U.S. DEPARTMENT OF ENERGY
Office of Electricity

SAND2019-9286PE

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 are imposed by capacitors and packaging

  - Higher Power
  - Greater Efficiency

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

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

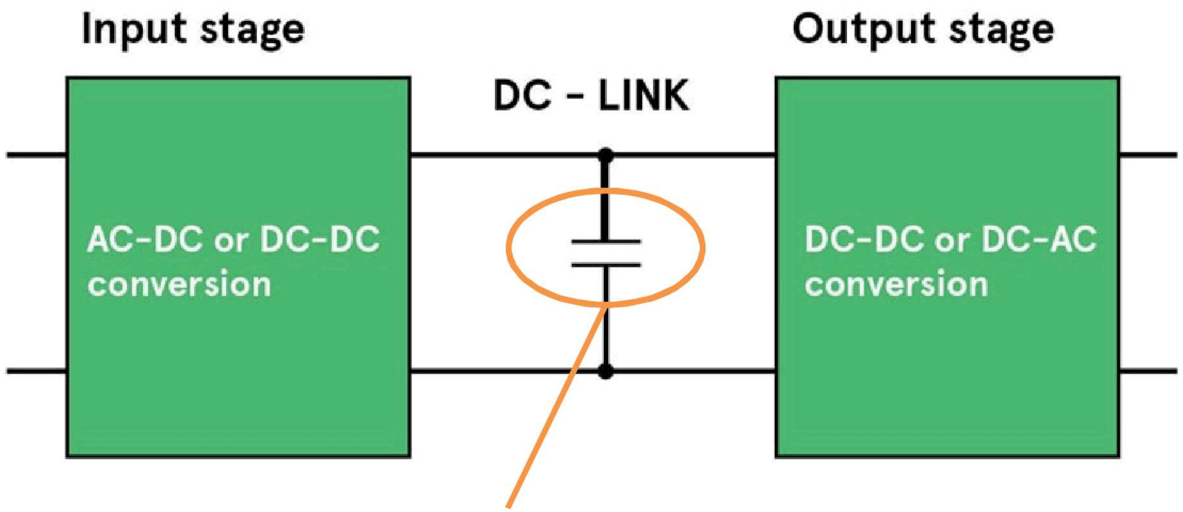
- Available high operating temperature capacitors fail to meet the criteria for desired performance and reliability

  - Severe Derating
  - Large Volume
  - Expensive

GOAL: Push forward reliable high temperature capacitor technology toward commercialization

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

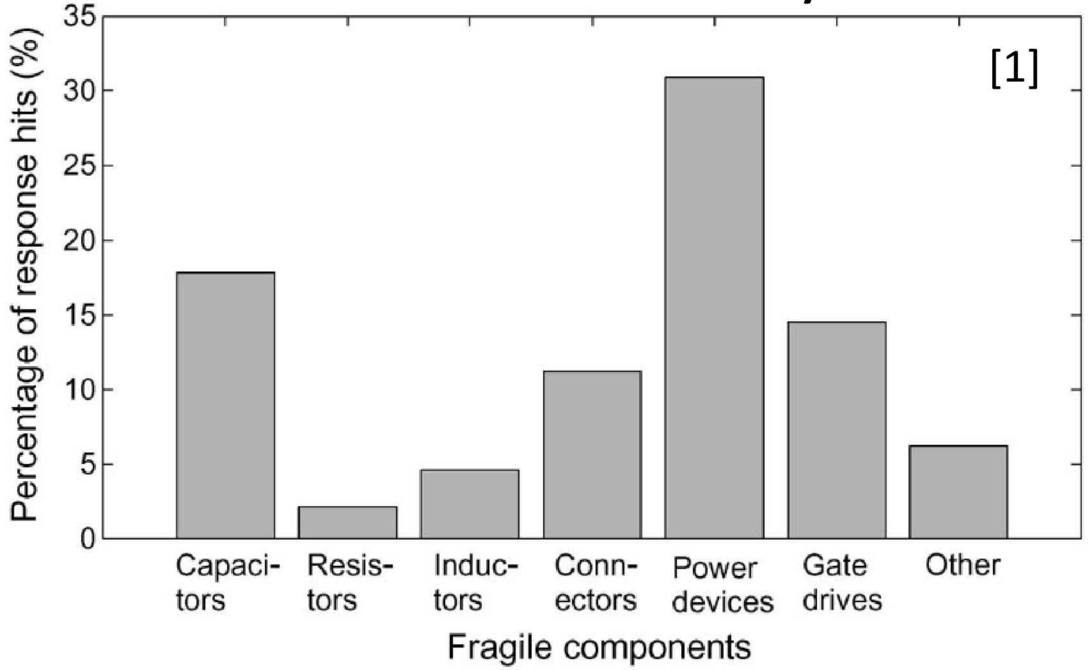
Challenges for DC Link Capacitors in Power Electronic Applications



<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's-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

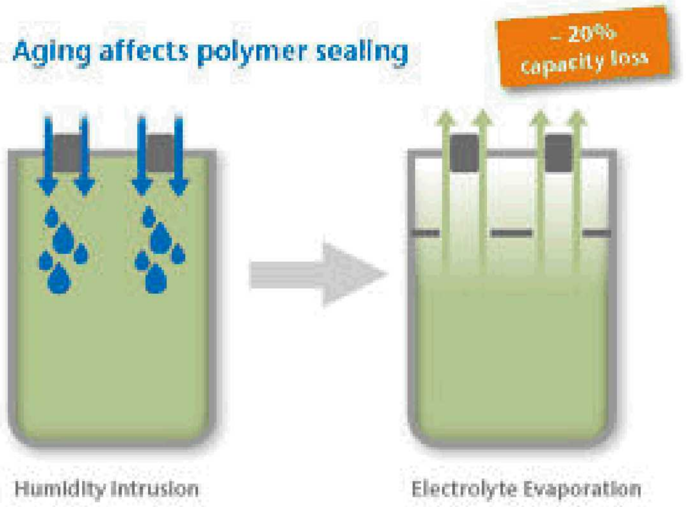
[1] S. Yang et al. IEE Trans. On Indus. App., 47 (3), 2001

Current State Of Capacitor Tech and Paths Forward

Aluminum Electrolytic

Challenges

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



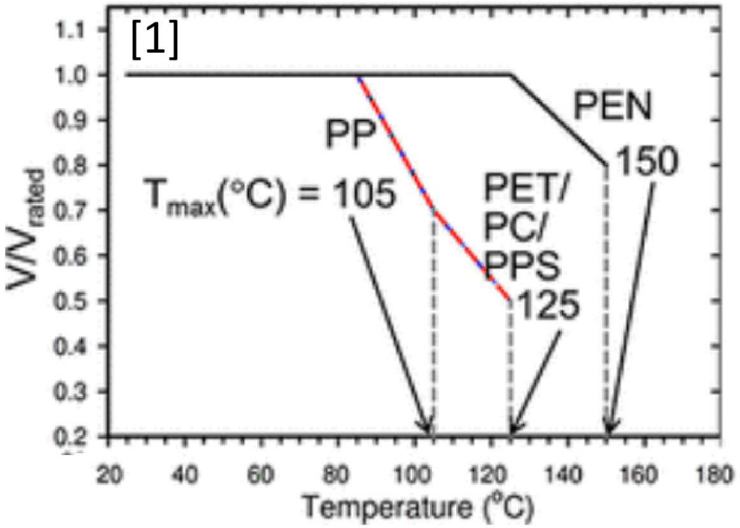
Strategies

- 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
- Pushing forward processing technology for current high-temp polymers to thin dielectric layers (PEI, PC)

[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

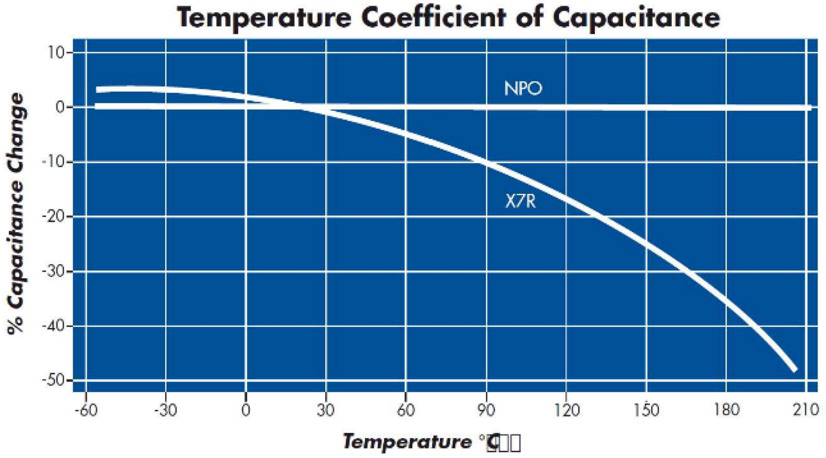
Class I

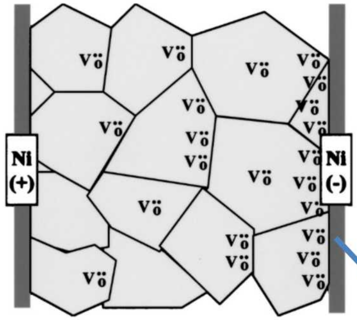
High Temp Stability (200C)
Low ESR/ESL (limited by stacking design)
High Reliability Margin
High Ripple Current Rating

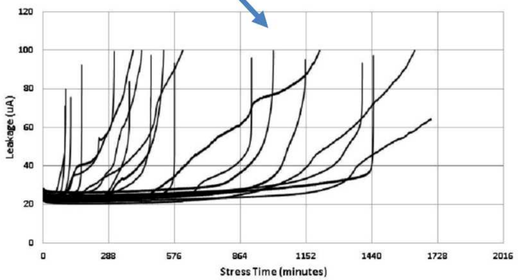
Low Capacitance

Class II

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

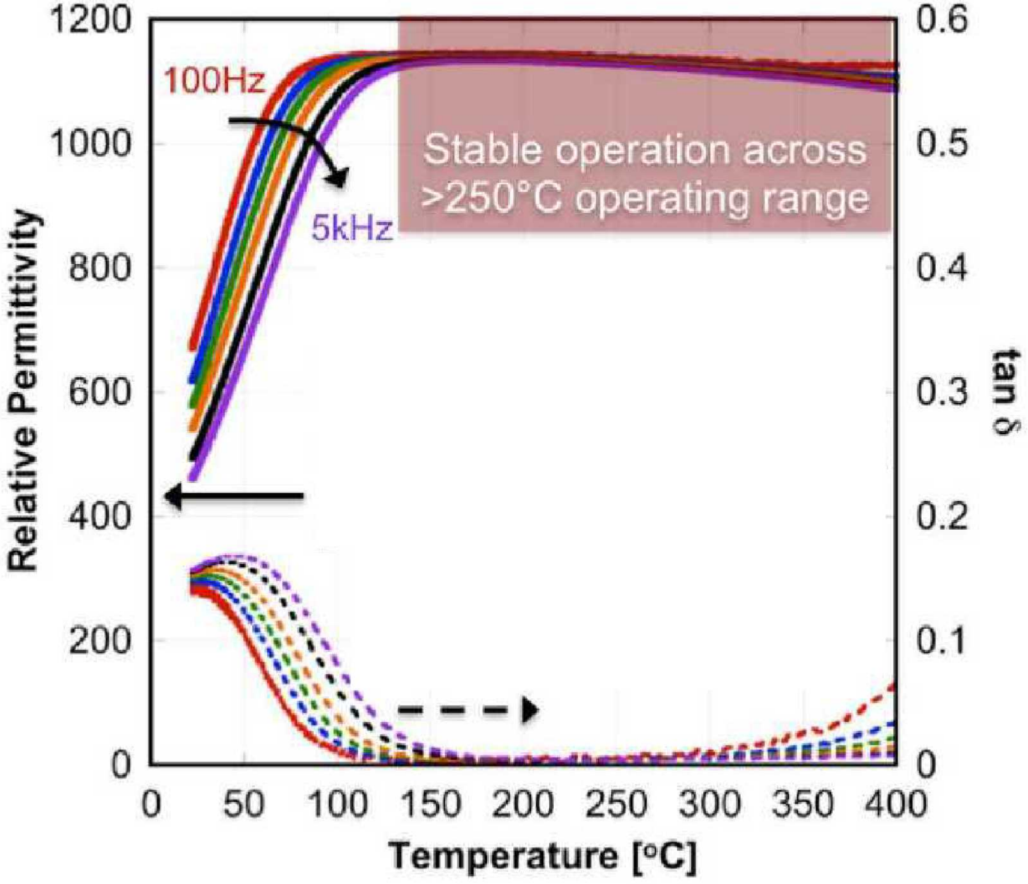


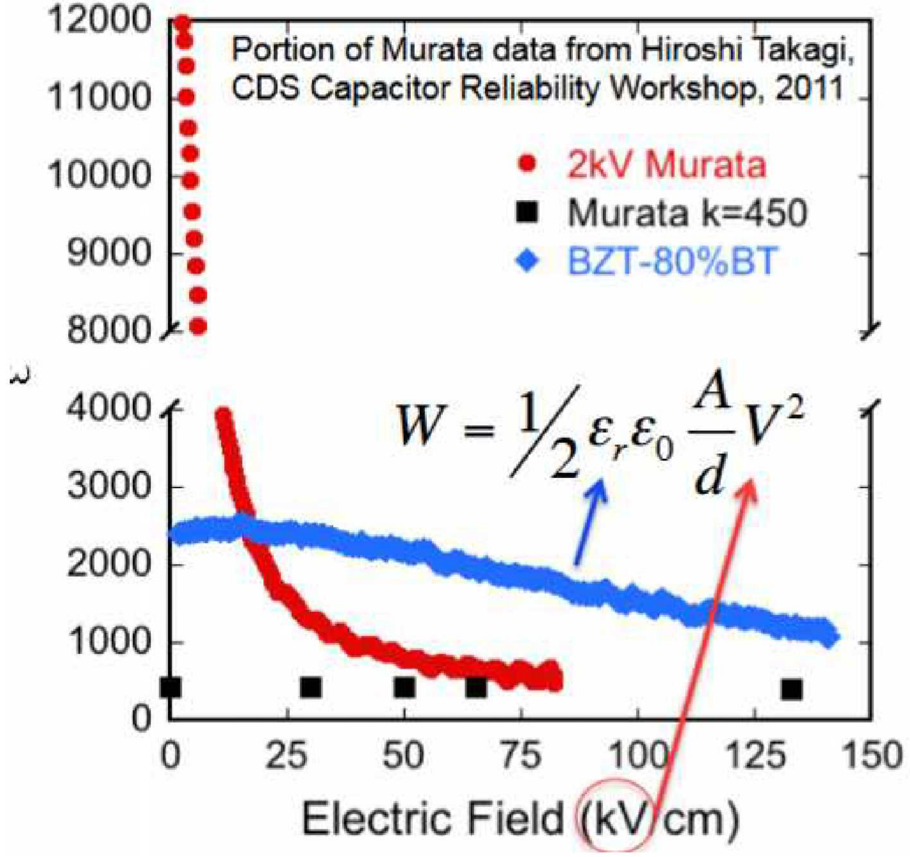




A Class II Ceramic Capacitor Materials Solution

E.g. $BiZnO_3$-$BaTiO_3$

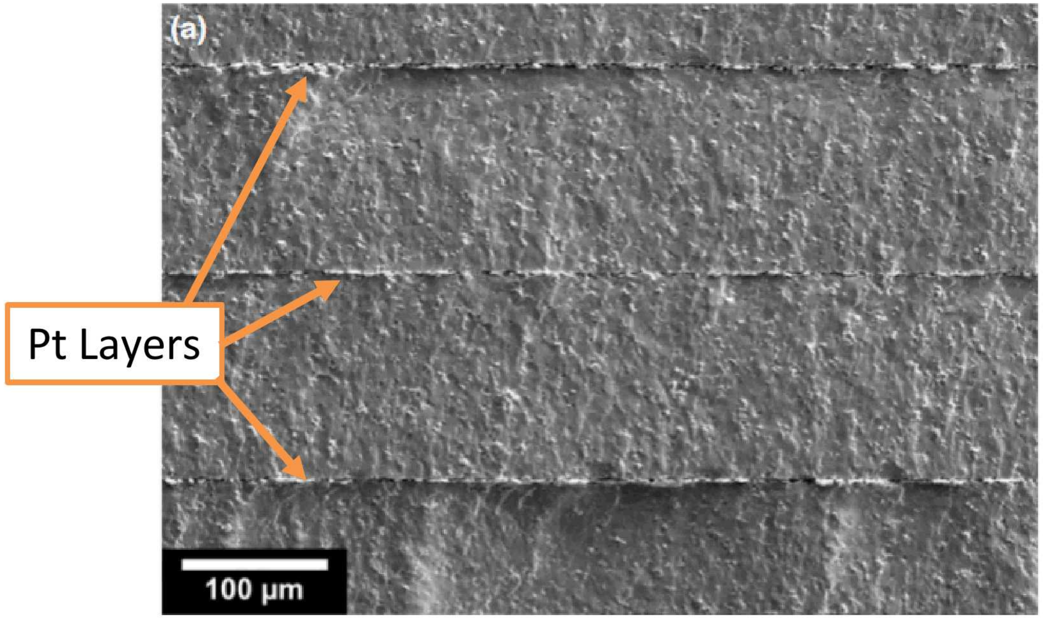




- Solid solutions of $BaTiO_3$ and various other materials ($BiZnO_3$, $BiScO_3$, $NaNbO_3$, etc.) allow for new high temperature Class II compositions

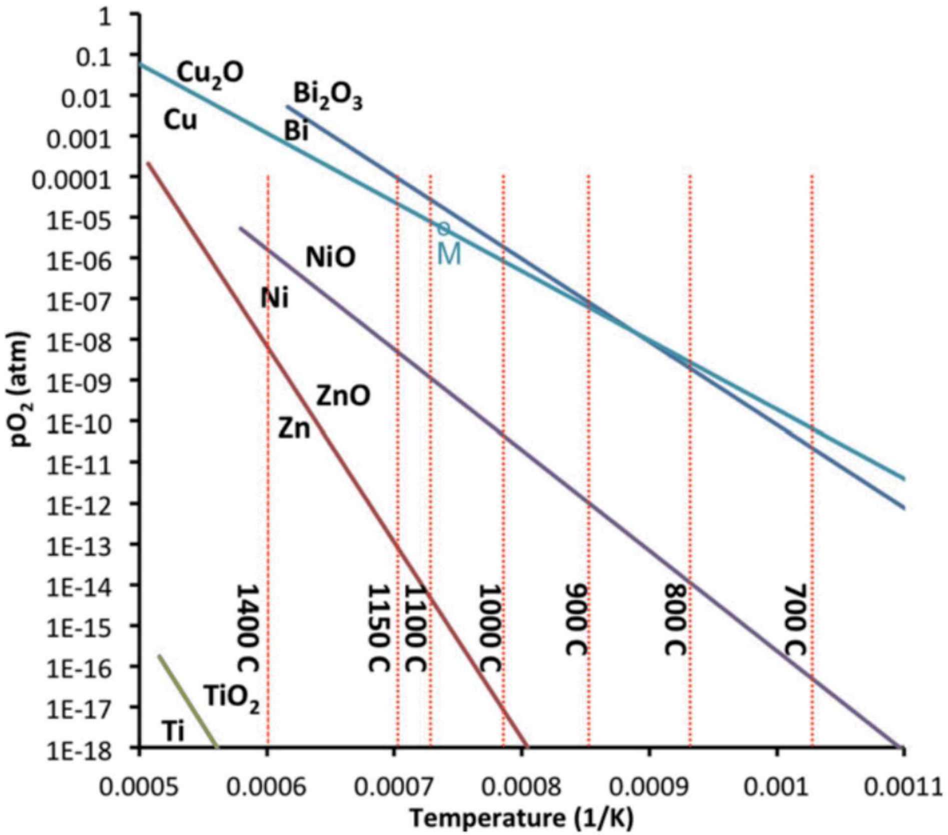
- Stable Capacitance at High Temperature
- Retains Capacitance at high E-fields
  - Allows for high energy density in PE Systems

Two Problems: Cost and Degradation



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

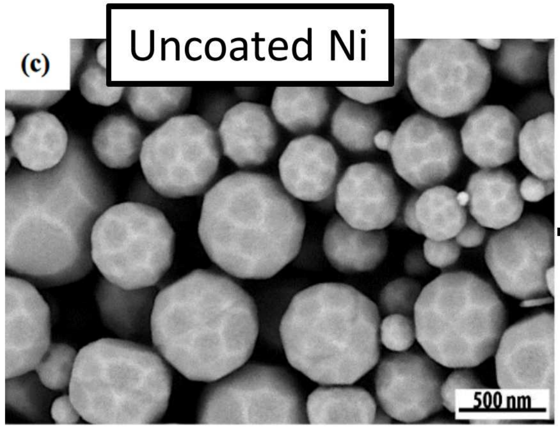
Switching to more common Ni or Cu electrodes is difficult – Bi metal will be formed if dielectric is reduced

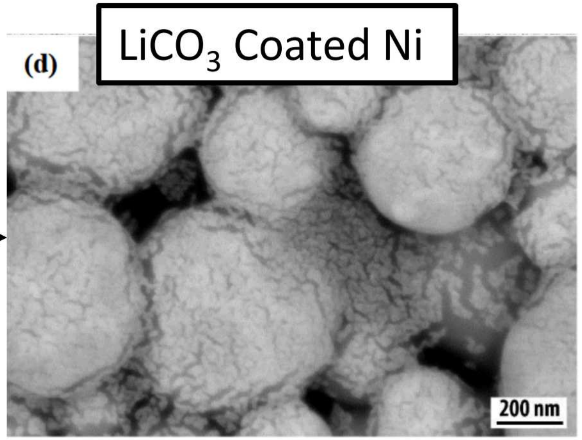


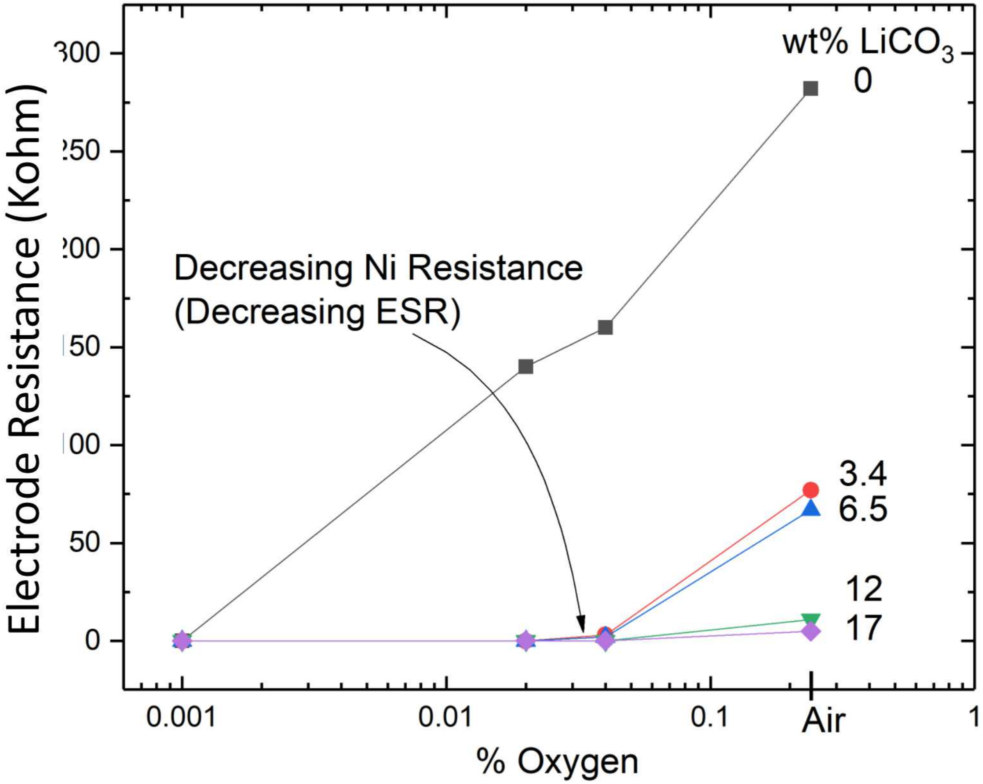
Novel processing techniques are needed to replace Pt electrodes with Ni or Cu for cost reduction

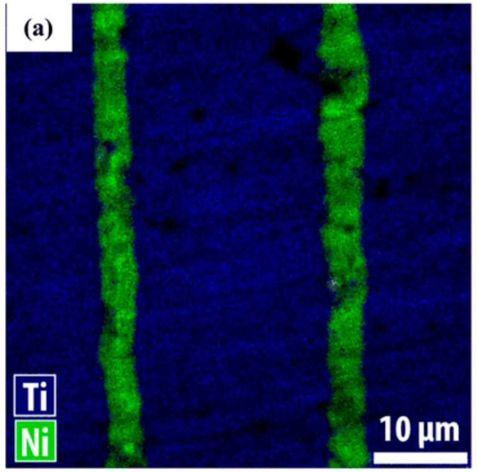
M. Beuerlein, et al., J. Am. Cer. Soc., 99 (9), 2849-2870 (2016)

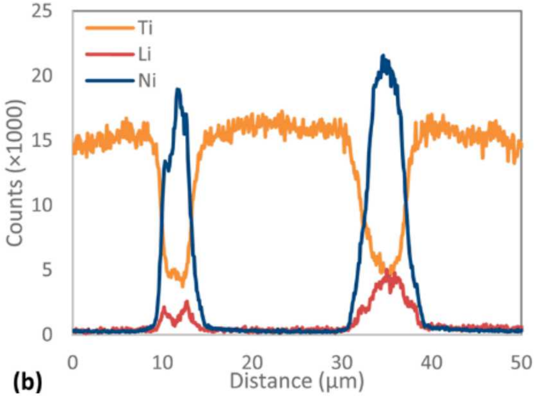
$LiCO_3$-coated Ni Particles for near-ambient pO_2 processing











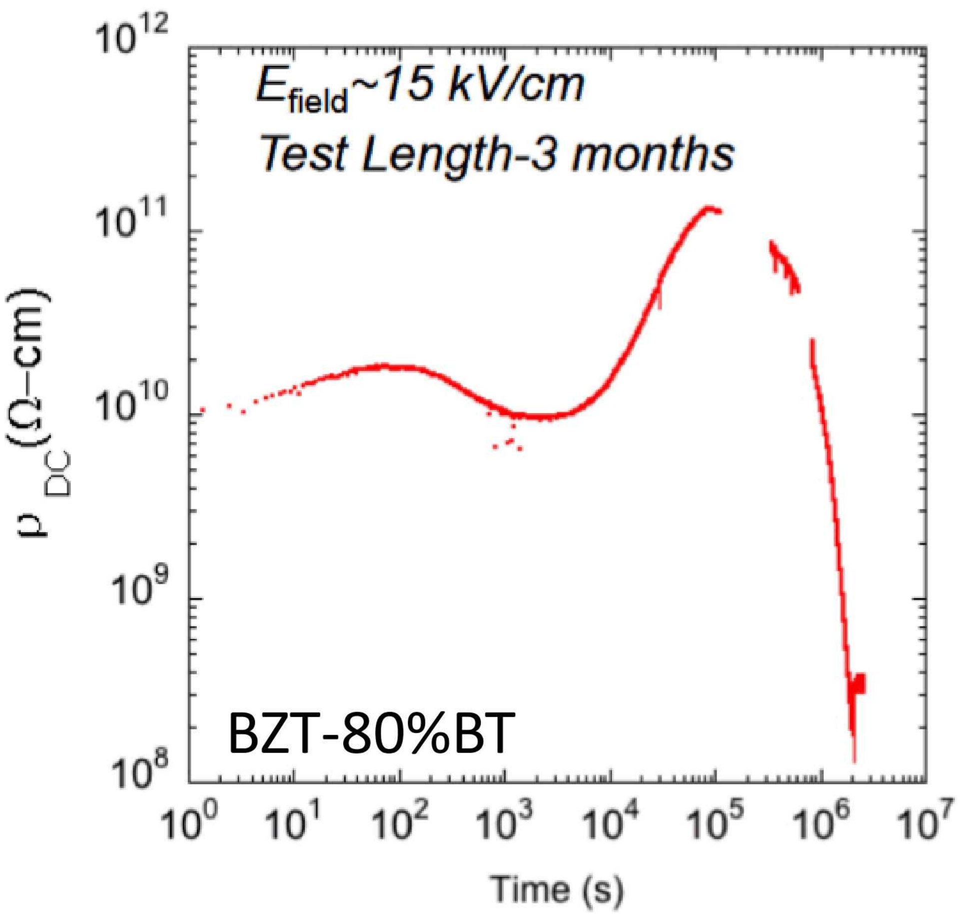
Successful Lab-scale $BaTiO_3$-based Capacitors have been fabricated

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

Utilizing Previous Research on Processing with Ni electrodes in high pO2, we may avoid oxygen vacancy formation and reduce cost (Pt->Ni)

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

Two Problems: Cost and Degradation



- Initial studies on disc capacitors show resistance degradation under DC Bias
- Most common cause is electro-migration of defects under DC Bias
- Process will limit lifetime of BZT-BT capacitors in DC Link applications

Electromigration of defects is key culprit

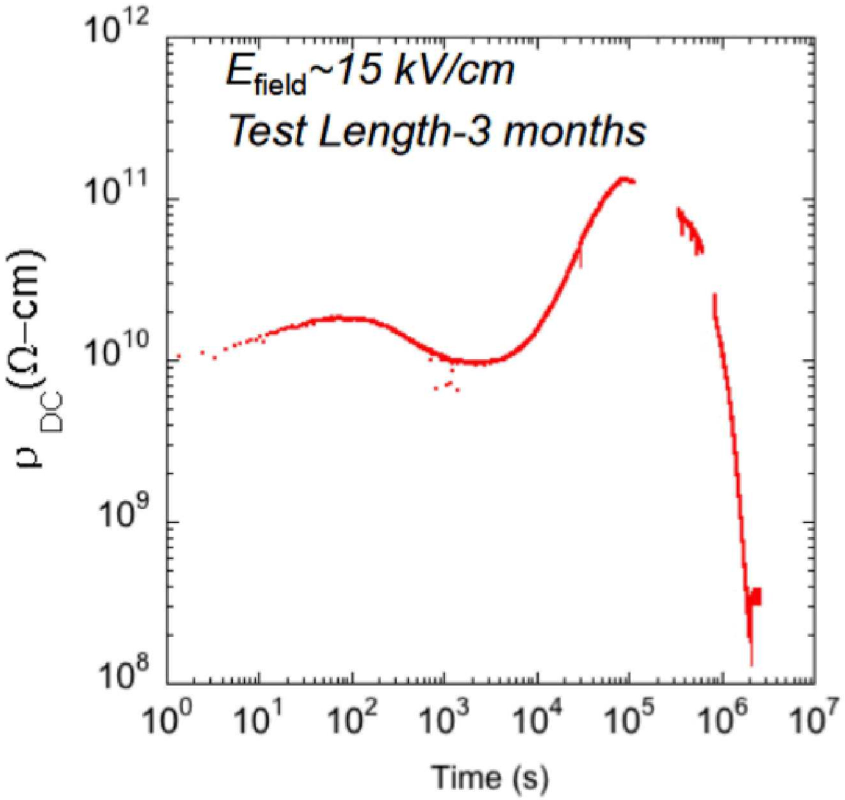
Doping strategies to maximize lifetime from $BaTiO_3$ (Amphoteric and acceptor doping) can be utilized

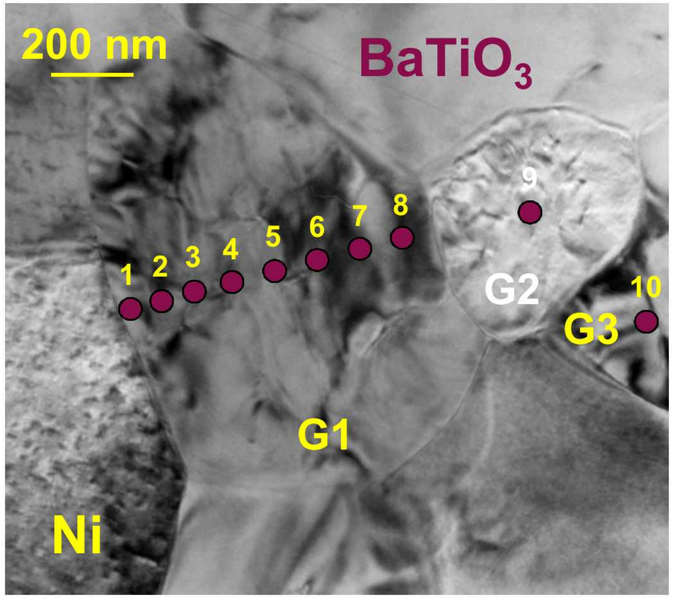
Understanding of Degradation Mechanism in BZT-BT is key for assuring long lifetime for DC Link applications

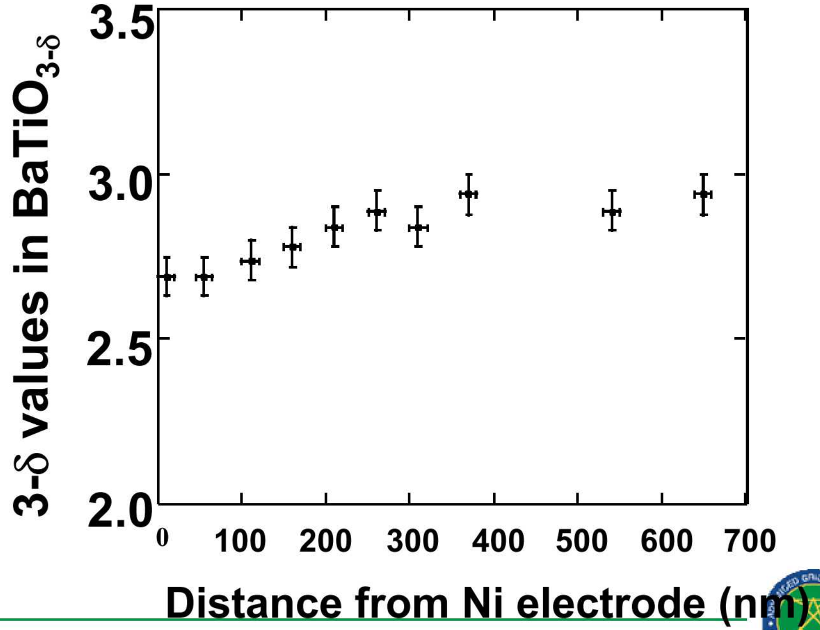
DC Lifetime experiments for BZT-BT materials

- Initial studies will degrade BZT-BT materials until resistance degradation occurs

- EDS/EELS will be used to identify compositional differences along grains/near electrode resulting form electromigrated of defects







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

Initial steps

- Begin Work in FY2020

- Initial compositional work
  - Confirm BZT-BT Processing route
  - Making Pt electrode capacitor
    - Dial in Tape Casting and printing procedures while developing Ni coating
  - Coat Ni particles and confirm low resistance behavior of previous work in bulk samples

- Degradation: Confirm electromigration hypothesis
  - Degrade BZT-BT pellets at High fields/Temp under DC life
  - Attempt acceleration vs. previous studies
  - Identify compositional inhomogeneity along field direction via EDS/EELS

Significance of the results, if successful

- Successful integration of Ni electrodes in Bi-based Compositions can drastically reduce cost of manufacture
  - Commercialization becomes move viable path forward

- Understanding of degradation mechanism can lead to increased understanding of engineering trade space for compositional down selection

- 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 and

Thank You

Questions?

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