Cost-Effective Fabrication of High-Temperature Ceramic Capacitors for Power Inverters*

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Project ID# APE-061

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Overview

Timeline

- Project start date: FY14
- Project end date: FY16
- Percent complete: 15%

Budget

- Total project funding (FY14 - FY16)
  - DOE: $3008K. Out of this total, subcontract to Delphi/Sigma Technologies = $810K & Penn State University = $150K
- Funding received in FY13: $1860K
- Funding for FY14: $1148K

Barriers addressed

- A & C (Cost & Weight): Overall size and cost of inverters

  Capacitors are a significant fraction of the inverter volume (≈35%), weight (≈23%), and cost (≈23%).

- D (Performance & Lifetime): High-temperature operation

  The performance and lifetime of capacitors available today degrade rapidly with increasing temperature (ripple current capability decreases with temperature increase from 85°C to 105°C).

Partners

- Delphi Electronics & Safety Systems
- Sigma Technologies International
- Penn State University
- Project Lead: Argonne National Laboratory

Relevance - Objectives

- **Overall objective:** Develop an efficient, cost-effective process for fabricating Pb-La-Zr-Ti-O (PLZT)-based DC-link capacitors for advanced power inverters in EDVs. PLZT-based capacitors are capable of operating at 140°C and 650 V (APEEM Goal).
- This project addresses key barriers (capacitance density, high-temperature operation, as well as fail-safe operation and manufacturability). Future availability of high-temperature inverters will advance the adoption of highly fuel-efficient electric drive vehicles in the marketplace.
- **Specific objective for March '13 – March '14:** Optimize process to produce submicron PLZT powders for high-rate aerosol deposition (AD); deposit PLZT films on metallized polyimide films by AD process & characterize the capacitors.
- **Uniqueness/impact:** Our approach will substantially reduce the size, weight, and cost of DC-link capacitors. PLZT films have high dielectric constant (k ≈100), high breakdown strength (>200 V/μm), & high insulation resistance (>10^{13} Ω-cm), and will meet APEEM requirements for capacitors operating at high temperature with high volumetric efficiency.

Milestones

Month/Year	Milestones or Go/No-Go Decision	Progress Notes
Dec. 2013	Synthesize sub-micron PLZT powder for use in AD process.	Sub-micron powders were synthesized, characterized & used in making AD films.
Mar. 2014	Demonstrate forming PLZT films on metallized polymer films by AD process.	Deposited ≈8-μm-thick (vs. ≈3-μm last year) film on Al-metallized polyimide films by AD and characterized dielectric properties.
June 2014	Establish materials, packaging, and process cost targets to meet the FOA requirement.	On-going.
July 2014	Evaluate parameters that impact the self-healing properties.	On schedule.
Sep. 2014	Go/No-Go decision: Decision on film coverage area.	On schedule.
Dec. 2014	Define capacitor specifications for the selected inverter design	On schedule.

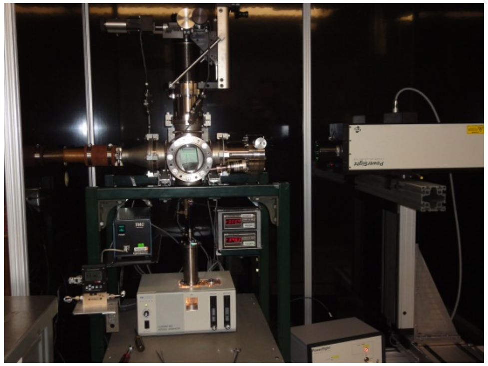
Technical Approach/Strategy

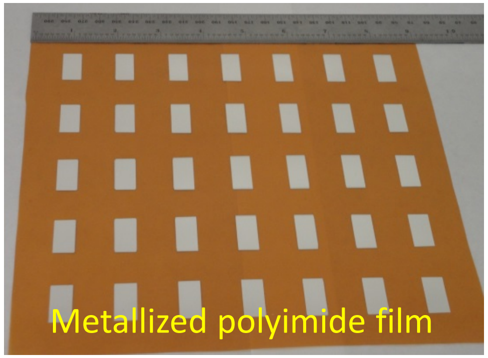
- Basic research demonstrated that a spin-coating process produces PLZT films that satisfy high-temperature and volumetric requirements for advanced capacitors; however, the spin-coating process is not practical for mass production of large area capacitors.
- Development work at Argonne recently demonstrated that a thick film can be prepared at room temperature in significantly shorter time (10 min vs. ≈ 5 days by spin-coating) using an Aerosol Deposition (AD) process.
- This project combines the superior attributes of PLZT-based high-temperature capacitors and a high-rate deposition process.
  - Combines the expertise of Delphi (critical knowledge of automotive power electronics), Sigma Tech. (roll-to-roll capacitor manufacturing), and Argonne (combustion synthesis for producing powders and the AD process).
  - Incorporates innovative electrode design to achieve benign failure.

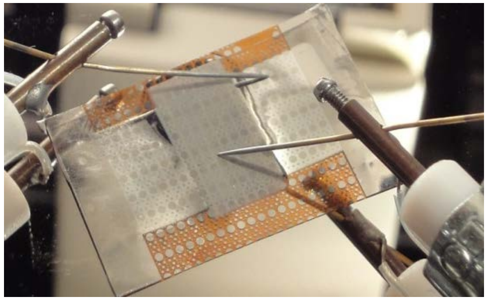
FY 14 Focus: Develop a process to synthesize sub-micron powders and optimize AD process to deposit PLZT on metallized polymer film substrates

Technical Accomplishments & Progress

- Demonstrated feasibility of material & approach to meet APEEM project objectives. *Addresses APEEM target for size and temperature goal for capacitors (140°C).*
- Delphi feels that this material has strong potential for producing a very small, lower cost, very reliable and durable high-temperature bulk capacitor for automotive power electronics; however, …
- The spin-coating process used to demonstrate material properties requires too many processing steps to be cost-effective.
- Aerosol deposition, a high-rate, room-temperature film deposition process, is being developed at Argonne to reduce the PLZT capacitor's cost. *Addresses APEEM requirements for low cost.*



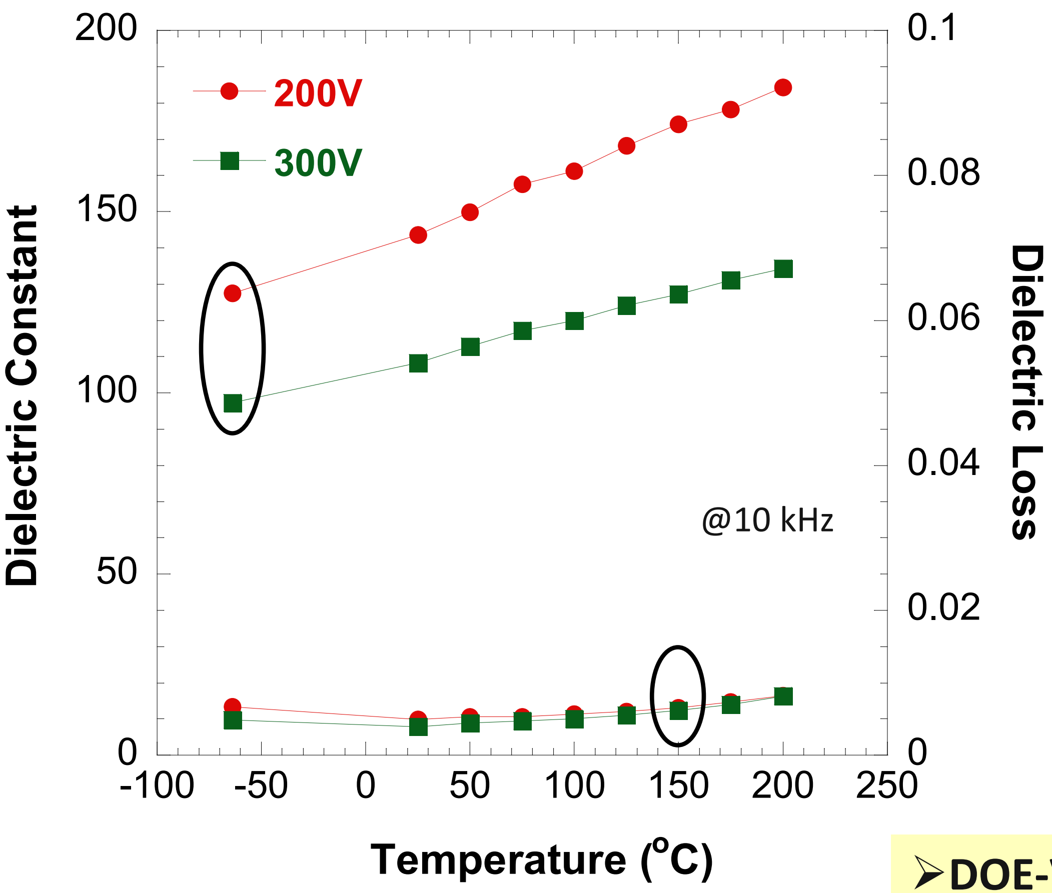




PLZT films have properties suitable for application in high-temperature inverters – meeting the APEEM goals for temperature & high volumetric efficiency

Technical Accomplishments/Results (Cont.)

High-temperature properties of PLZT on Ni foil made by spin-coating (*previous accomplishment*)



Measured k ≈110 & loss ≈ 0.004 (i.e., 0.4%) @ 10 kHz & 300 V bias at room temperature on a 3 µm thick PLZT on Ni-foil

ESR = DF/2πfc (DF = loss factor; f = frequency; c = capacitance).

Calculated ESR for 1000 µF cap. based on measured material properties

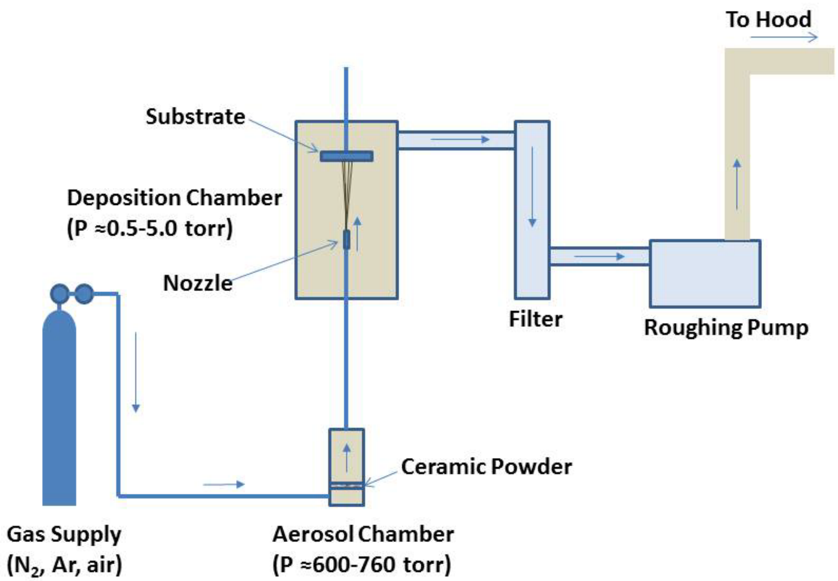
Bias Voltage (V)	ESR @ -64°C (mΩ)	ESR @ RT (mΩ)	ESR @ 150°C (mΩ)
200	0.11	0.08	0.10
300	0.08	0.06	0.10

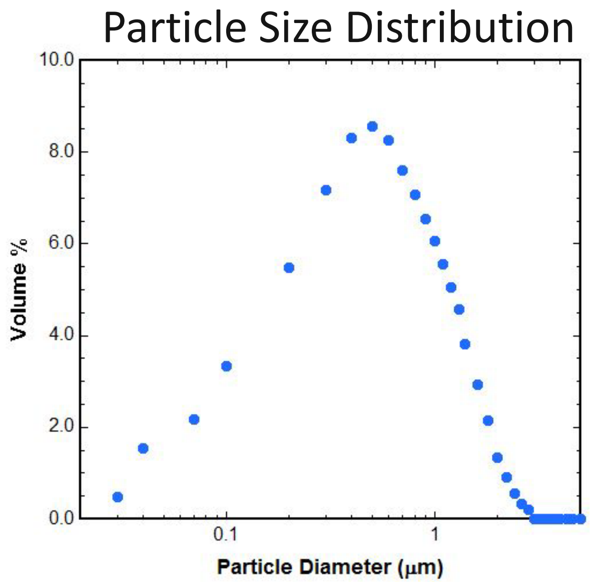
➢**DOE-VT DC Bus Capacitor Goal ≤3 mΩ**

PLZT film has high dielectric constant at high voltages, low ESR, and high-temperature capability.

Technical Accomplishments/Results (Cont.)

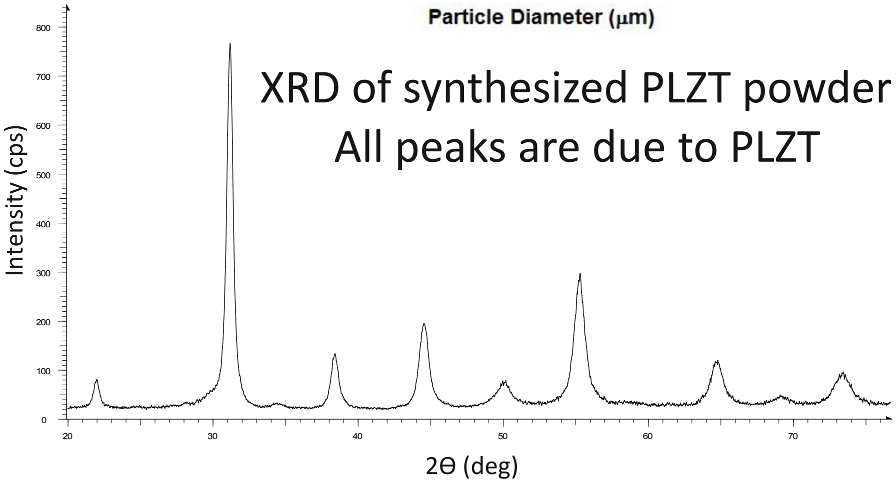
Aerosol (high-rate) Deposition of PLZT Films (*present results*)





Synthesis of sub-micron PLZT powder

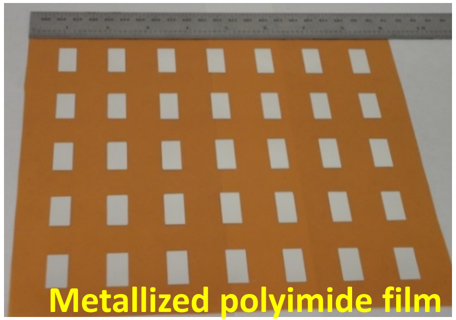
- Prepare aqueous solution containing fuel, oxidant, and cations
- Heat solution on hot plate to initiate combustion that is completed after only 2-3 min.

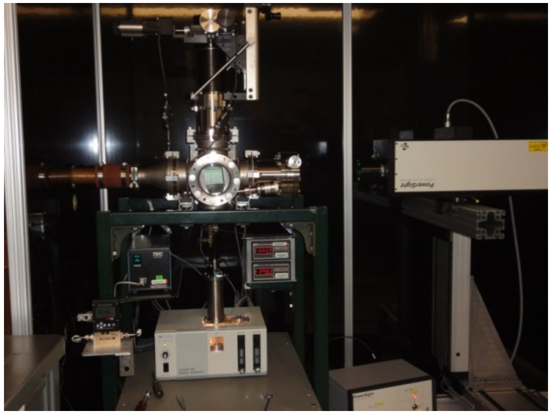


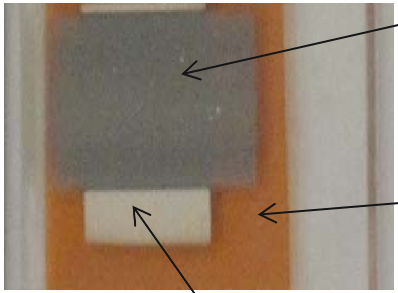
Installed AD system; developed solution chemistry to make submicron PLZT powders for high-rate deposition process.

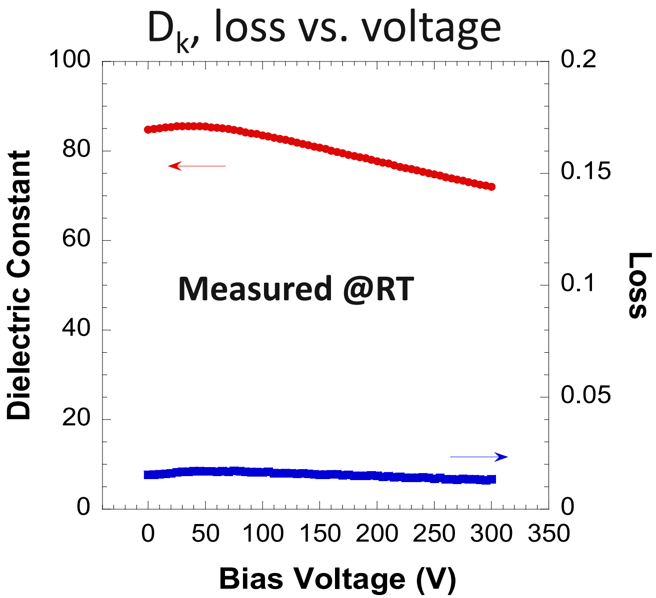
Technical Accomplishments/Results (Cont.)

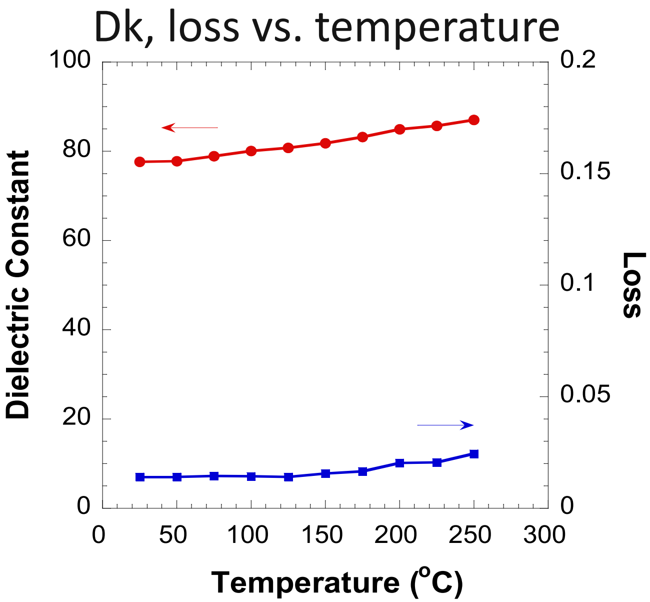
Properties of ≈8-μm-thick PLZT on Al-metallized polyimide films by AD process









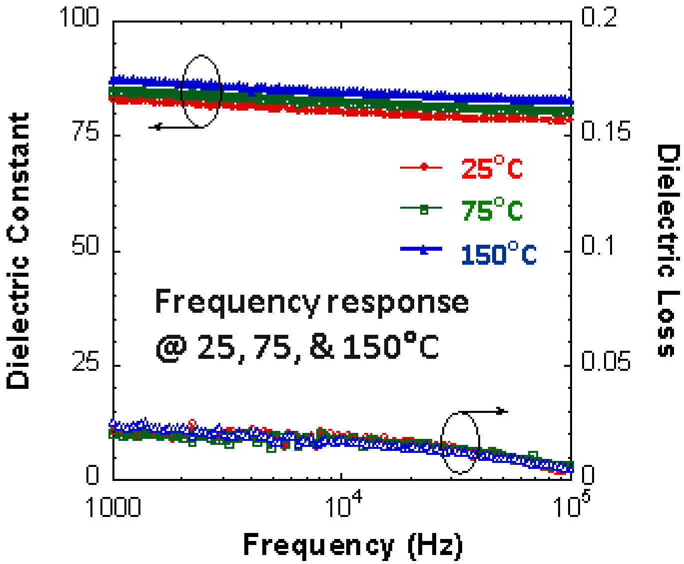


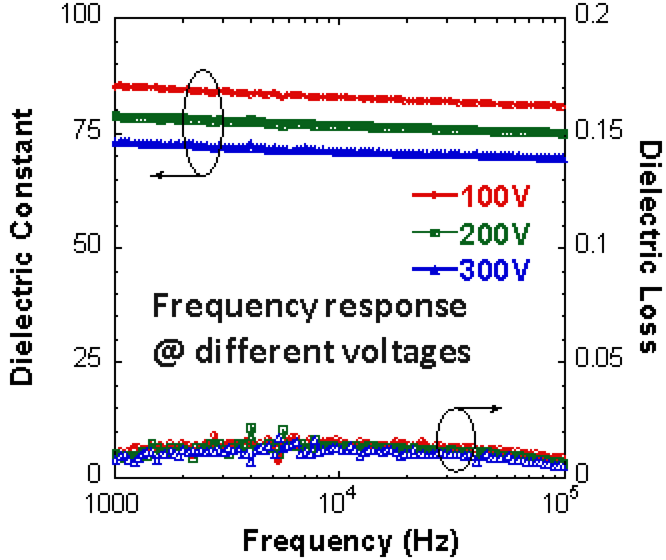
- Deposited ≈8-μm-thick PLZT film in 10 min by AD (vs. ≈5 days by spin coating process)
- AD process is un-optimized as of now

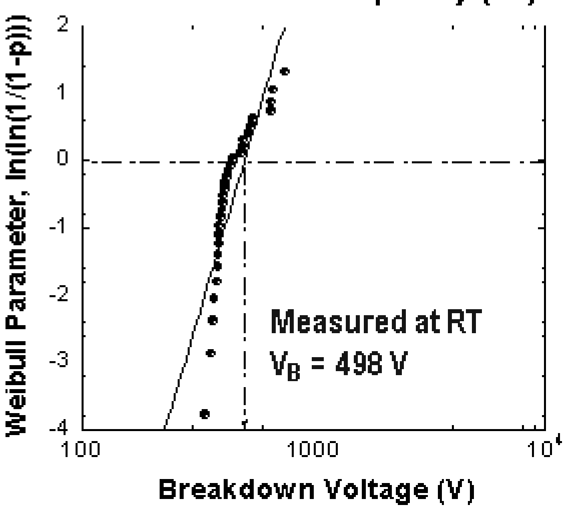
Demonstrated fabrication of PLZT films on metallized polymer films at room temperature by high-rate AD process. PLZT has high dielectric constant (≈80) and low loss (<2%) at 300V bias.

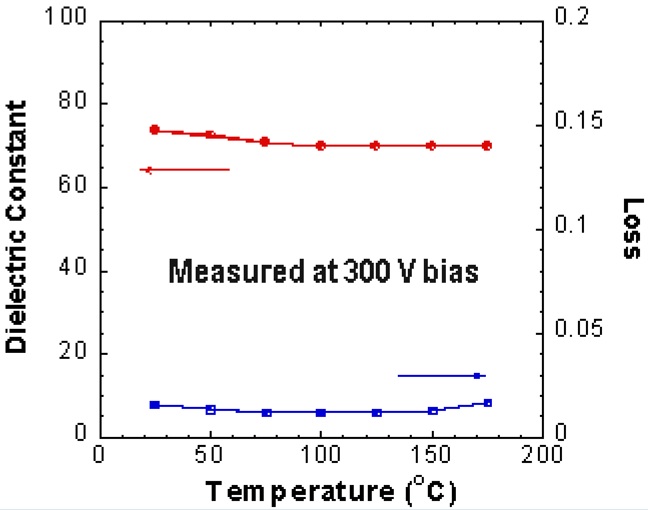
Technical Accomplishments/Results (Cont.)

Properties of ≈8-μm-thick PLZT made by AD on Al-metallized polyimide films







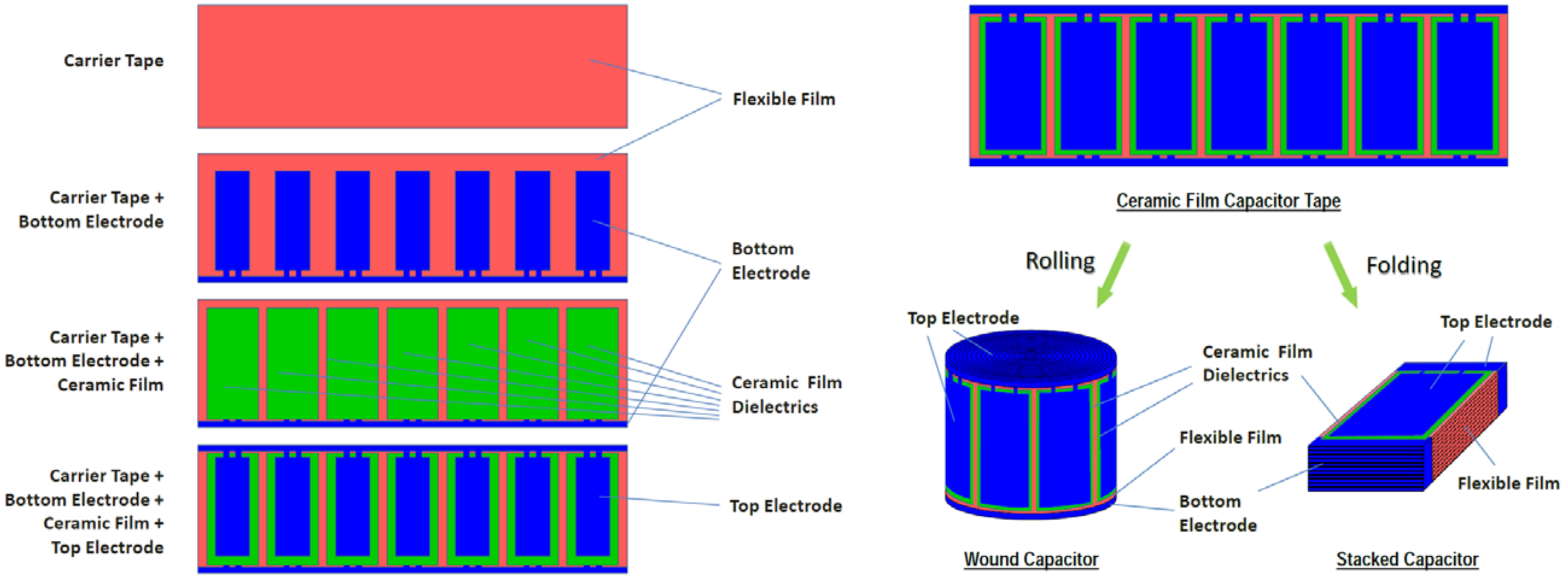


- Vapor-deposited Al metallization further enhances the cost-effectiveness of AD process

AD-deposited PLZT films on metallized polymers exhibit dielectric properties suitable for high-temperature applications.

Response to Previous Year's Reviewers' Comments
(This is a new start but a related project was reviewed last year)

- **Approach**
  - Comments: "the volume reduction, ripple performance over-temperature, and thermal performance, in general, all look excellent"… "this PLZT technology would just short out catastrophically. Therefore, the solution of decoupling capacitor from the inverter bus needs to be explained"
  - Response: Our approach incorporates innovative electrode design to achieve benign failure in PLZT capacitor. Already demonstrated and patented benign failure mechanism in film-on-foil PLZT.



Response to Previous Year's Reviewers' Comments

(This is a new start but a related project was reviewed last year)

- **Technical Accomplishments**
  - **Comments:** "the project focused on production processes and how they impact cost and performance, which this reviewer described as outstanding"… "it was very good that the researchers are addressing thermal issues early"… "the thermal performance over temperature was good"
  - **Response:** Positive comments, project direction/focus being maintained.

- **Proposed Future Research**
  - **Comments:** "the reviewer expressed interest in seeing the mechanism of culling –out the defects in sheets "… "the reviewer expressed interest in the possibility of using the AD process to increase the thickness of the PLZT"
  - **Response:** We are now depositing ≈8-µm-thick PLZT by AD process; therefore, pin-holes (which are common defects in thin films) become much less an issue.
- PLZT powders with well-defined stoichiometry are made by wet-chemical process and PLZT films are deposited at room-temperature (unlike in conventional MLCC process where PLZT is sintered at temperatures >1000°C); so, deleterious defects (like pyrochlore phase formation) are eliminated.
- Our effort will be focused on nozzle design, deposition pressure and powder feed conditions to control thickness uniformity over larger area PLZT films.

Collaboration and Coordination with Other Institutions

DELPHI

Inverter design engineering (direct customer for the technology), defining overall capacitor requirements, supplying critical knowledge of automotive power electronics, testing/validating results, demonstrating DC-link capacitor with an automobile power inverter.

SigmaTechnologies

Roll-to-roll deposition systems, multilayer coating technologies, coating capacitor films to improve breakdown and self-healing properties, background to convert lab-scale process into an industrial-scale process.

PENNSTATE

Dielectric characterization, reliability testing, electrode design & deposition, testing/validating results.

Remaining Challenges and Barriers

- **Can PLZT be deposited on metallized ≈5-µm-thick polymer films by AD process?**
  - The metallized polyimide film used in the preliminary work is ≈50-µm-thick; earlier we deposited PLZT on ≈8-µm-thick Al foil.

- **Can PLZT-based films be produced with a roll-to-roll process?**
  - Sigma has in place several roll-to-roll and batch metallizing and coating systems that will be retrofitted to perform AD process on continuously moving substrates.

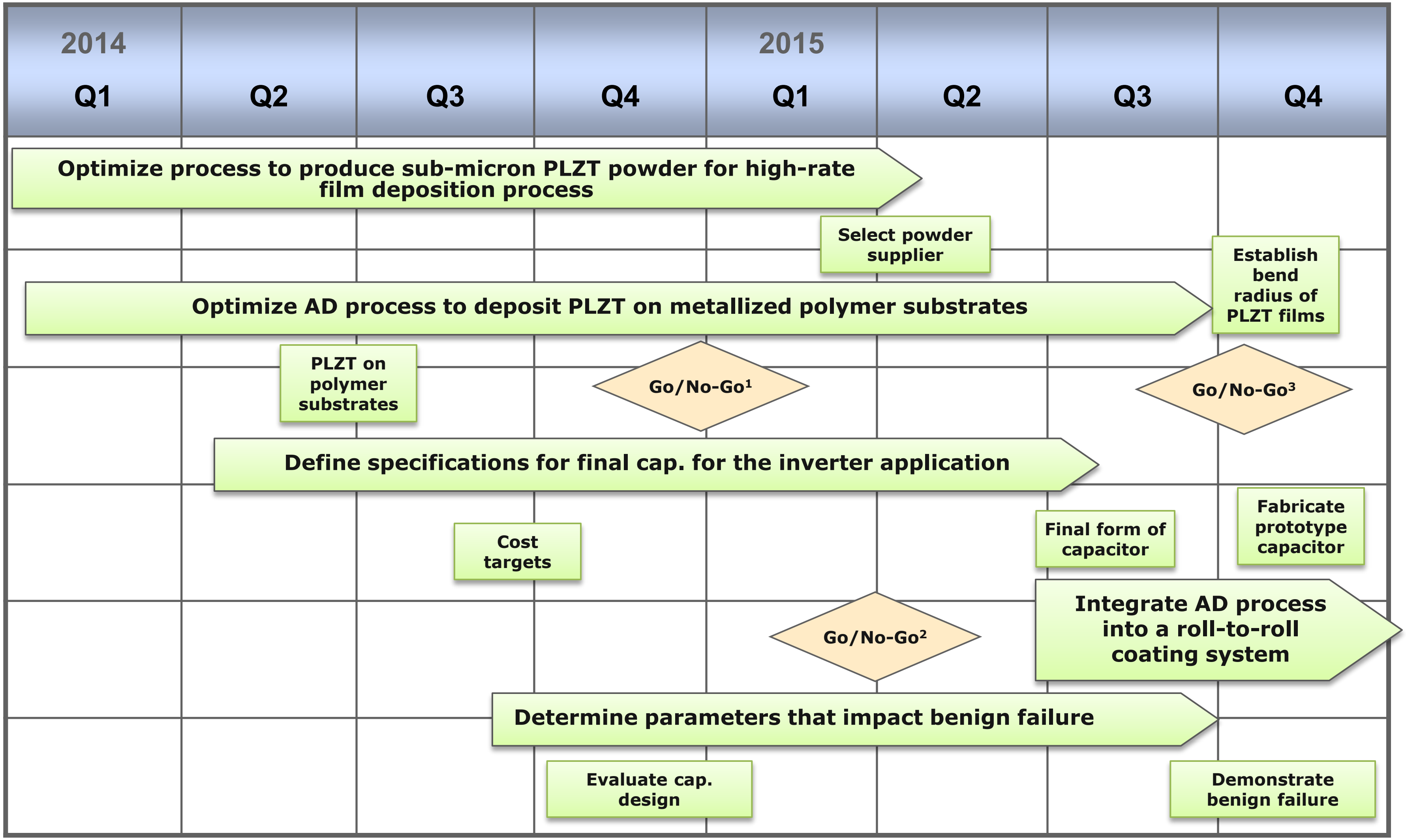
- **Can the thin ceramic dielectrics be wound similar to polymer film capacitors?**
  - The risk involved in winding the rolls of metallized PLZT films is the formation of micro-cracks. The stress-strain properties dictate the minimum bend radius.

Proposed Future Work

- **Establish materials, packaging, and process cost targets**
- **Optimize AD process parameters to deposit PLZT films on metallized thin (≈5-µm-thick) polyimide films and characterize the capacitors**
  - Optimize particle size distribution, particle velocity, chamber pressures, carrier gas, nozzle design (convergent-to-divergent nozzle), & distance between nozzle and substrate
  - Identify optimum conditions by correlating the deposition rate and measured properties
- **Determine parameters that impact benign failure of PLZT capacitors**
  - Evaluate different designs with heavy edge electrodes to maximize self-healing process
- **Define specifications for final capacitor for inverter applications**
  - Define dielectric properties, capacitor form factor, and mechanical property requirements for the final capacitor for the inverter application

FY15 Focus: Fabricate prototype ≈10 µF capacitors with benign failure feature; integrate AD process into a roll-to-roll coating system.

Tasks to Achieve Key Deliverables



Go/No-Go Decisions:
1. Decision on film coverage area.
2. Down-select capacitor design (double-metallized film substrate or double-metallized PLZT dielectric approach).
3. Decision on winding the film.

Summary

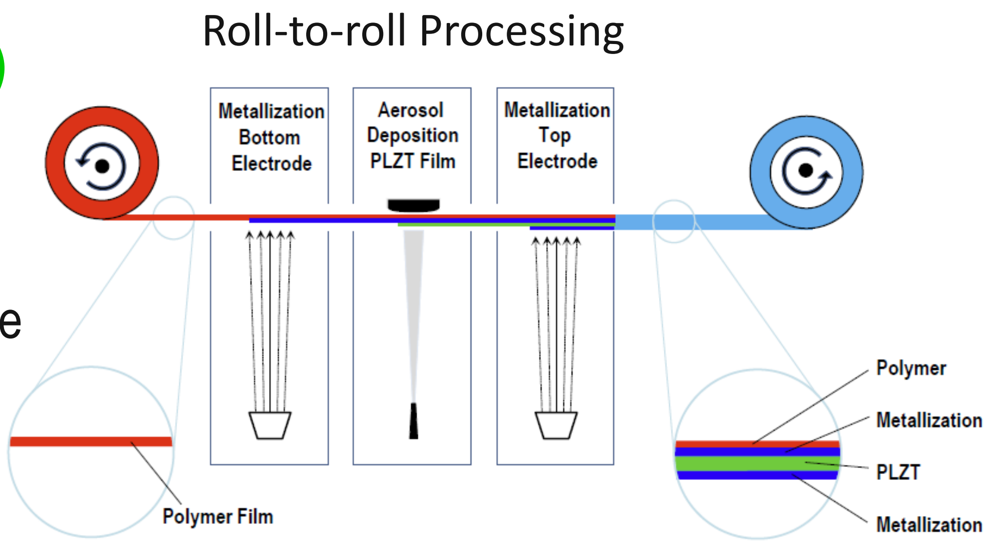
We are developing an efficient, cost-effective process for fabricating high-temperature DC-link capacitors for advanced power inverters. This project will substantially reduce the size, weight, and cost of DC-link capacitors, which will enable the fabrication of smaller, lighter, and less costly EDV power inverters – *Addressing barriers A & C (cost & weight) and D (high-temperature operation)*

- Aerosol deposition, a high-rate, room-temperature film deposition process, is being developed at Argonne to reduce capacitor cost.
- Processes to produce sub-micron PLZT powders suitable for high-rate deposition processes have been developed.
- Deposited ≈8-μm-thick films on Al-metallized polyimide films by AD and characterized their dielectric properties.
- This research directly impacts the need of industry for advanced DC-link capacitors that will be part of the next generation power inverters for EDVs.

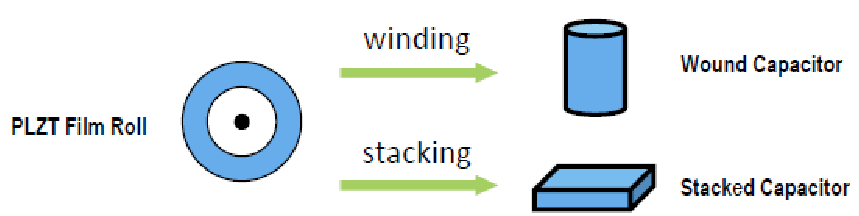
Technical Back-up Slides

Uniqueness of Project and Impact

- **Specifications for "On-the-Road" technology capacitor (State-of-the-Art)**
  - Volume of cap. modules rated for 85°C:
    2010 Prius (888 μF): Vol. ≈1.5 L
    2011 Sonata (680 μF): Vol. ≈1 L
  - Limited to temperature of ≈85°C, because ripple current capability degrades rapidly at temp. >85°C



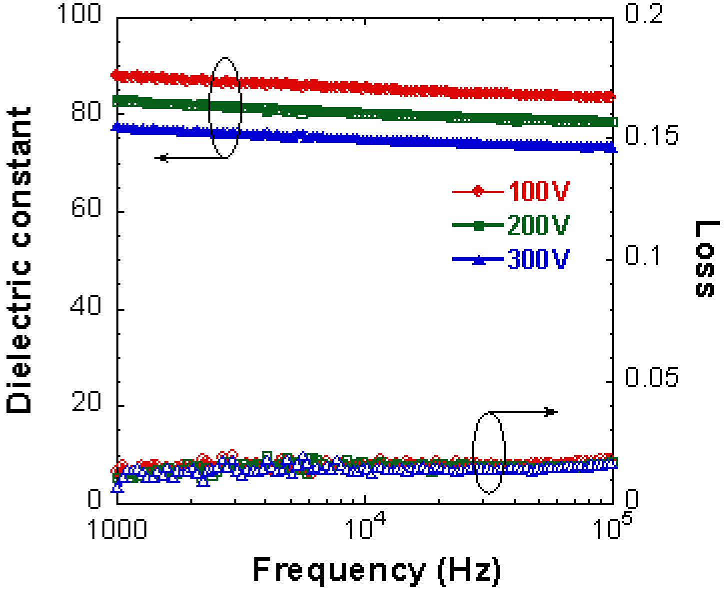
- **PLZT film capacitor projected performance**
  - Dielectric volume for a 1000 μF/450 V capacitor is ≈0.3 L (high degree of volumetric efficiency)

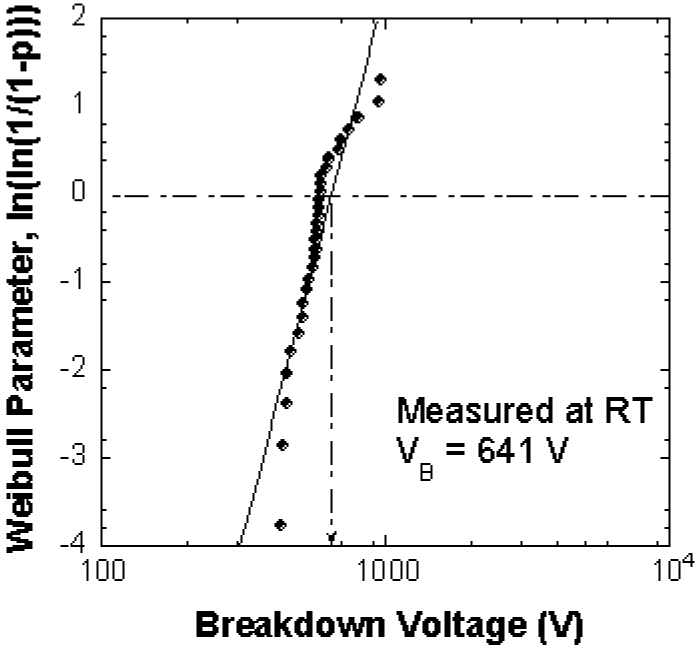


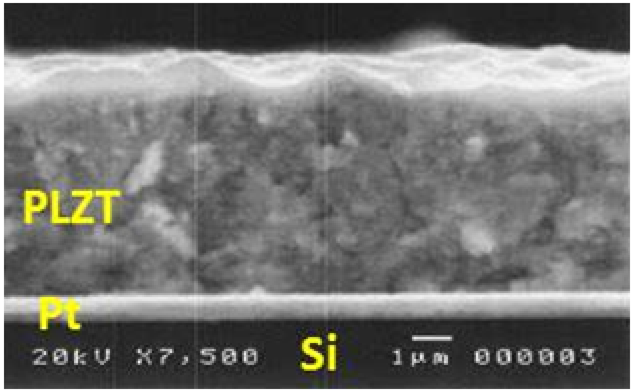
- No ripple current decrease between 85°C and 150°C.
  Projection is based on measured high-temperature dielectric loss data
- Possible to make wound capacitors
- Stacked and/or embedded capacitors significantly reduce component footprint, improve device performance, and provide greater design flexibility

Technical Accomplishments/Results

Deposition of ≈8-µm-thick PLZT on Pt/Si by AD process





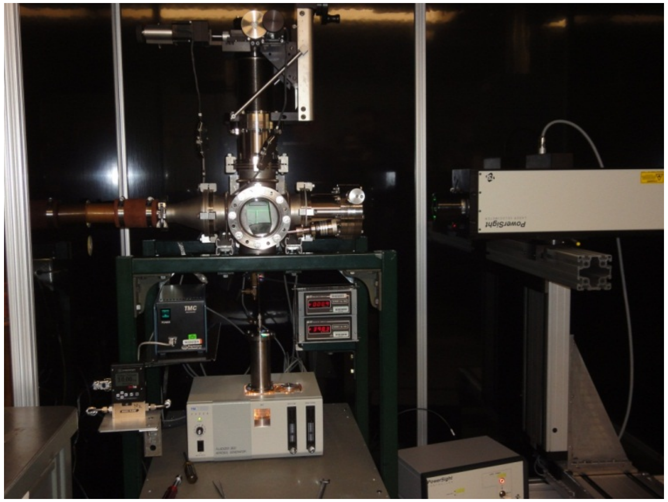


- Deposited ≈8-µm-thick PLZT film in 10 min by AD (vs. ≈5 days by spin coating process)
- AD process is un-optimized as of now

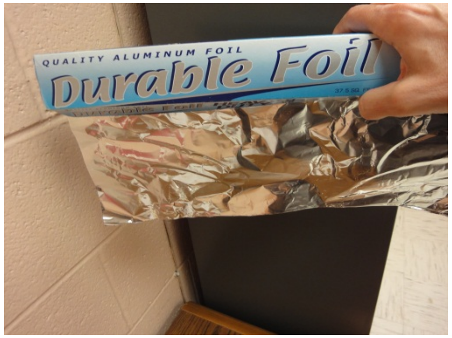
AD process has potential to significantly reduce the PLZT capacitor's cost.

Aerosol Deposition (AD) of PLZT on Flexible Substrates

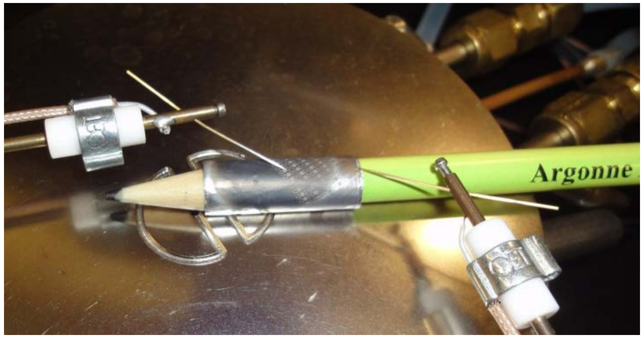
AD unit in action



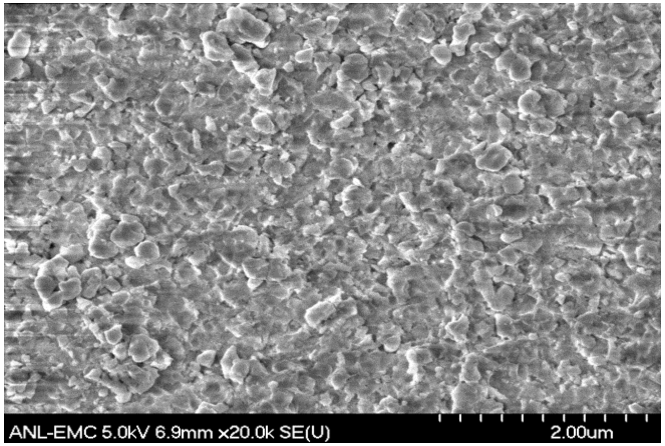
Al foil



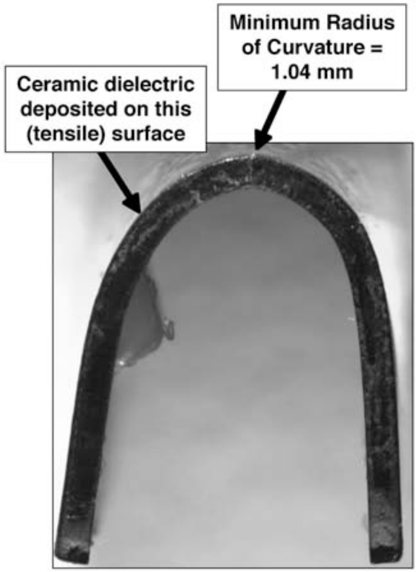
Dielectric layer on Al foil



SEM of as-deposited film surface



AD process has potential to produce wound ceramic film-on-foil capacitor



Strain-tolerance of film-on-foil
Measured by Andy Wereszczak (ORNL)

AD process will lower the capacitor manufacturing cost

Traditional Multilayer Ceramic Capacitors (MLCC) vs. Film-on-Foils

- In MLCCs, dielectric & electrode layers are co-fired at elevated temperatures; electrode layers are too-thick
- No benign failure mechanism in MLCCs (used in microelectronic applications)
- In film-on-foil approach, very thin metallized polymer films are used and PLZT is deposited at room-temperature; possible to choose a wide range of electrode materials (aluminum metallization is used in this work)
- Benign failure mechanism is available with film-on-foils
- A variety of substrate materials (polymers, Al, Ni, Cu, Si) can be used in the film-on-foil approach
- Film-on-foils can tolerate certain bend radius
- Film-on-foil approach can produce wound ceramic capacitors