable dielectric thickness for current high-temp polymers (increase capacitance)

[1] J. S. Ho, S. G. Greenbaum, ACS Appl. Mater. Interfaces 2018, 10, 35, 29189-29218

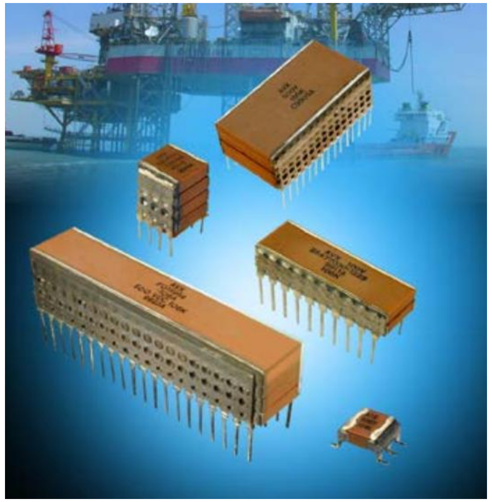
Current State Of Capacitor Tech and Paths Forward

Ceramic Capacitors

Class I

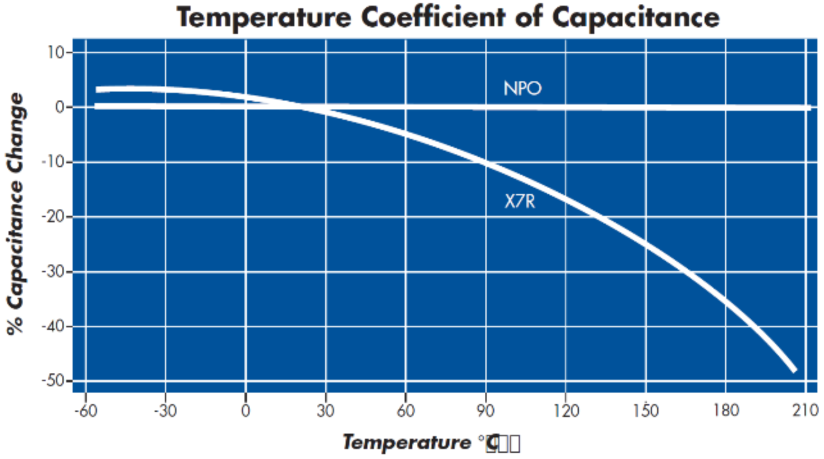
High Temp Stability (200°C)
Low ESR/ESL (limited by stacking design)
High Reliability Margin
High Ripple Current Rating

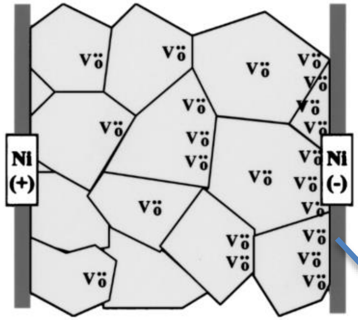
Low Capacitance

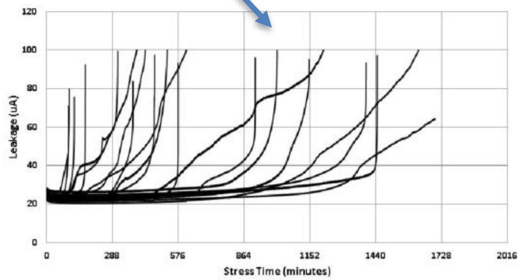


Class II

- High Capacitance
  - Decreases at temperature decreases (X7R)
- Low ESR, ESL
- Low Loss
  - Increases at high (200°C+) temperatures
- Long DC Lifetime
  - Worsens with temperature - Resistance Degradation

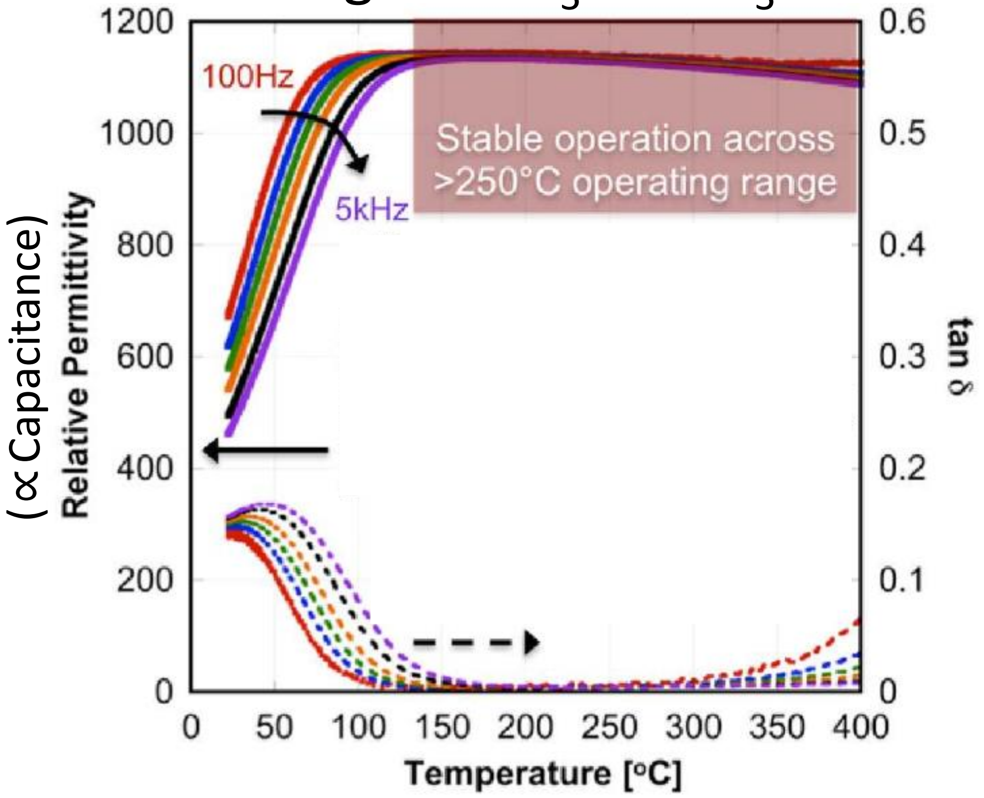


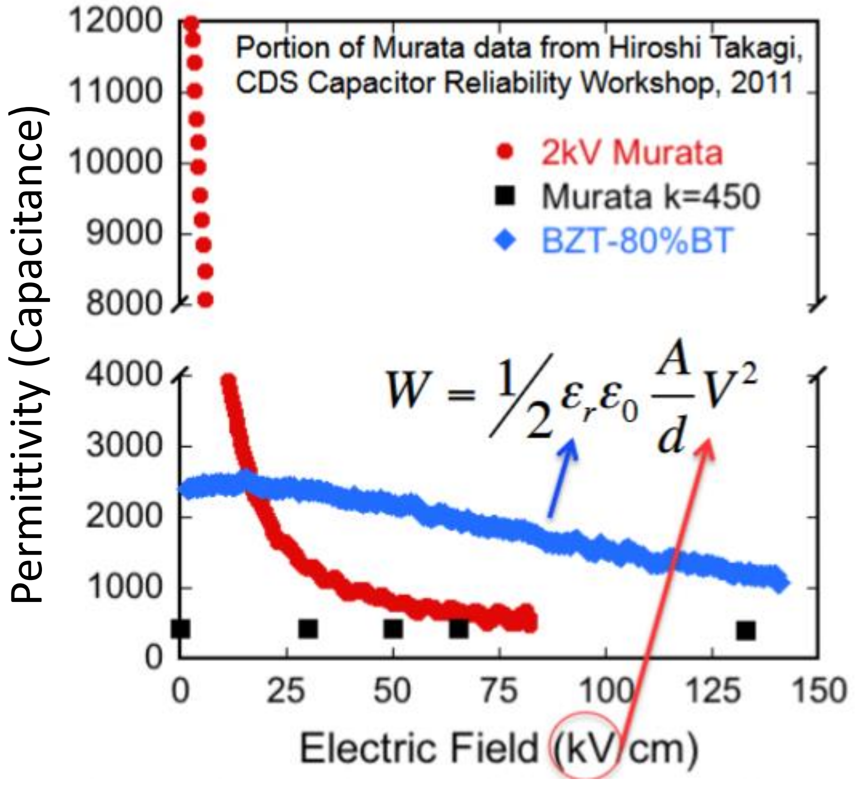




A Class II Ceramic Capacitor Materials Solution

E.g. $BiZnO_3$-$BaTiO_3$



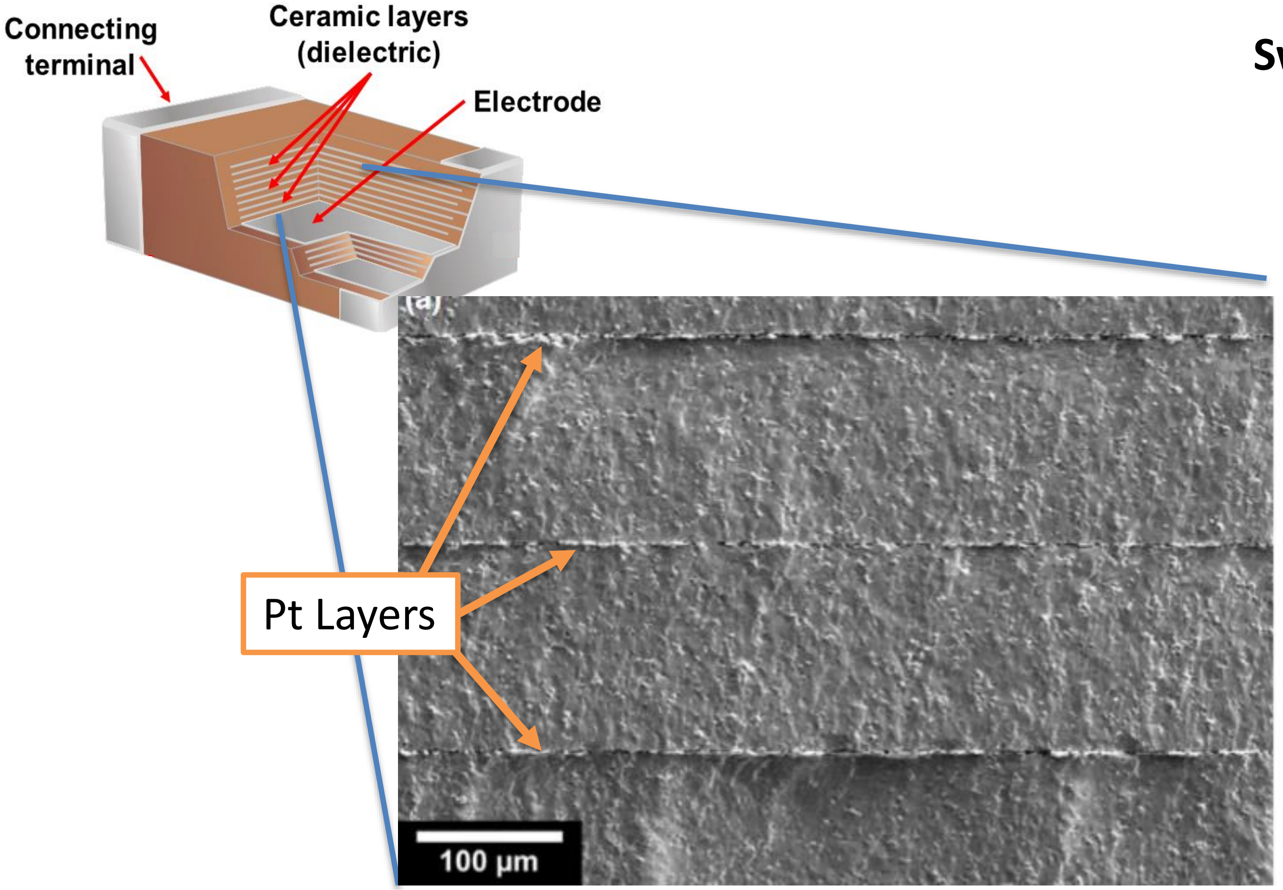


- Solid solutions of $BaTiO_3$ and various other materials ($BiZnO_3$, $BiScO_3$, $NaNbO_3$, etc.) allow for new high temperature Class II compositions

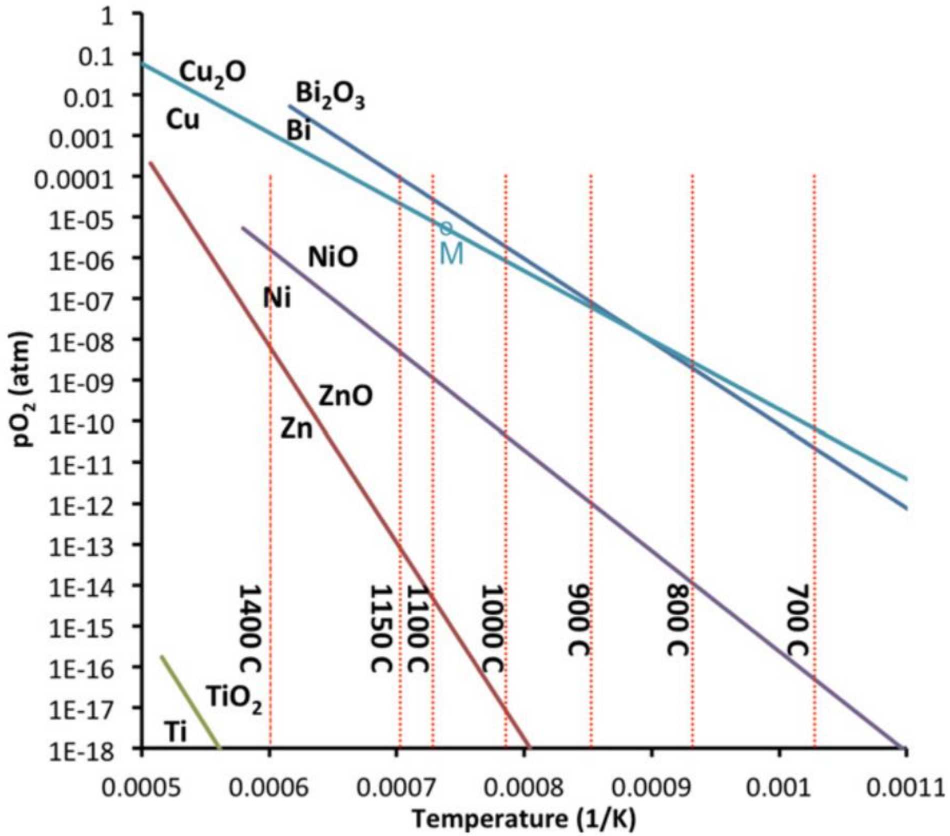
- Stable Capacitance at High Temperature
- Retains Capacitance at high E-fields
  - Allows for high energy density in PE Systems

Modified dielectrics which enable high capacitance at high voltage and temperature have been identified

Two Problems: Cost and Degradation



Switching to more common Ni or Cu electrodes is difficult – Bi metal will be formed if dielectric is reduced

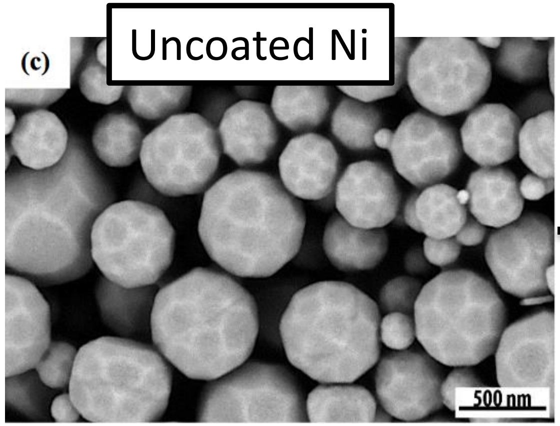


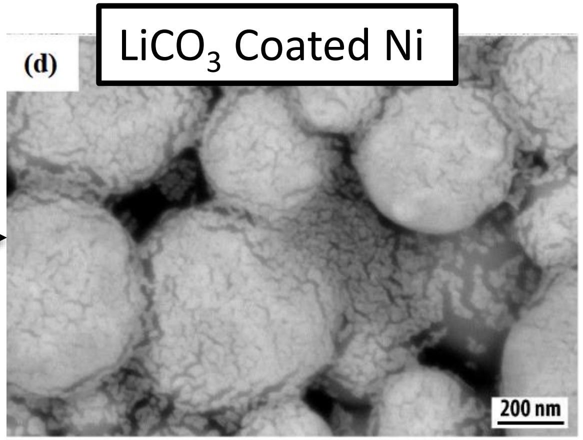
- Lab-Scale MLCC Production Shown
- Pt Electrodes used
  - Cost Impact, Commercialization Unlikely

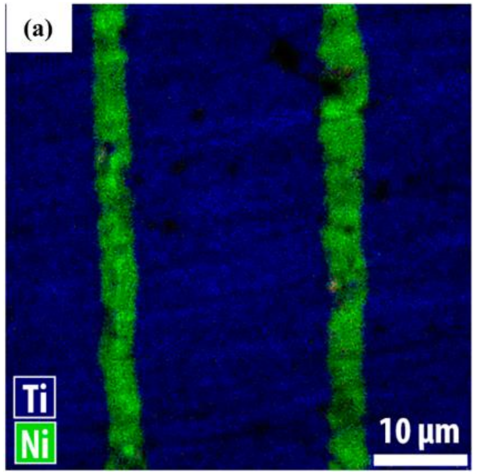
Novel processing techniques are needed to replace Pt electrodes with Ni or Cu for cost reduction

M. Beuerlein, et al., J. Am. Cer. Soc., 99 (9), 2849-2870 (2016)

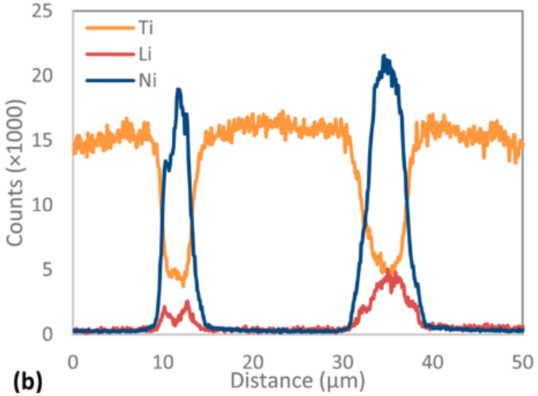
$LiCO_3$-coated Ni Particles for near-ambient pO_2 processing

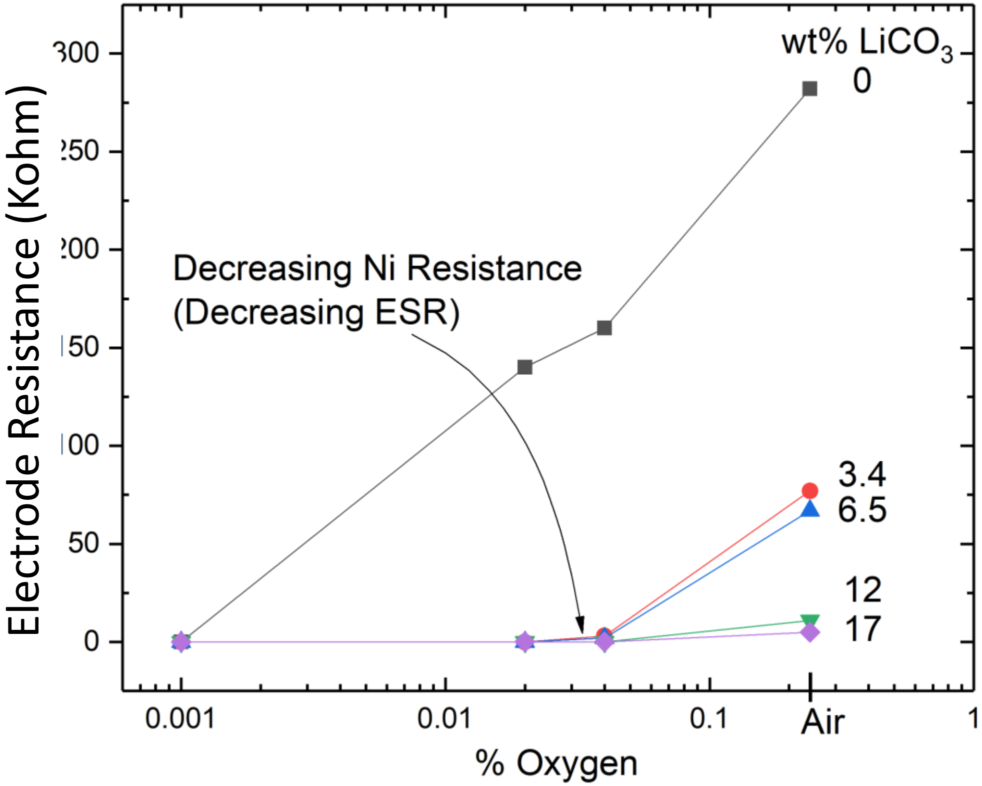






Lab-scale BTO capacitors showed successful fabrication in previous studies





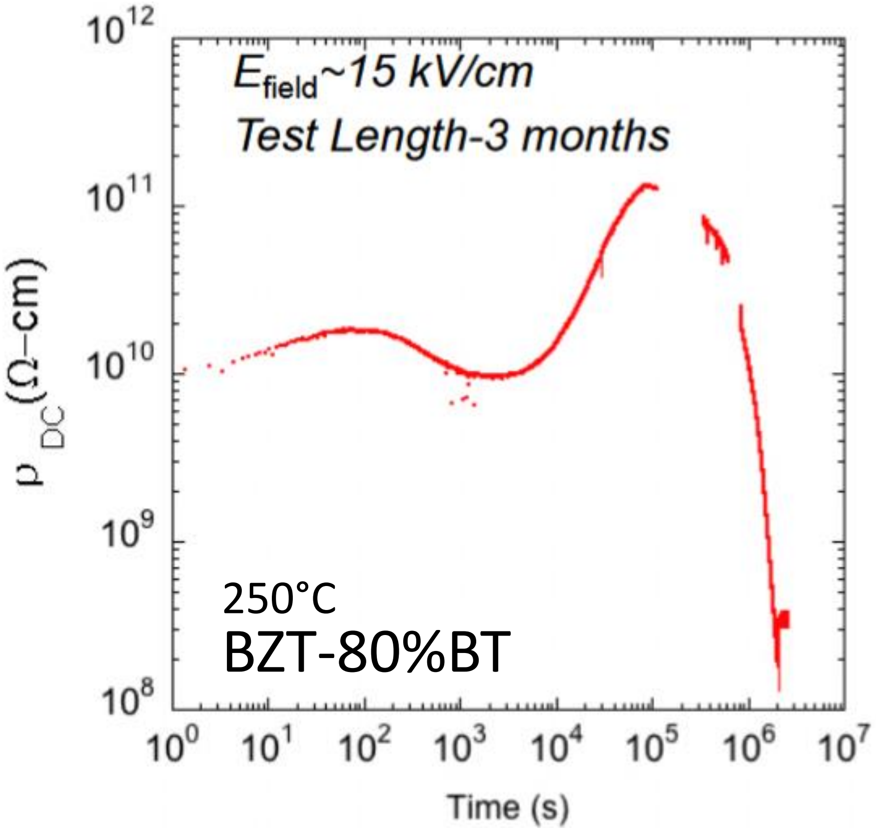
Higher pO2's can be used during processing, limiting Bismuth metal formation

If successful, replacement of Pt with Ni will significantly reduce cost

DBS Heidary, Ph.D. Dissertation, "Novel Processing Coating Techniques Toward Improved Electro-Ceramics" (2016)

Two Problems: Cost and Degradation

Degradation: High Temperature Dielectric Material Tested Under High Temp/Field for extended times



- Initial material studies show dielectric will become more conductive given time under temperature and voltage (degradation).
- Degradation process will limit lifetime of BZT-BT capacitors in DC Link applications
- We must understand this phenomenon to help extend lifetime of DC link capacitors

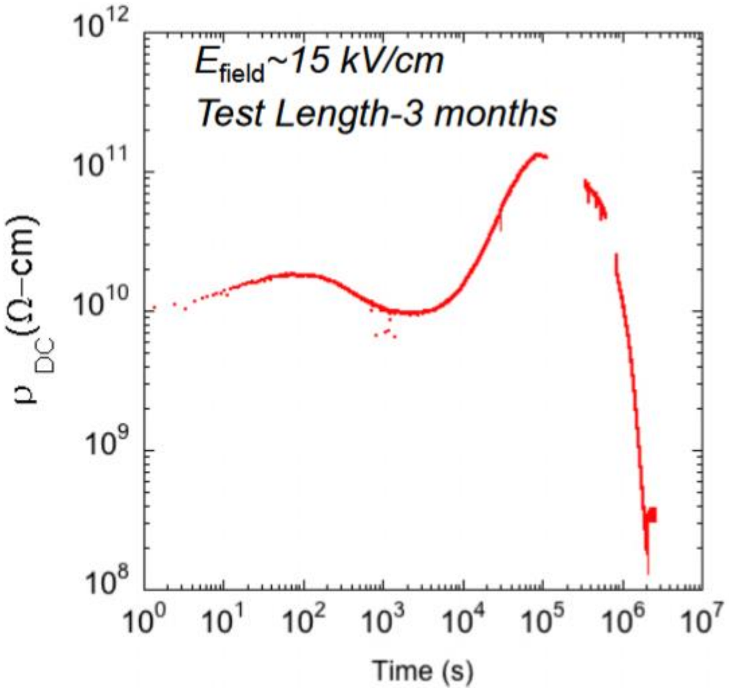
Electromigration of defects is key culprit

Doping strategies to maximize lifetime from X7R($BaTiO_3$) capacitors can be utilized

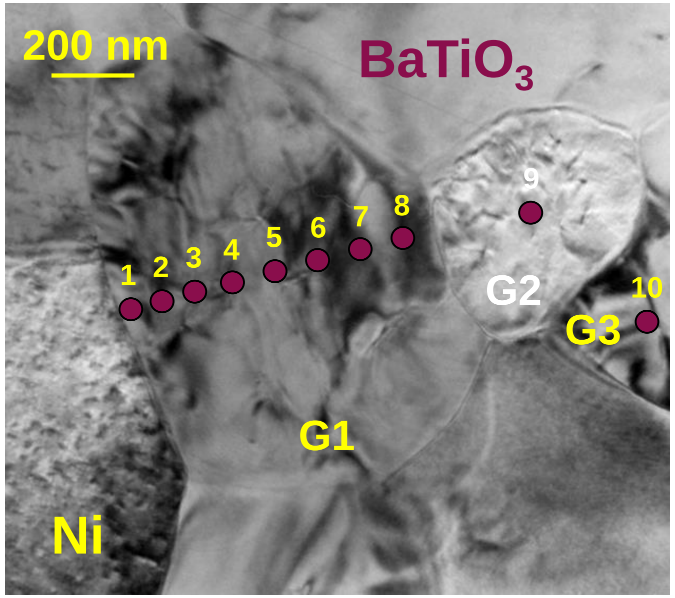
Understanding Root Cause of Degradation Can Point Toward Mitigation Strategies, and Increase DC Lifetime

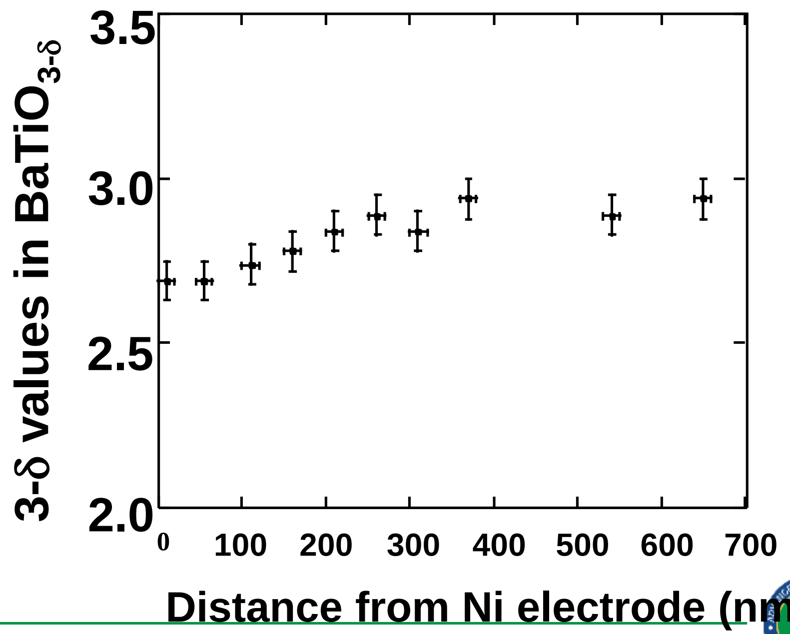
DC Lifetime experiments for BZT-BT materials

- GOAL: Accelerate Degradation Phenomenon at high temperatures and fields
- Similar to $BaTiO_3$ Identify the defects/cations which are migrating, and confirm mechanism
- Use knowledge to adjust/down select dielectric material



Example from $BaTiO_3$





Yang, et al., J. of Appl. Phys, 96 (12), 2004

Initial steps

- Begin Work in FY2020

- Initial compositional work
  - Confirm Dielectric Processing route
  - Dial in lab-scale manufacturing procedures
  - Coat Ni particles and confirm low resistance behavior in air

- Degradation: Identify electromigration species
  - Degrade dielectric pellets under accelerated conditions at High fields/Temp
  - Identify compositional inhomogeneity along field direction via EDS/EELS
  - Down-select key candidates for dielectric modifications to maximize lifetime

Significance of the results, if successful

- Successfully adding Ni electrodes into high temp Class II capacitors can drastically reduce cost of manufacture
  - Commercialization becomes move viable path forward

- Understanding of loss of dielectric resistance (degradation) can lead to a path forward for increasing DC lifetime

- Low ESR, High Temperature, Long Lifetime, High Energy Density capacitors enable higher reliability, decreased complexity, and higher power density power electronics

Anticipated challenges and risk mitigation strategies

Risks	Realization Effects	Mitigation Strategies
Tape casting/screen printing procedures difficult to dial in on new systems	Timeline delays due to increased MLCC development time	Currently reaching out to internal ceramics processing team to identify SNL tape casting expertise to speed up development
Staff Time Over commitment	Lower time commitment than suggested	Investigating increased staffing including technical staff
Large variability in DC lifetime testing results/Wide Weibull	DC Lifetime test overburden	Identifying scale-up strategies of DC lifetime testing equipment

Thank You

Questions?

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