Advanced Capacitors for Future Power Conversion Systems

Project # 1853191

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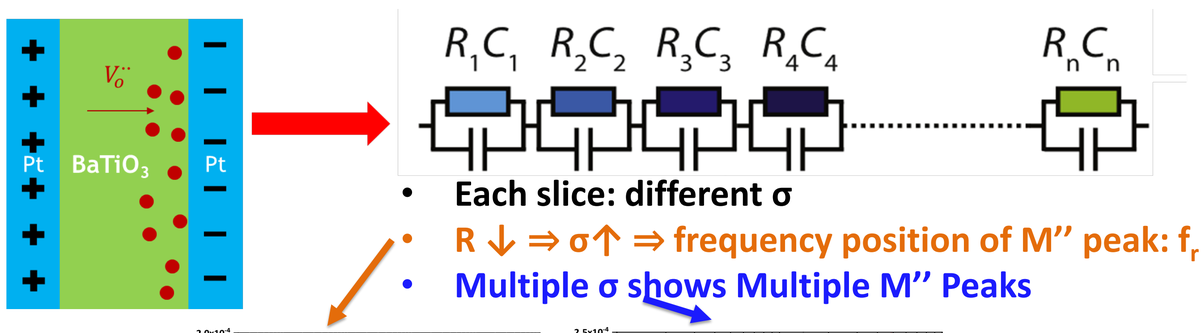
Abstract

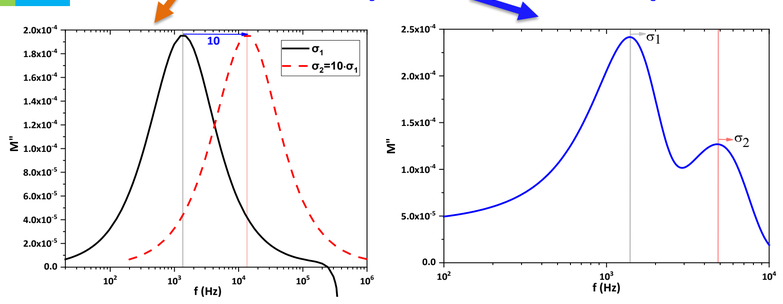
The overall goal of the project is to improve reliability of high density, high voltage capacitors, which allows higher frequency operation, reducing the size and cost of passive components in the power converter**.** Capacitors are critical for voltage source converter functionality. DC-link capacitors are known to have reliability issues. Resistance degradation at high temperature is one of the primary failure modes in capacitors, leading to high leakage current and thermal runaway. Reducing resistance degradation is key.

Resistance Degradation Model

- Oxygen vacancy ($V_O^{\cdot\cdot}$) migration to the cathode leads to resistance degradation
- Modulus spectroscopy[1)] shows there are at least 2 different conduction mechanisms

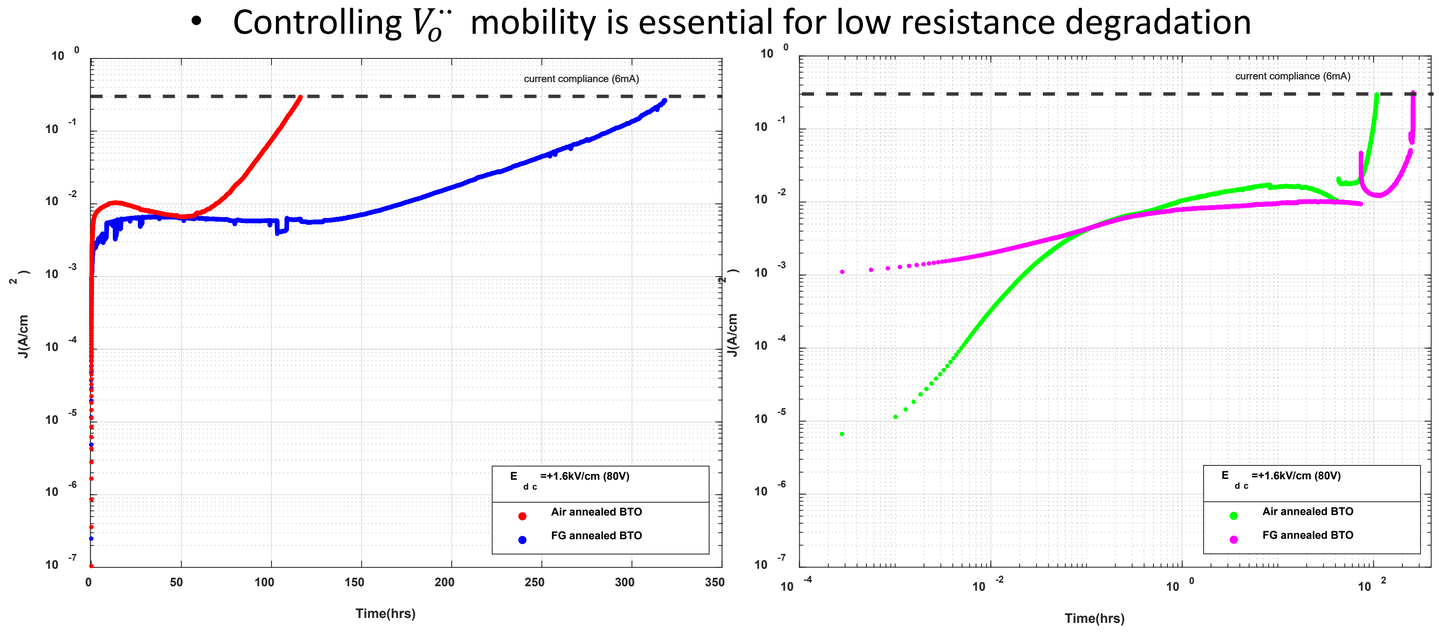


- **Each slice: different σ**
- **R ↓ ⇒ σ↑ ⇒ frequency position of M'' peak: f_r ↑**
- **Multiple σ shows Multiple M'' Peaks**



Accelerated Life Testing to Reduce Resistance Degradation

- ***Separate effects of $V_O^{\cdot\cdot}$ concentration vs. $V_O^{\cdot\cdot}$ mobility vs. interface barrier height***
  - There are 3 different resistance degradation regimes at +1.6 kV/cm and 200° C
  - To determine which regime is controlled by $V_O^{\cdot\cdot}$ concentration, we annealed single crystal $BaTiO_3$ in 95% N_2 / 5% H_2 (FG) for 10 hours at 900°C to increase the $V_O^{\cdot\cdot}$ concentration
- ***Experimental Results***
  - Increasing the $V_O^{\cdot\cdot}$ concentration increases the initial leakage current (see right side of figure)
  - Increasing the $V_O^{\cdot\cdot}$ concentration greatly reduces the resistance degradation (see left side of figure below) over a long-time scale
  - Modulus spectroscopy shows that regime 2 is much more stable in FG annealed samples
- ***Explanation***
  - High $V_O^{\cdot\cdot}$ concentration leads to di-vacancy formation
  - Di-vacancies have much lower mobility, reducing resistance degradation
- ***Proposed Solution***
  - Controlling $V_O^{\cdot\cdot}$ mobility is essential for low resistance degradation



Comparison of Air-Annealed vs. Forming Gas-Annealed Capacitors on Single Crystal $BaTiO_3$ at +1.6 kV/cm and 200°C

Accomplishments

2021:

- Developed a SPICE model for a dual bridge converter topology which allows us to simulate the operating characteristics of the converter as a function of capacitor characteristics and degradation
- $BaTiO_3$ capacitors show 3 different stages of degradation, with the 3rd region being a rapid increase in resistance degradation.

2022:

- Capacitors fabricated on Sandia's ceramic show much slower degradation than single crystal $BaTiO_3$ under similar conditions.
- Impedance spectroscopy shows there are at least 3 different dominant conduction mechanisms as the resistance degradation process proceeds.

2023:

- Use modulus spectroscopy to determine the mechanism behind the 3-stage degradation behavior in single crystal $BaTiO_3$ vs. ceramic $BaTiO_3$
- 95% N_2 / 5% H_2 (FG) annealed capacitors last longer than air annealed capacitors when subjected to a DC electric field of 1.6 kV/cm at 200°C.
- Controlling $V_O^{\cdot\cdot}$ mobility is essential for low resistance degradation

Conclusion

- Understanding degradation behavior as a function of capacitor operating parameters is critical to design of reliable power converter.

Future work

- Understanding degradation of passive components in harsh environments (temperature, voltage, radiation, mechanical, etc.) will be critical for long-term, reliable, smart grid operation

Acknowledgements

This work is supported by the DOE Energy Storage program and Dr. Imre Gyuk. We would like to thank Dr. Stan Atcitty and Dr. Jon Bock at Sandia National Lab, for their technical leadership and many thoughtful technical discussions.

Reference

[1)] Randall, C., 2019. The Role of Interfaces in Performance, Degradation, and Breakdown of Non-Linear Dielectrics Under Extreme Conditions. Penn State Univ., University Park United States.