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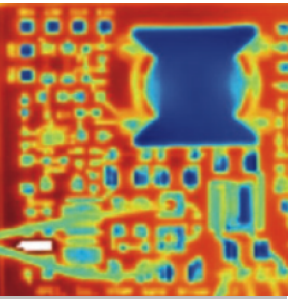

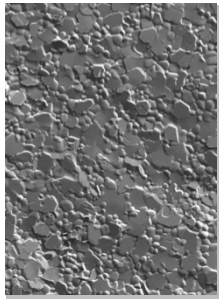

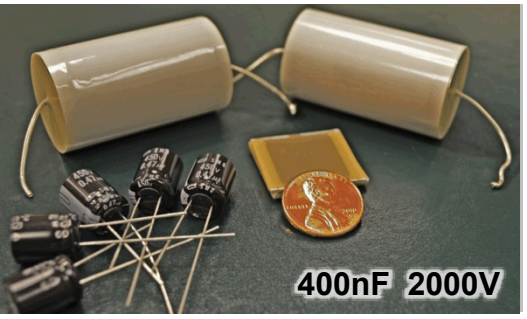


# Capacitor Development for Reliable High Temperature Operation in Inverter Applications

23 October 2013

Geoff Brennecka and Harlan Brown-Shaklee

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    - John Borchardt
    - Adrian Casias
    - Kelsey Meyer, Ryan Wilkerson, and Kevin Ring
    - Stan Atcitty
    - Prof. Wayne Huebner, Missouri S&T
    - David Shahin, MS student

*Team combines expertise and advanced capabilities in use design, fabrication, integration, degradation and reliability, characterization, and applications*

# Project

- Power electronics systems with reduced thermal management requirements are highly desirable for stationary and transportable storage

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

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

- Available high operating temperature capacitors fail to meet all of the criteria for desired:

  **Performance / Volume / Reliability / Cost**

**Impact on system**

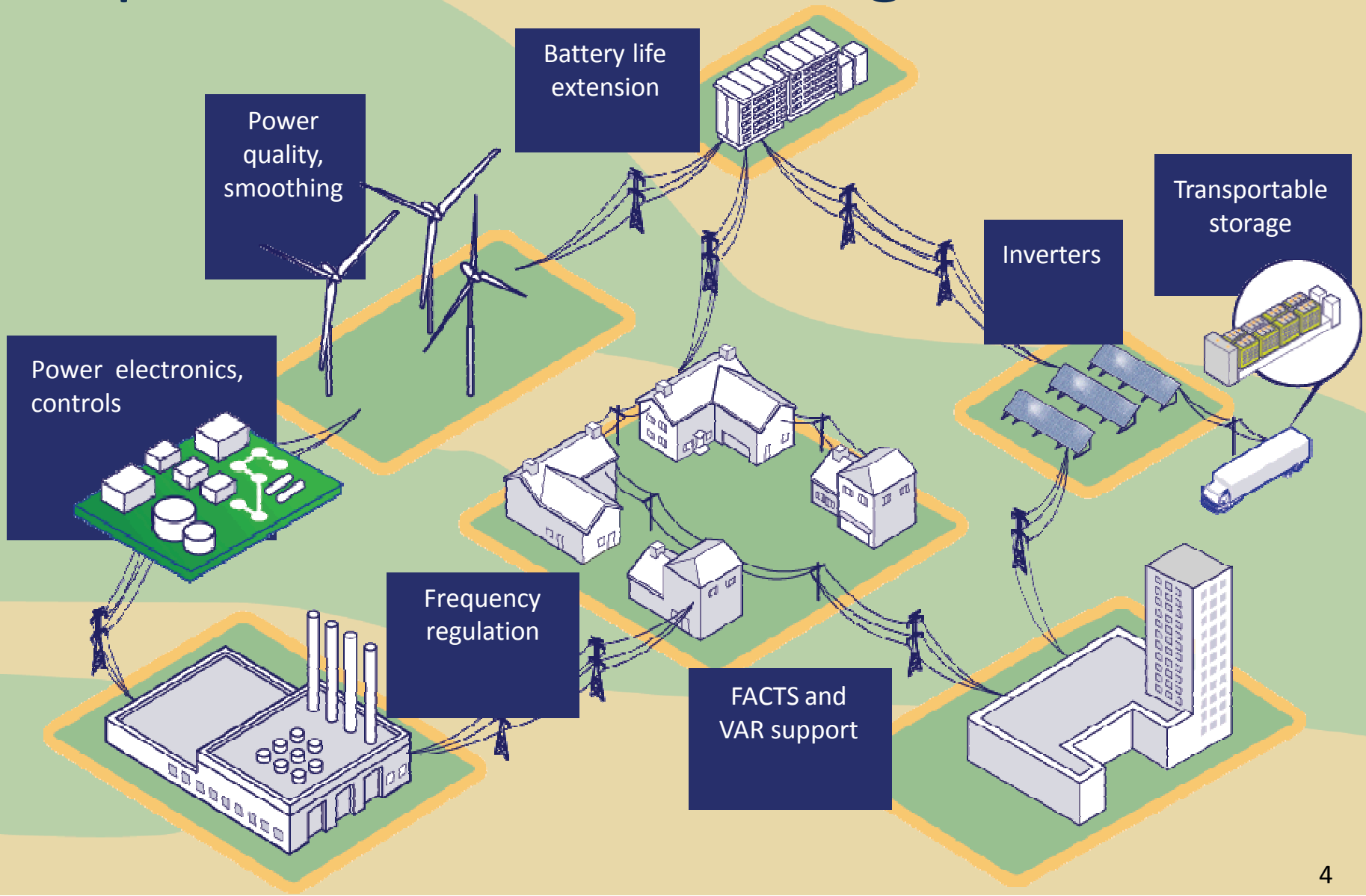
- High power density
- Reduced complexity
- Reduced cooling-related failures

- Higher power
- Greater efficiency
- Reduced cooling

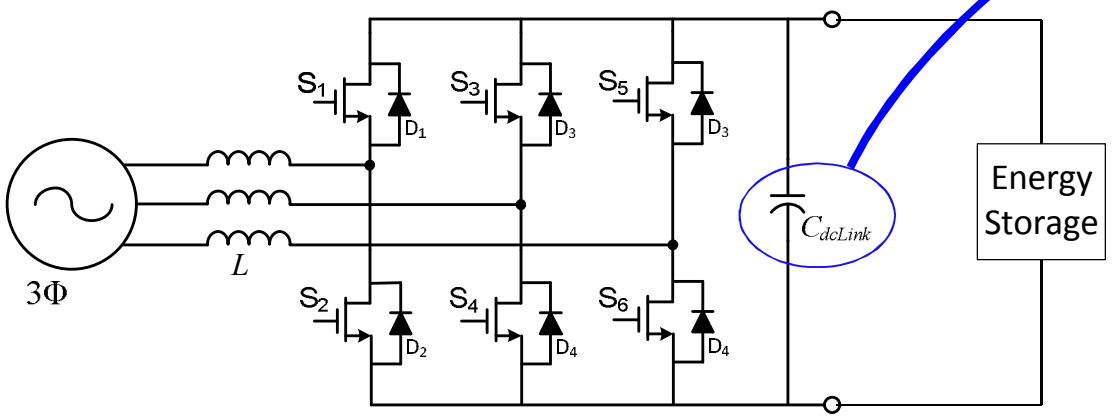
Image of failed electrolytic capacitor after high temperature operation courtesy of Jack Flicker, SNL

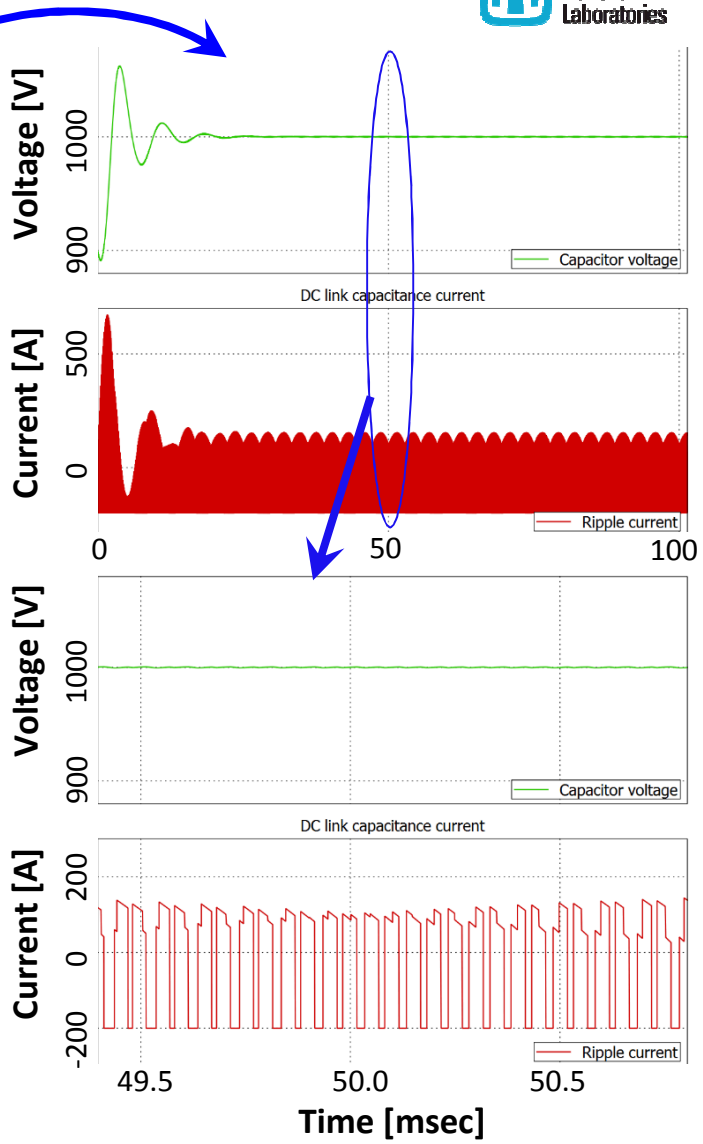
- Severe derating
- Large volume
- Expensive

# Capacitor Needs for Storage



# Application Space




- Capacitance density, energy density, operating voltage
- Operation above 200°C needed, 300°C desired
- ***Low ESR is critical for high frequency response, ripple current and power handling***

Scale-up proof of concept demonstrated, currently in early stages of discussions with potential commercial partner(s).


200nF 2000V MLCC

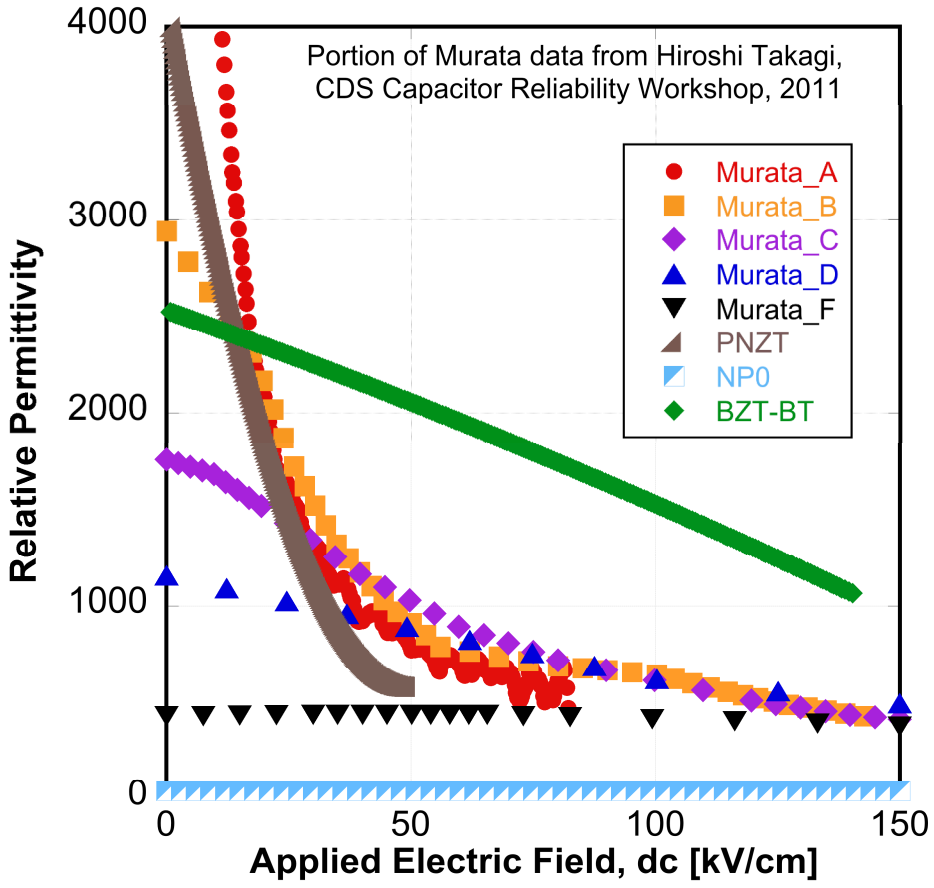
*Simulation courtesy of Eric Green and Stan Atcitty*

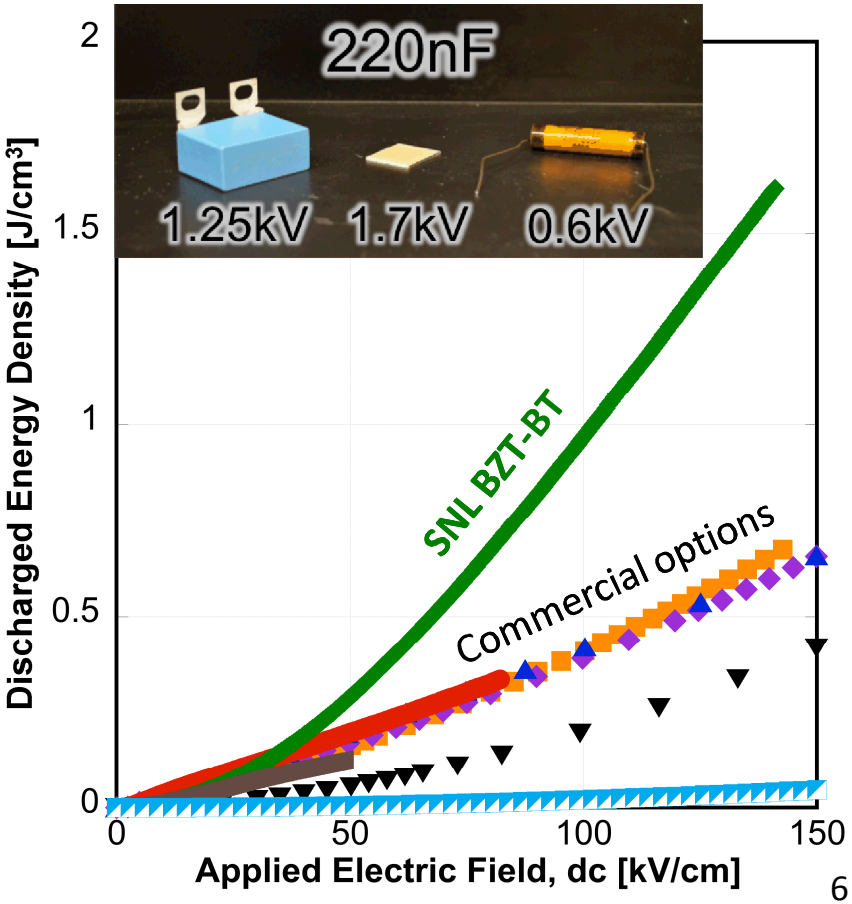
# High Energy Density Dielectrics

$$J = \int_0^{Vmax} CV^2 \longrightarrow \int_0^{Emax} KE^2$$

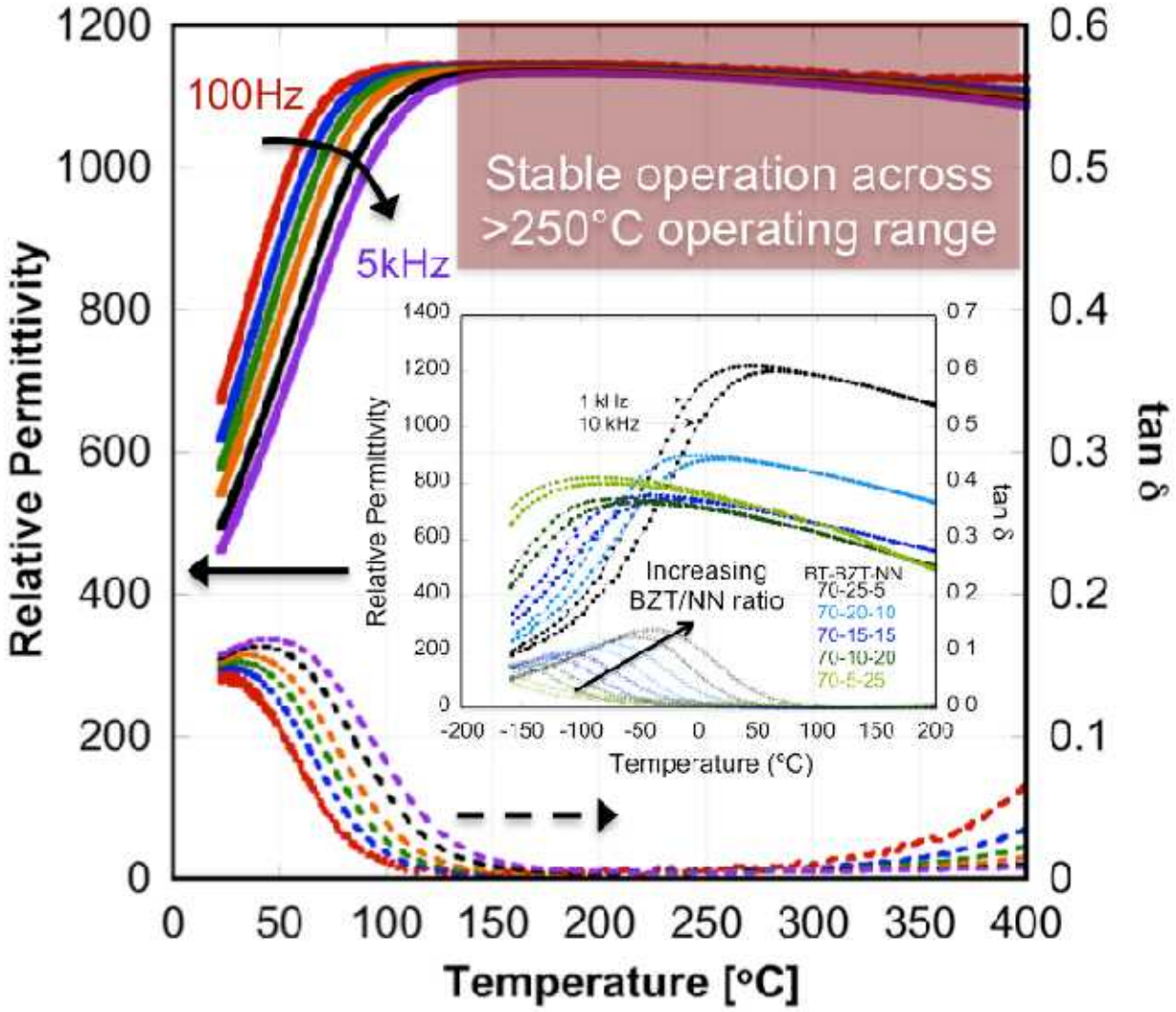
For high-K materials, K=K(E)

→ maintaining high K at high E is important



# High Temperature Operation

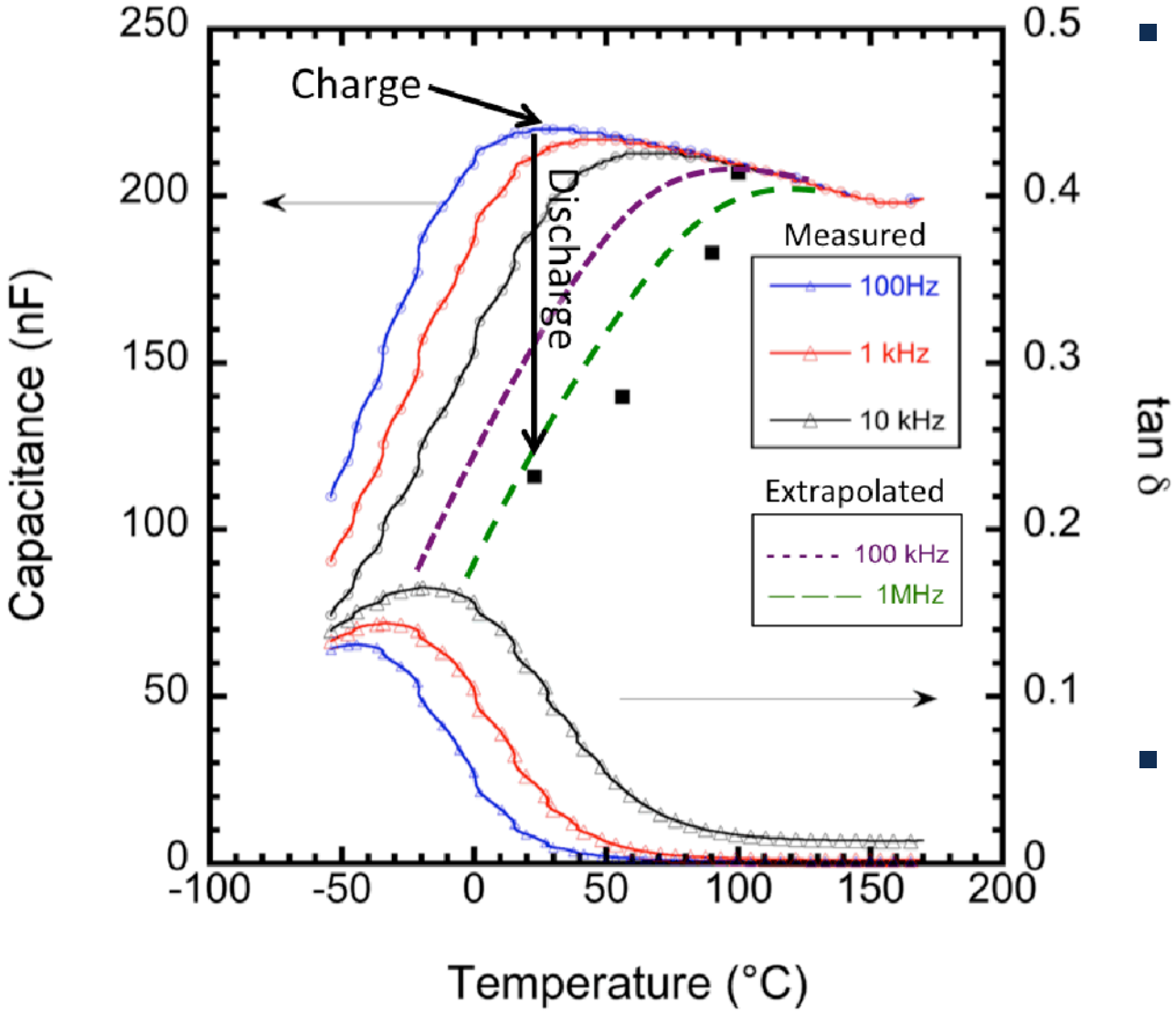



- $BiScO_3$ stabilizes high temperature permittivity
- $SrTiO_3$ or $NaNbO_3$ additions shift relaxor transition to lower temperatures

**We can shift the temperature range for stable operation around by ~250°C via chemical modification *without sacrificing voltage stability***

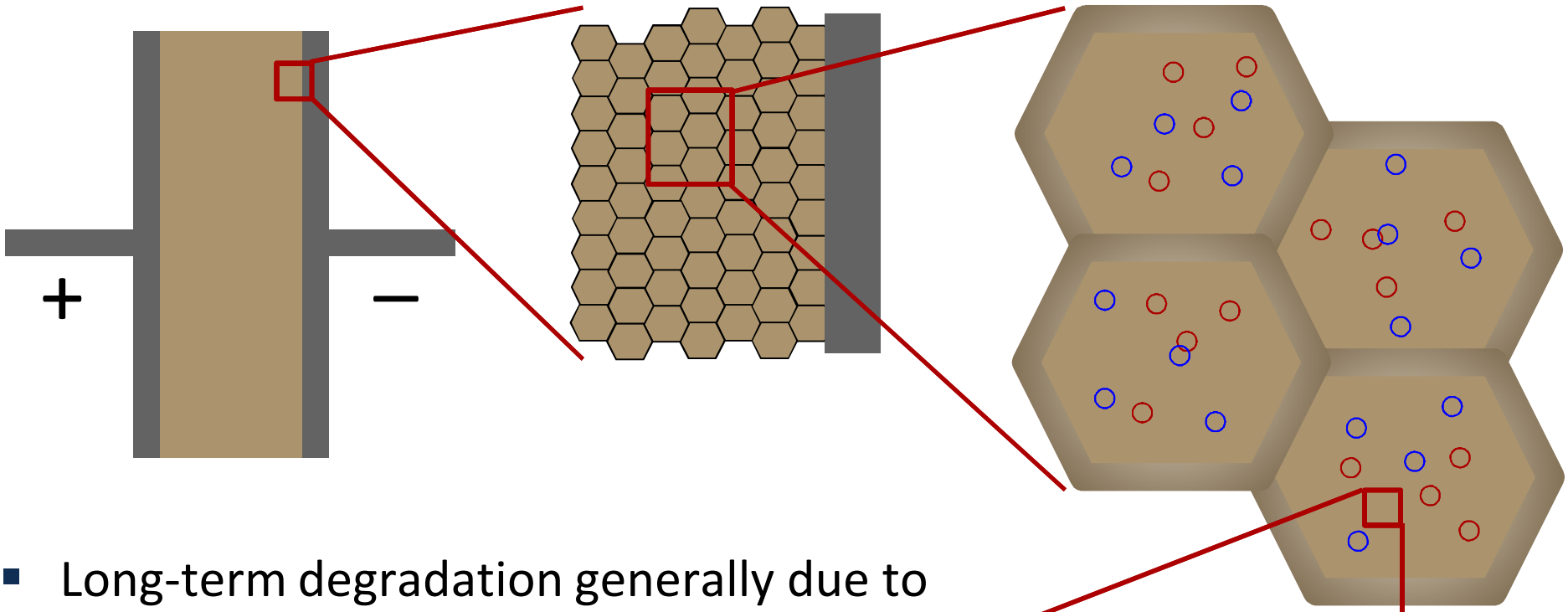
*with Prof. David Cann, Oregon State University*

# Time Domain Performance

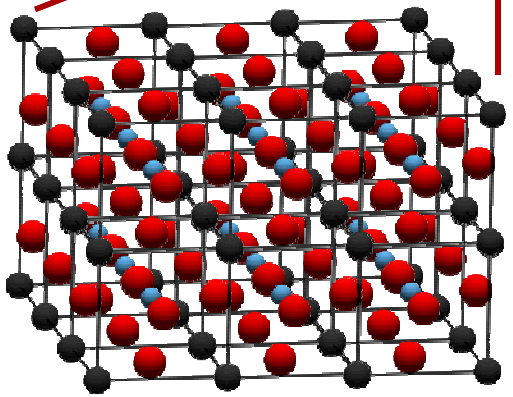



- Relaxor dielectrics exhibit characteristic frequency dispersion over relatively broad temperature ranges
  - For switched inverter designs which charge slowly and discharge quickly at irregular intervals, which values are relevant?
- Direct time-domain measurements map well to frequency domain data

# Degradation in Ceramic Dielectrics

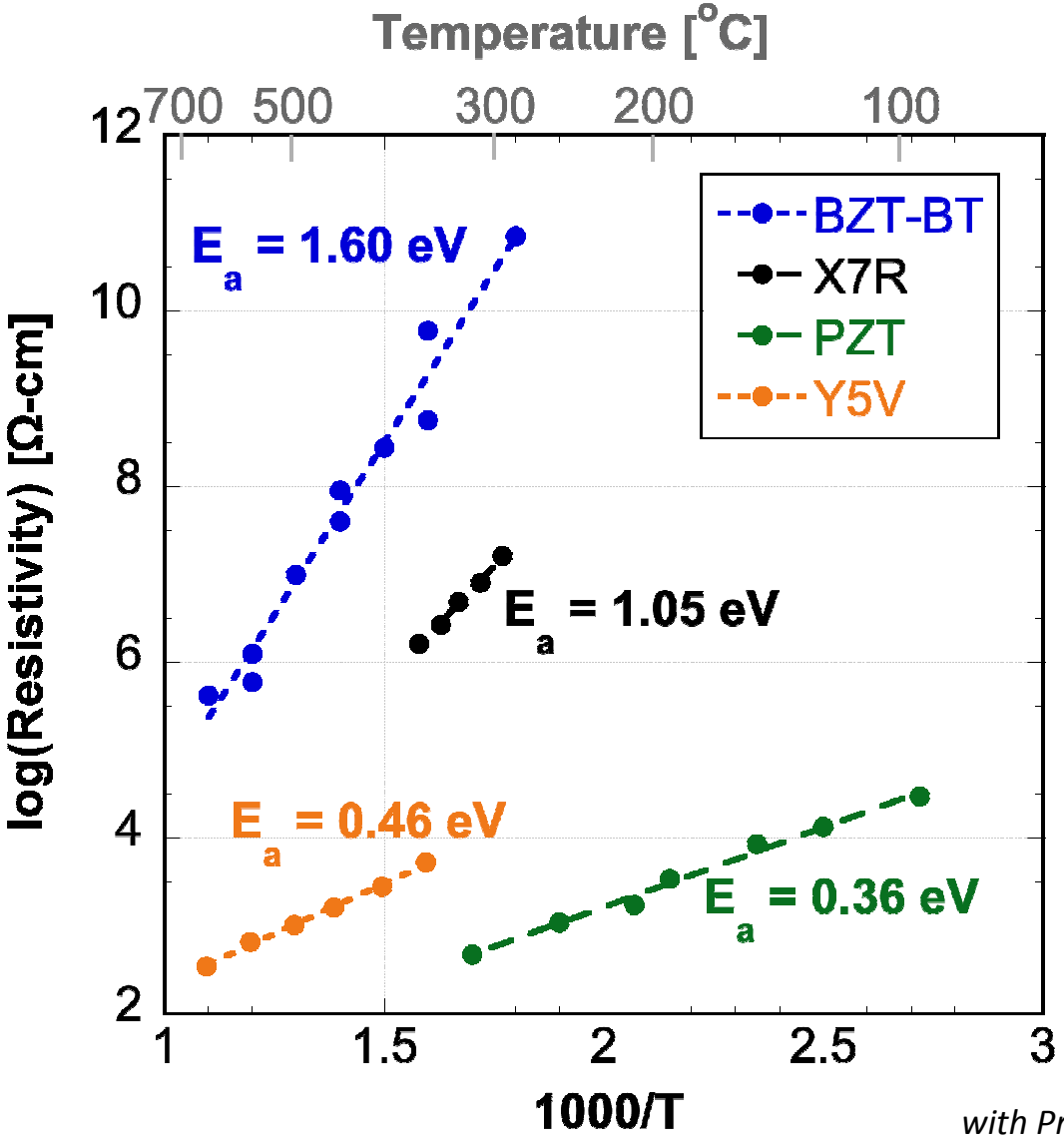


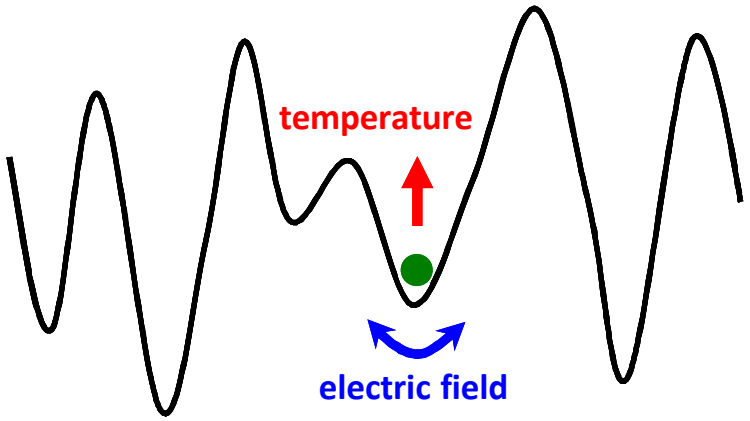

- Long-term degradation generally due to migration of charged ionic defects
- HALT and MTTF prediction require quantitative description of mechanisms



For excellent discussion, see Randall *et al.*, *J. Appl. Phys.* **113**, 014101 (2013) doi: 10.1063/1.4772599

# Resistivity: First step towards HALT

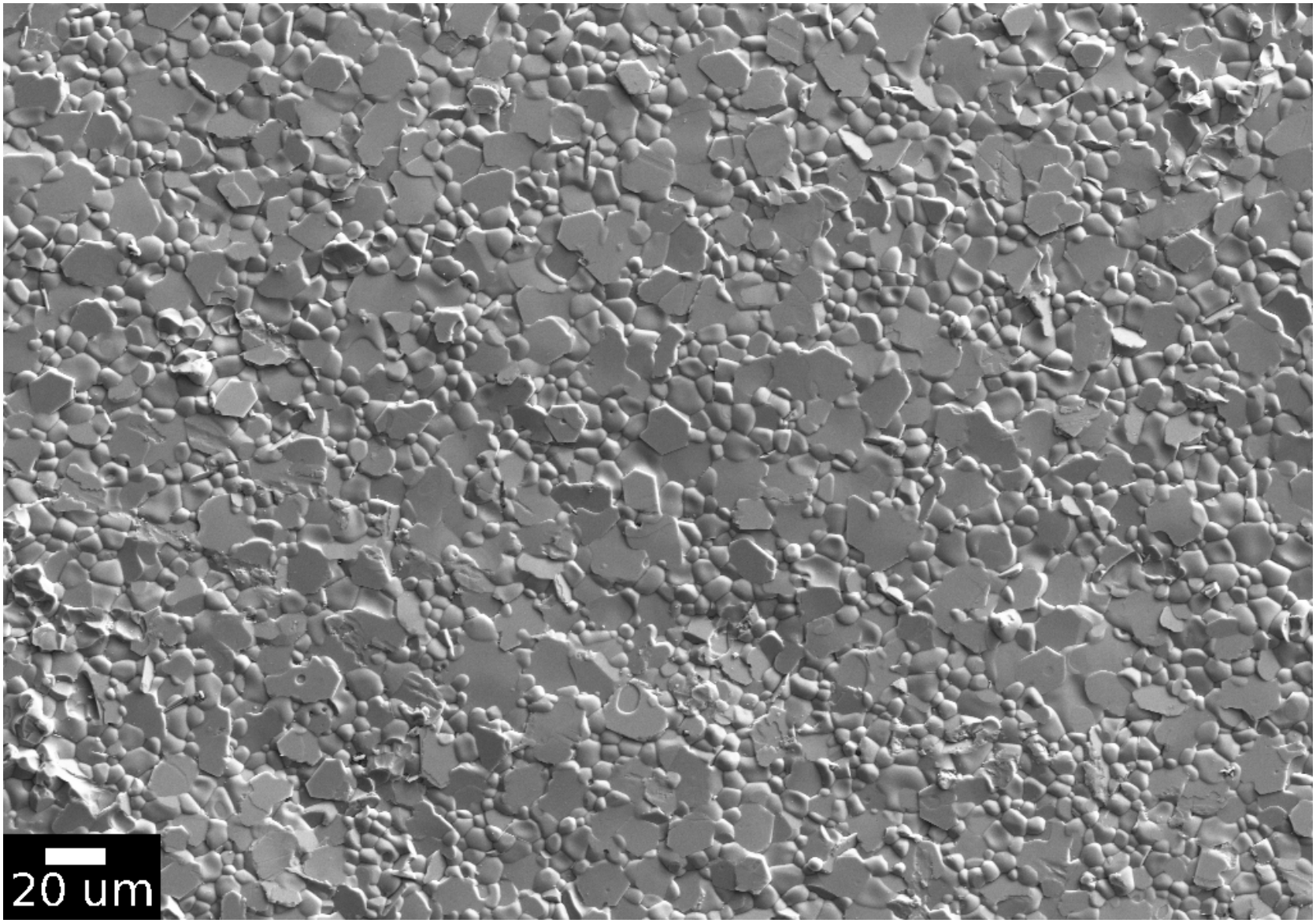


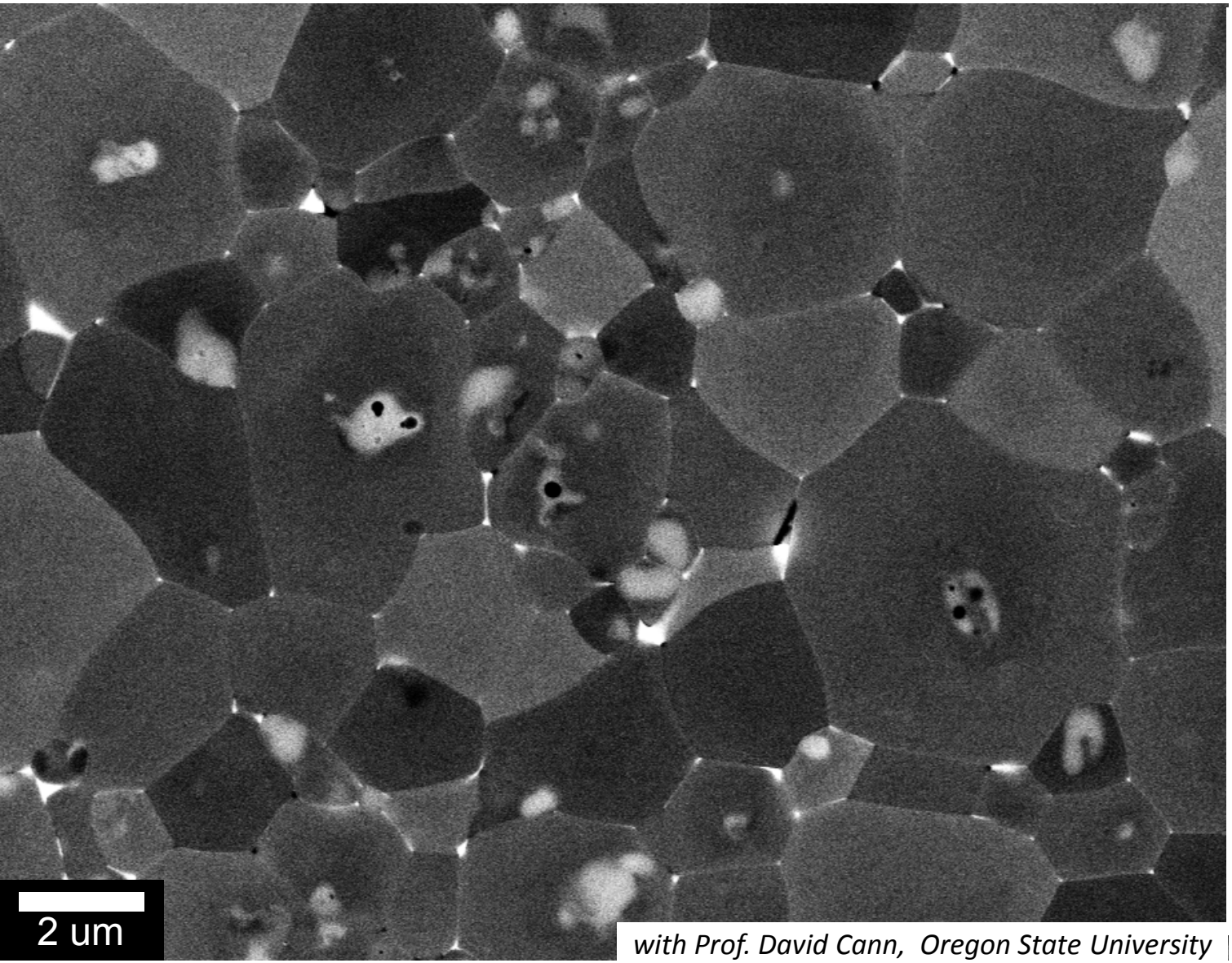

**Higher resistivity and larger activation energy for conduction both translate into longer lifetimes and higher reliability, particularly at elevated temperatures.**

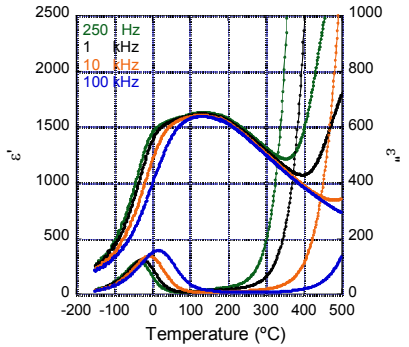
*with Prof. David Cann, Oregon State University*

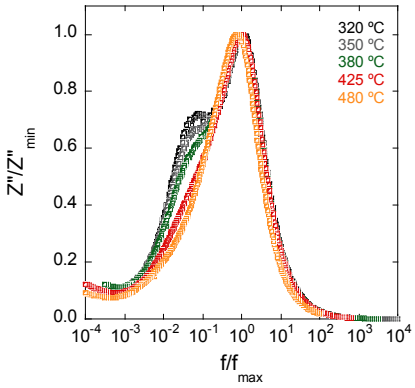
# SEM of Typical Dielectric Surface

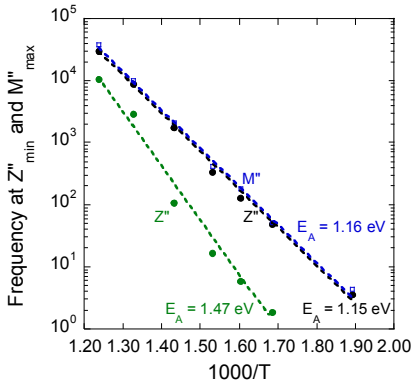


# Microscale Heterogeneity



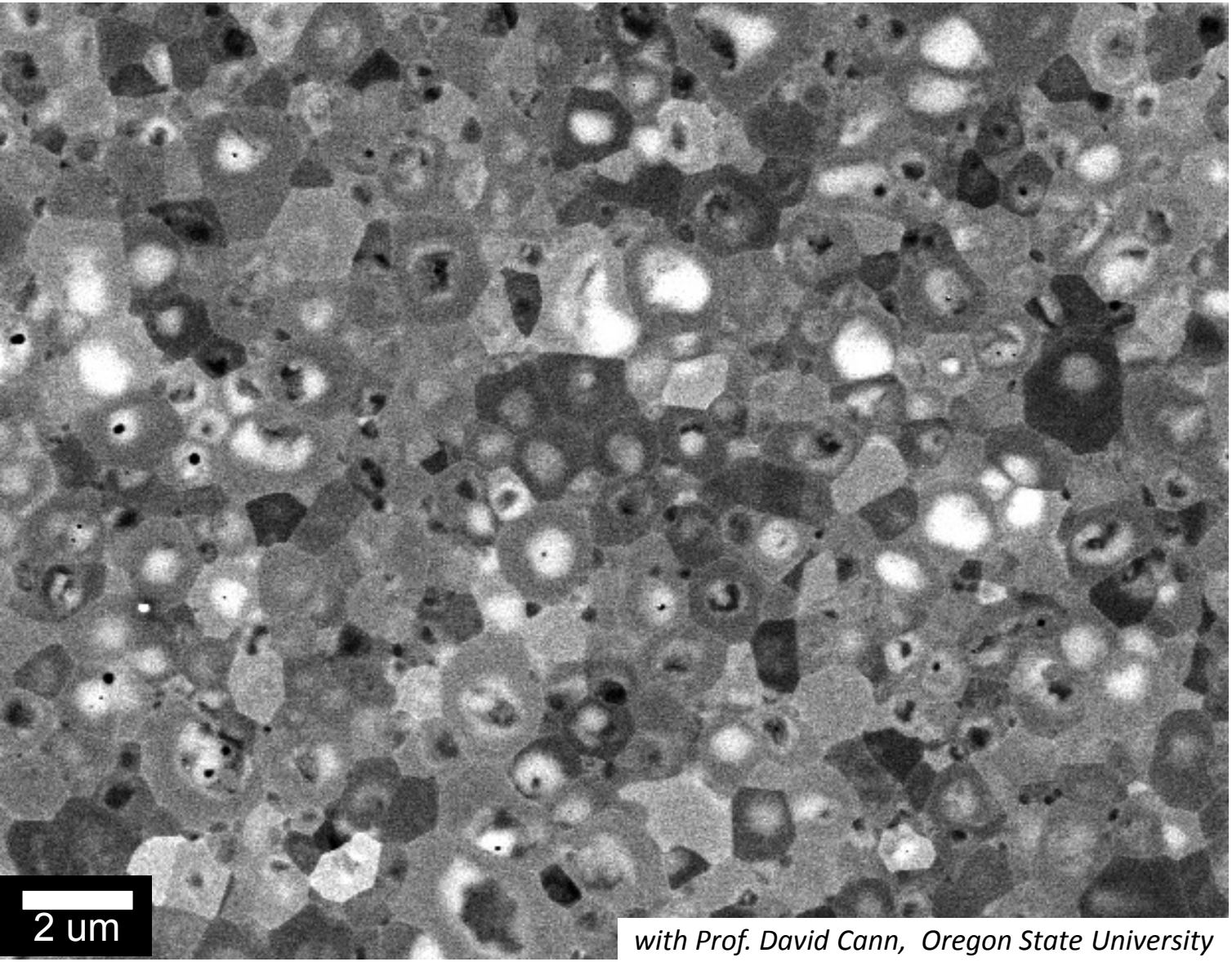



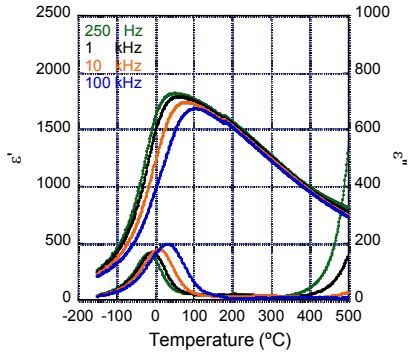



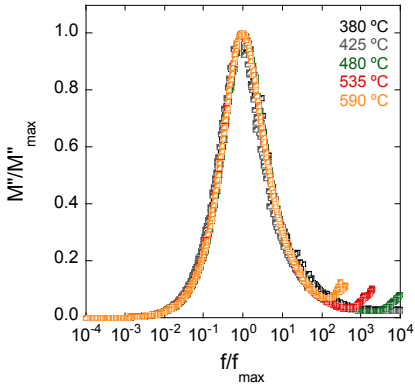



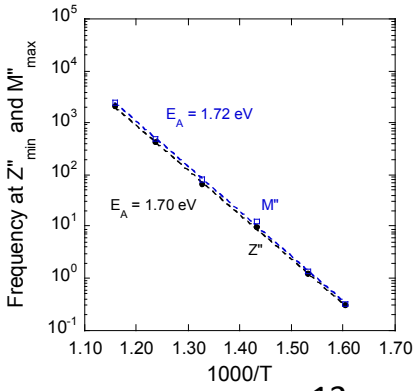

*with Prof. David Cann, Oregon State University*

# Microscale Heterogeneity



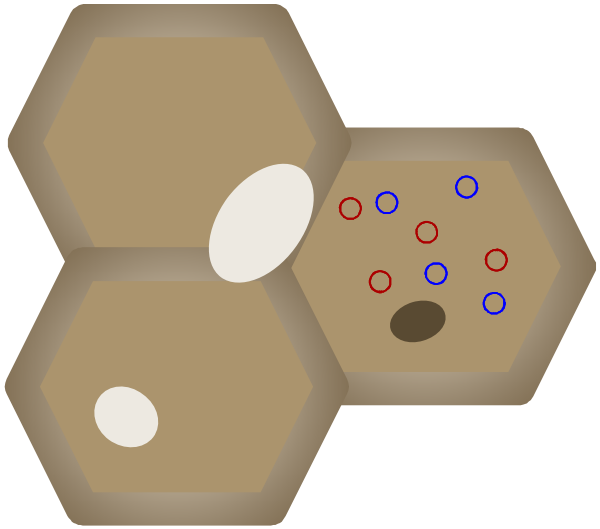



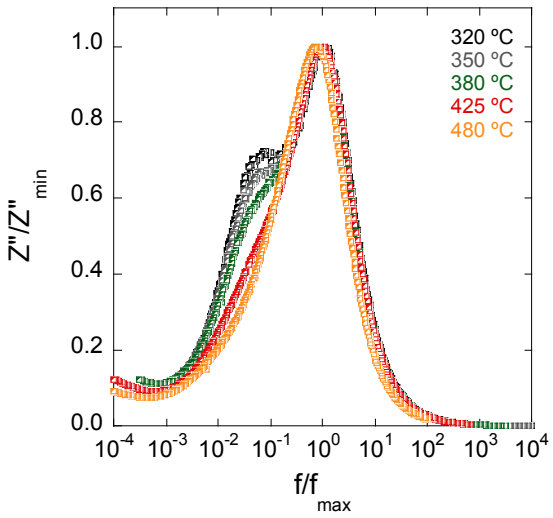



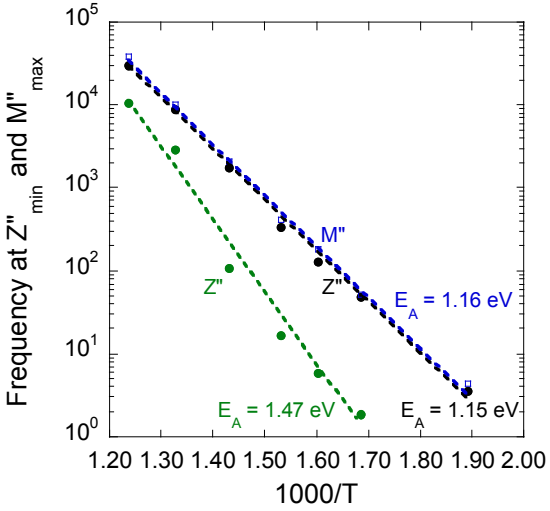



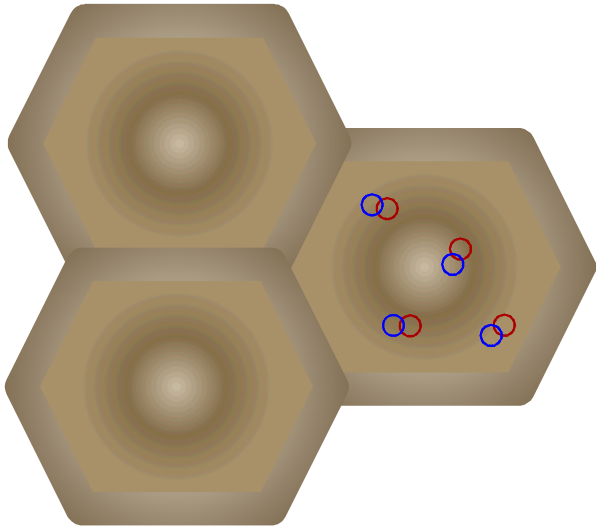

*with Prof. David Cann, Oregon State University*

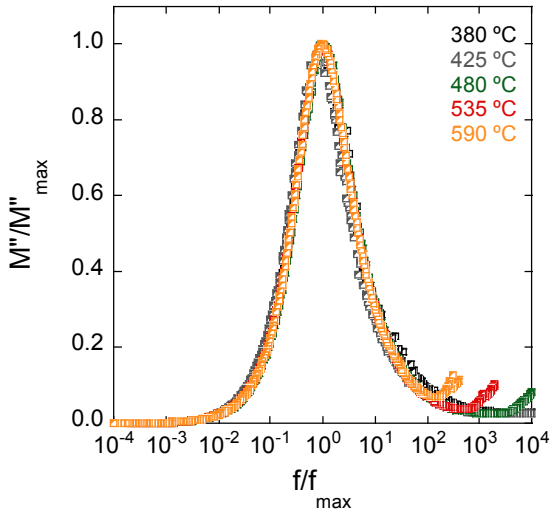
# Microscale Heterogeneity

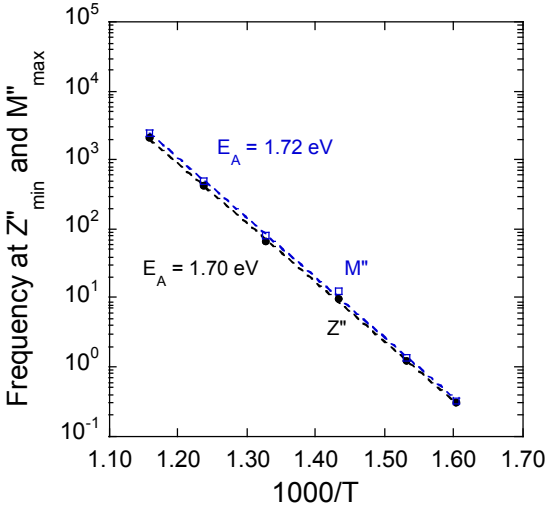







*with Prof. David Cann, Oregon State University*

# Summary

- Performance
  - High permittivity and low loss, stable across >250°C operating range and up to 150kV/cm
  - Composition modifications shift stability range by >250°C
- Volume
  - Demonstrated energy densities on parts of relevant sizes with >3X volume savings over competing technologies
  - Low ESR relaxes total capacitance requirement
- Reliability
  - High resistivity, large activation energy and microstructure tied to defect chemistry; mechanism studies for HALT and MTTF prediction underway
- Cost
  - Fabrication via highly scalable tape casting process
  - Integration with low-cost electrodes ongoing

**Impact on system**

- High power
- High efficiency
- Reduced thermal management

- High power density
- Reduced system volume

- Reduced losses
- Increased system lifetime, reliability
- Predictable MTTF

- In discussions with capacitor manufacturers

# Next Steps: FY14 Milestones

- Publish mechanisms underlying voltage and temperature stability
- Publish results of ongoing electrode compatibility studies
- Demonstrate mechanism-based applicability of acceleration testing for MTTF prediction
- Demonstrate prototype capacitors in relevant test bed (such as WBG inverter module) at elevated operating temperatures
- Partner with commercial manufacturer(s) for technology transfer

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# FY13 Milestones and Results

- Investigate fundamental science underlying voltage and temperature stability (crystallographic and chemical studies)
  - Critical microstructural and doping-related insights gained, optimization ongoing
- Pursue integration with low-cost electrodes
- Continue work on transient liquid phase processing for reduced processing temperatures and higher density, higher operating fields
- Perform accelerated lifetime and reliability testing
  - Significant progress; studies of both processing and use/reliability compatibility with low-cost electrodes ongoing
- Submit ≥2 manuscripts for publication in peer-reviewed journals
  - 2 published during FY13, several more coming in FY14
- Direct application testing of prototype capacitors
  - Delayed for time-domain studies to guide appropriate composition selection
- Explore partnership with commercial manufacturer(s)
  - Early stage talks ongoing, encouraging