High Dielectric Constant Capacitors for Power Electronic Systems*

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Project ID# ape_05_balachandran

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Overview

Timeline

- Project start date: FY04
- Project end date: FY12
- Project continuation & direction determined annually by DOE
- Percent complete: 60

Budget

- Total project funding
  - DOE share: 100%
- Funding received in FY08: $940K
- Funding for FY09: $800K

Barriers addressed

- Overall size and cost of inverters

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

  The performance and lifetime of presently available capacitors degrade rapidly with increasing temperature (coolant temperature of 105°C).

Partners

- Penn State University
- Delphi Electronics
- Project Lead: Argonne National Laboratory

Objectives

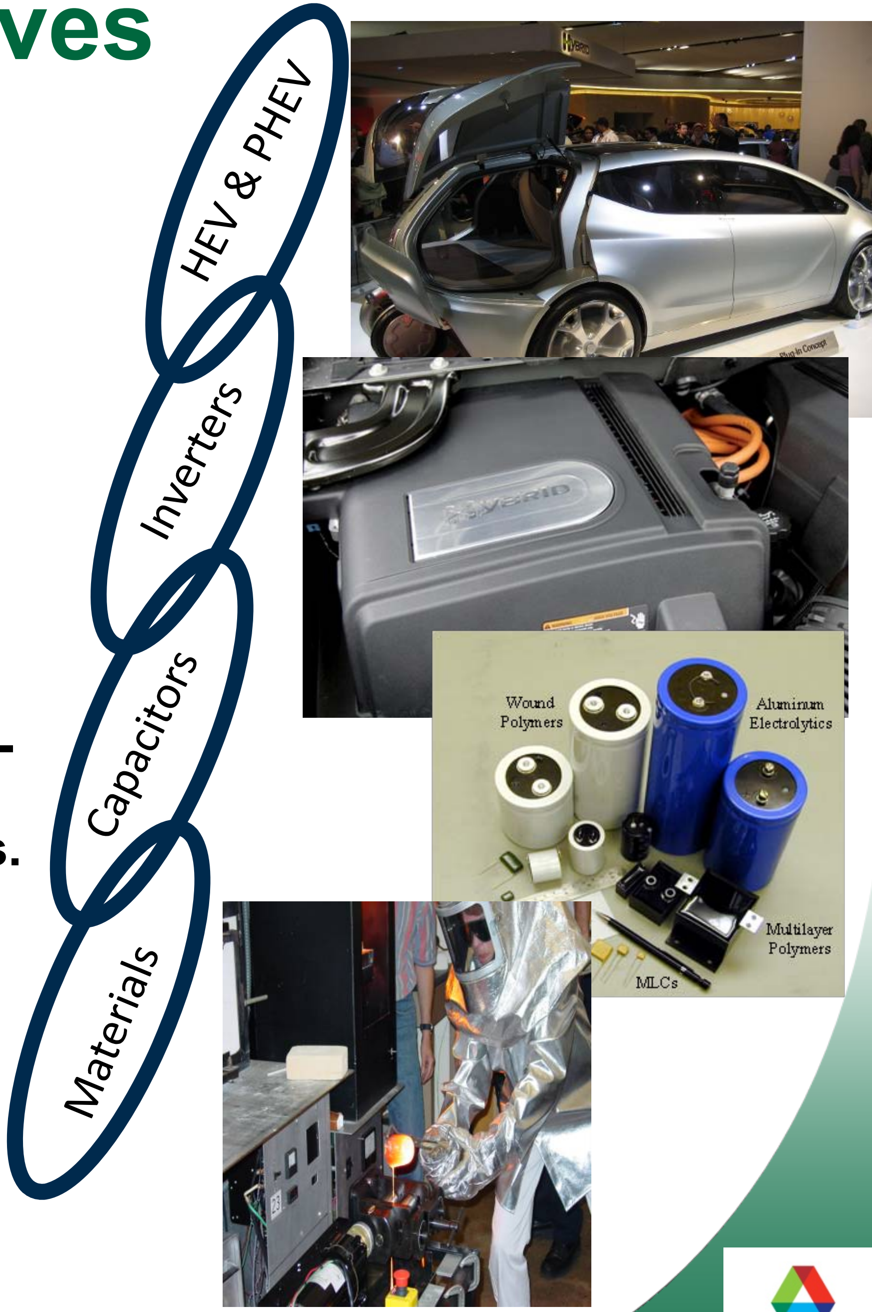
- **Overall objective is to develop technology for fabricating a range of new, high performance, economical, capacitors for power electronic systems in HEVs, PHEVs, and FCVs.**

  DC bus capacitors for inverters

  – ***(600 V, 2000 μF, <3 mΩ ESR, 250 A ripple current,140°C, benign failure)***

- **Objective for FY08 was to fabricate and characterize high voltage capable dielectric films on base-metal foils (“film-on-foils”) that meet or exceed the needs of hybrid electric vehicle power inverters.**

- **Dielectrics films will have:**
  – **An operational temperature range of -50°C to +140°C**
  – **600 V DC bus capability**
  – **High k (>1000) and E_b (>3 MV/cm) to meet weight & volume target**



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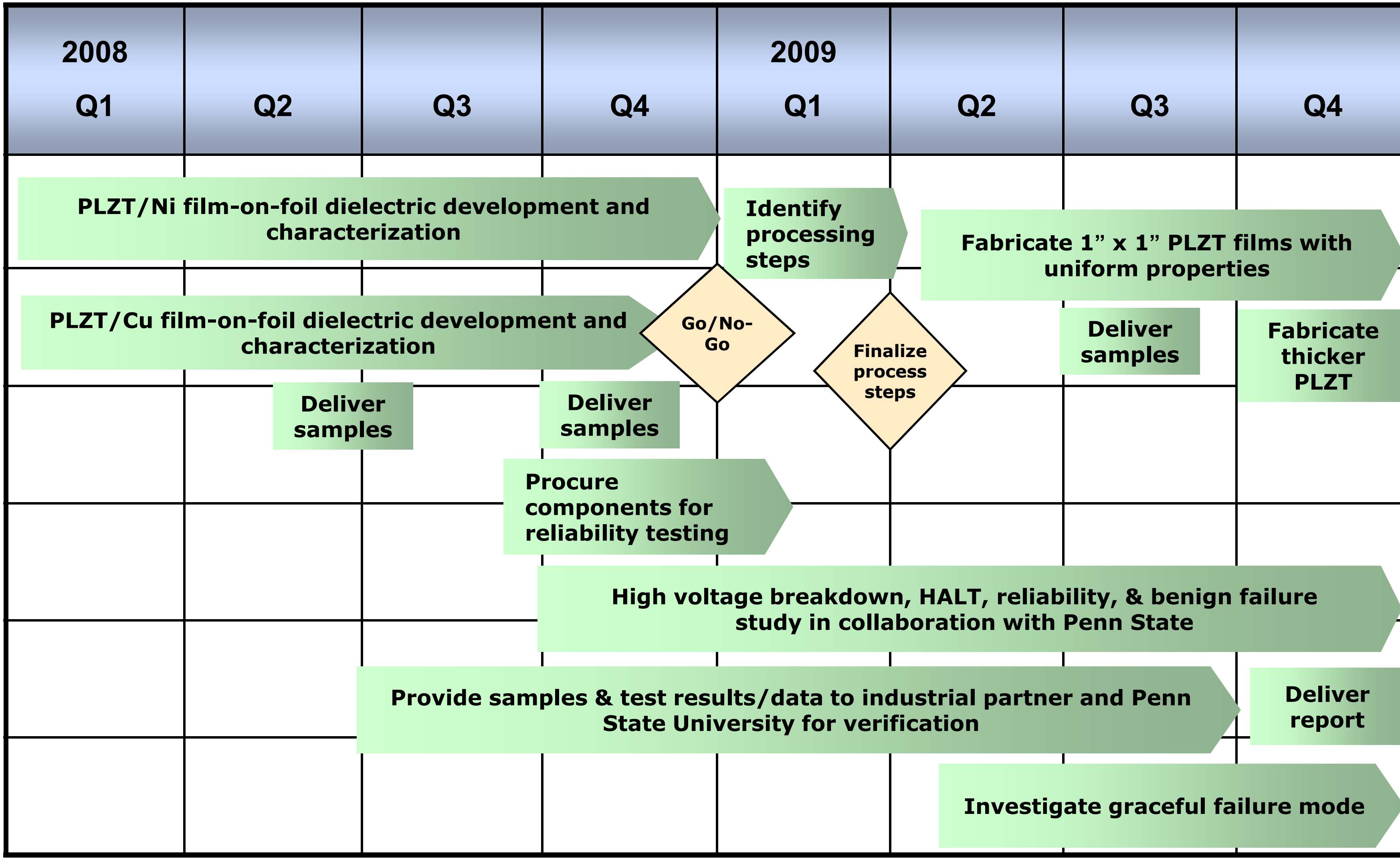
Relevance to Overall DOE Objectives of Petroleum Displacement

- Advanced inverters are essential for electric traction operations in HEVs, PHEVs, and FCVs.
- Future availability of advanced high-temperature (together with lower cost, weight, & volume) inverters will advance the marketplace application of highly fuel efficient & environmentally beneficial hybrid vehicles.
- Capacitors have direct impact on overall size, cost, & performance of inverters.
- Capacitor development will reduce the size & increase the temperature of operation of one of the largest components in the inverter: the DC bus capacitor.

This project is developing dielectric films that has potential to reduce size, weight, and cost, concomitant with increased capacitance density & high temperature operation, for capacitors in inverters in HEVs, PHEVs, and FCVs.

Milestones



Decision point: Either continue the two-pronged approach, i.e., PLZT/Ni and PLZT/Cu, or down-select one over the other.

Finalize processing steps: Polishing procedure, surface roughness, & defect density in the foil will be quantified. Defects in foils translate into defects in PLZT films.

Technical Approach

- Develop ferroelectric (PLZT) dielectric films on base-metal foil (“film-on-foil”) that are either stacked on or embedded directly into the printed wire board.
- Integration of base-metal (Ni, Cu) electrodes provides a significant cost advantage over noble metal electrodes that are used in conventional multilayer capacitors.
- Ferroelectrics possess high dielectric constants, breakdown fields, and insulation resistance. With their ability to withstand high temperatures, they can tolerate high ripple currents at under-the-hood conditions.
- Stacked and/or embedded capacitors significantly reduce component footprint, improve device performance, provide greater design flexibility, achieve high degree of volumetric efficiency with less weight, and offer an economic advantage.
- Our approach focuses on fabricating films by chemical solution deposition, developing a fundamental understanding of processing effects on properties, and arriving at robust processing strategies.

Argonne’s project addresses the technology gap in an innovative manner

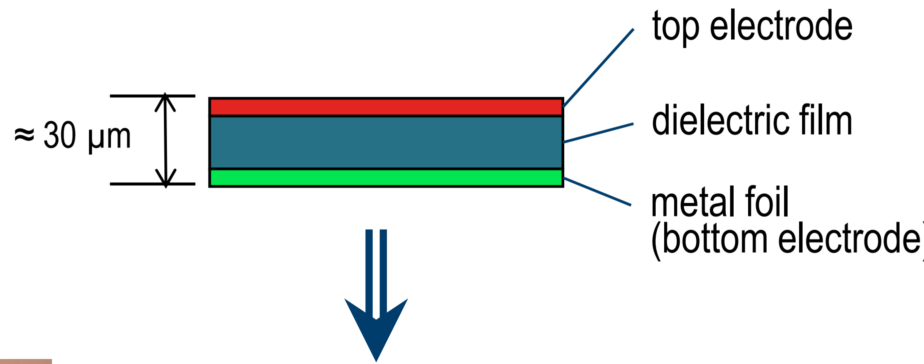
Uniqueness of Project and Impact
(caps embedded directly into PWB – caps are “invisible”)

Basic Element

Metal foil coated with thin film PLZT dielectric

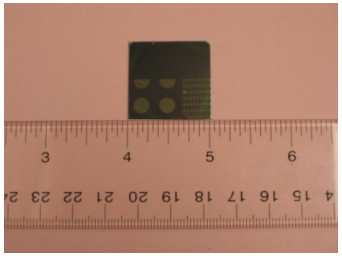
- PLZT/Ni Film-on-Foil
- PLZT/Cu Film-on-Foil

Film-on-foil capacitor

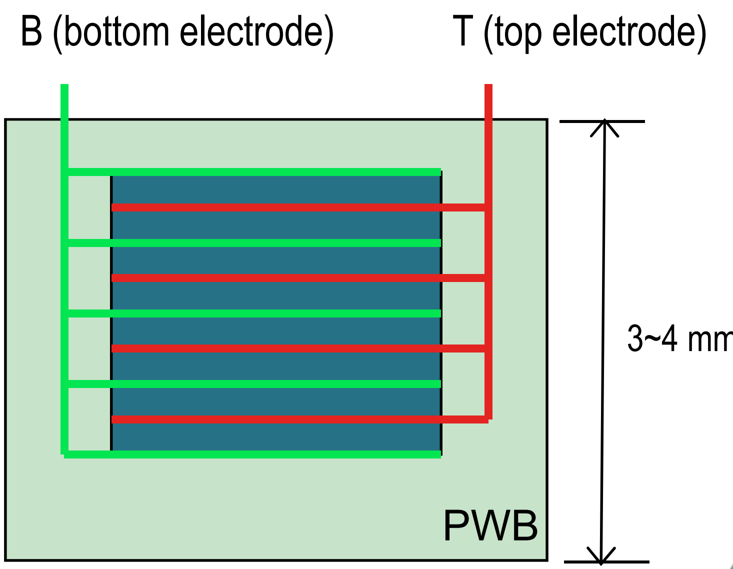


Component

Stack on or embed coated foils directly into printed wire circuit board for power electronics in (P)HEV



PWB Embedded capacitor with interconnections



Advantages

Reduces component footprint

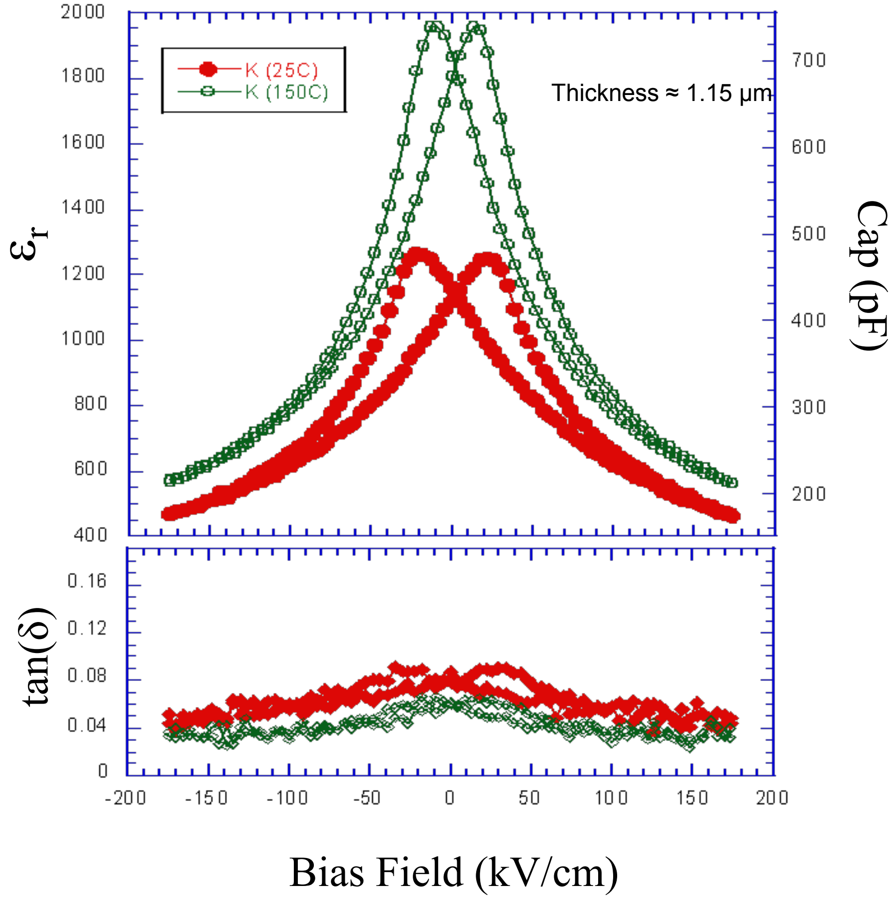
Shortens interconnect lengths

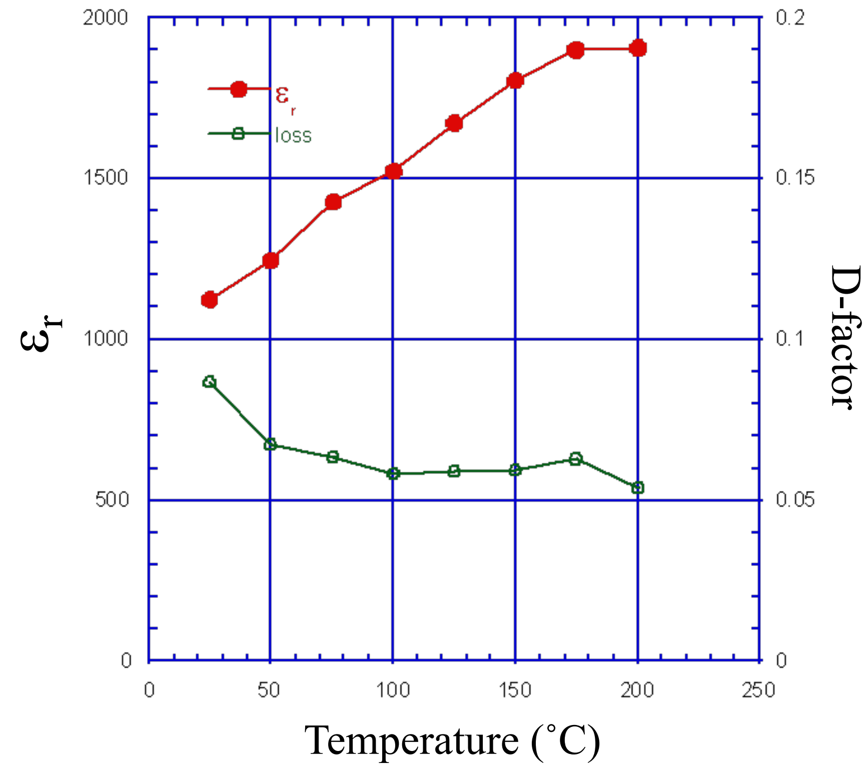
Reduces parasitic inductive losses & electromagnetic interference

Reliability is improved because the number & size of interconnections are reduced. Solder joints that are most susceptible to failure are no longer needed.

Accomplishments/Progress/Results

PLZT/Ni





- **Fabricated PLZT on Ni foils with k ≈1300 & DF ≈0.08 @ 25°C and ≈1800 & 0.06 @ 150°C; mean breakdown strength >6.0 MV/cm.**

(measurements made on 250-500 μm top electrodes)

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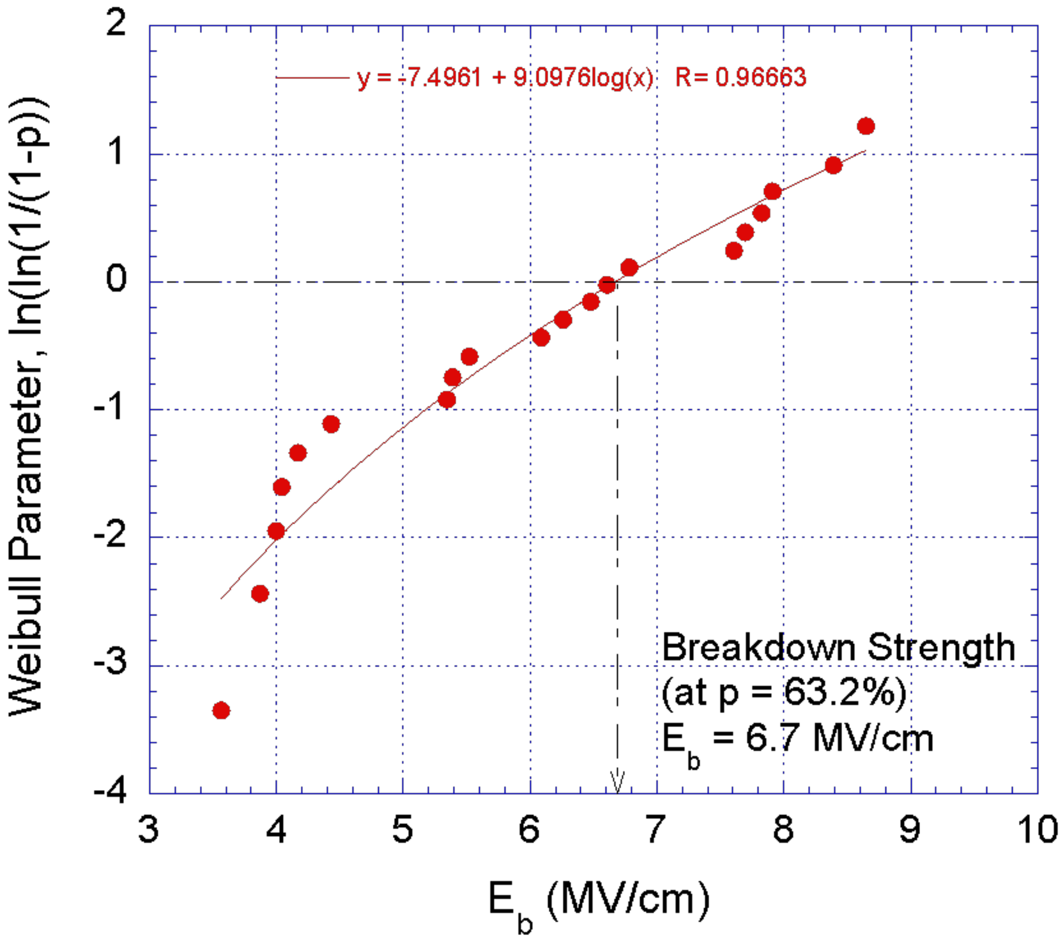
Accomplishments/Progress/Results (Cont.)

Breakdown strength of PLZT on Ni foil – Weibull analysis



Film thickness: 1.15 µm

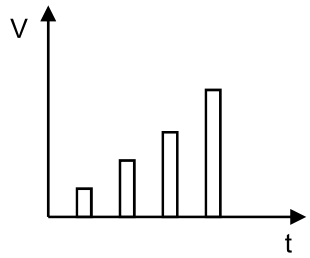
Electrode diameter: 250 µm

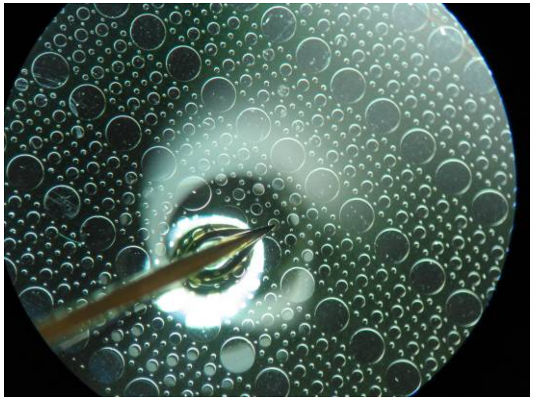
Test condition:

voltage: 200~1000V

step time: 0.5 sec

zero time: 1 sec

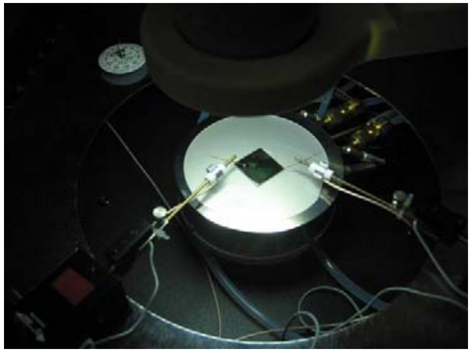


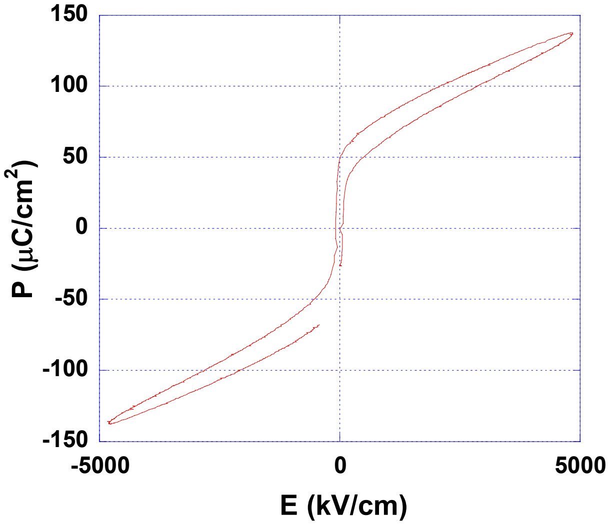


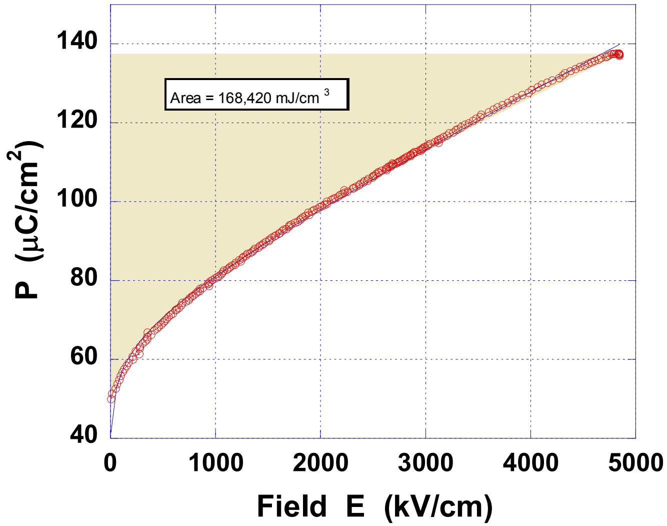
- **Higher E_b increases capacitance density and reduces dielectric layer thickness & cost of the capacitors for inverter applications.**

Accomplishments/Progress/Results (Cont.)

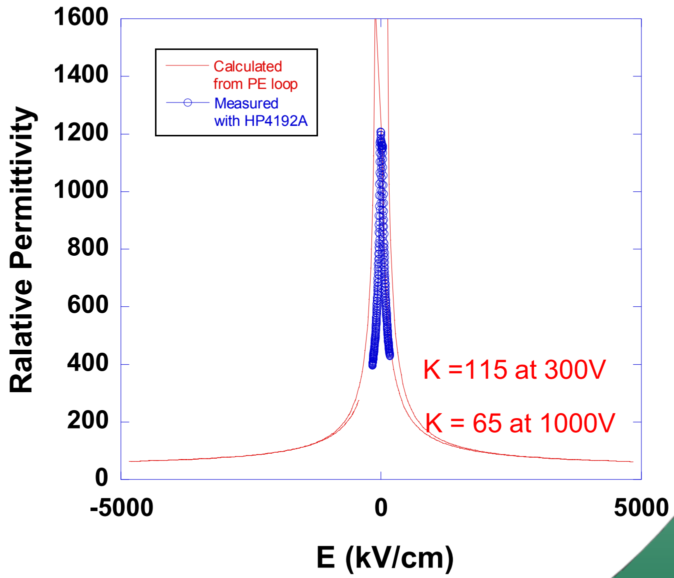
Polarization & Energy Density Measured on PLZT/Ni Foil







Film thickness ≈2.0 μm
Applied voltage = ±1000 V
Dielectric constant ≈ 1100 at zero-bias &
115 at 300 V; 65 at 1000 V
Energy density = 168.4 J/cm^3
Electrode diameter = 250 μm

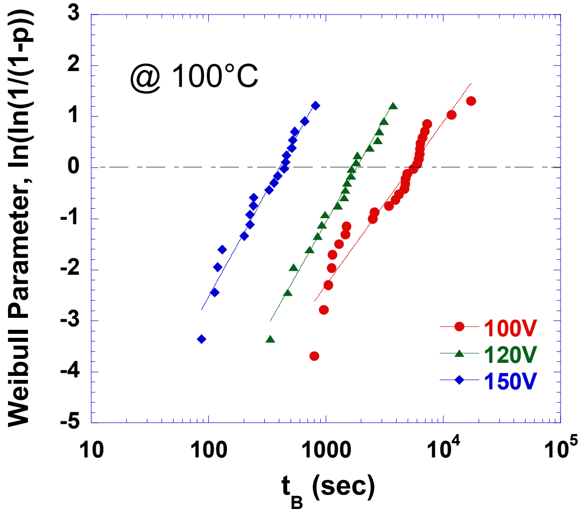


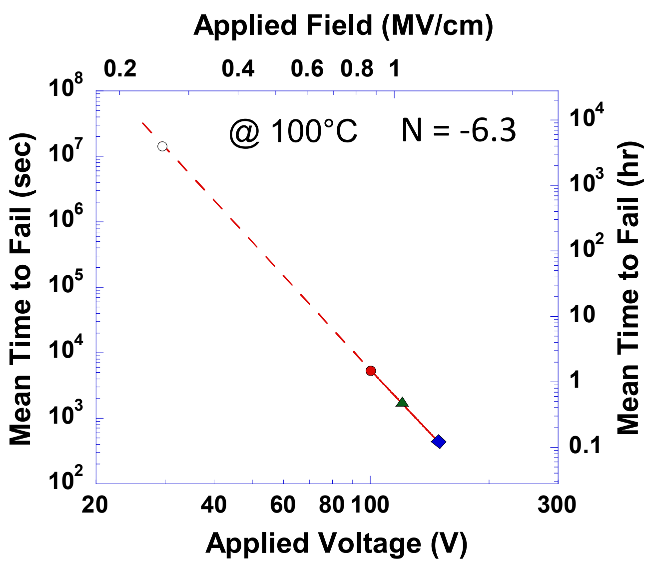
- **Energy density ≈170 J/cm^3 was measured at 1000 V.**

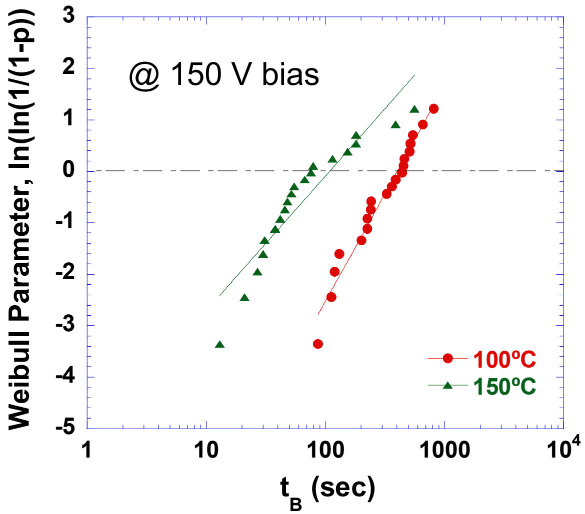
Accomplishments/Progress/Results (Cont.)

High-temperature measurement to predict capacitor life-time

(preliminary measurement on ≈1.15 μm PLZT/Ni using 250 μm Pt electrode)







- Lifetime estimated by measuring time to failure vs. applied voltage as function of temperature.
- Mean time-to-failure (MTF), voltage acceleration factor (N), and activation energy (E_a) are obtained from reliability measurement.

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Accomplishments/Progress/Results (Cont.)

Breakdown Strength of PLZT film on Ni foil

Film thickness: 1.15 μm

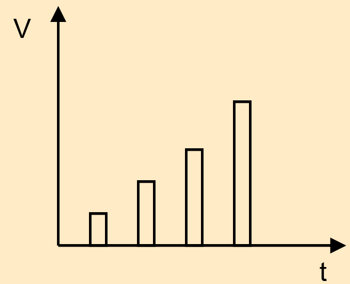
Electrode diameter: 250 μm

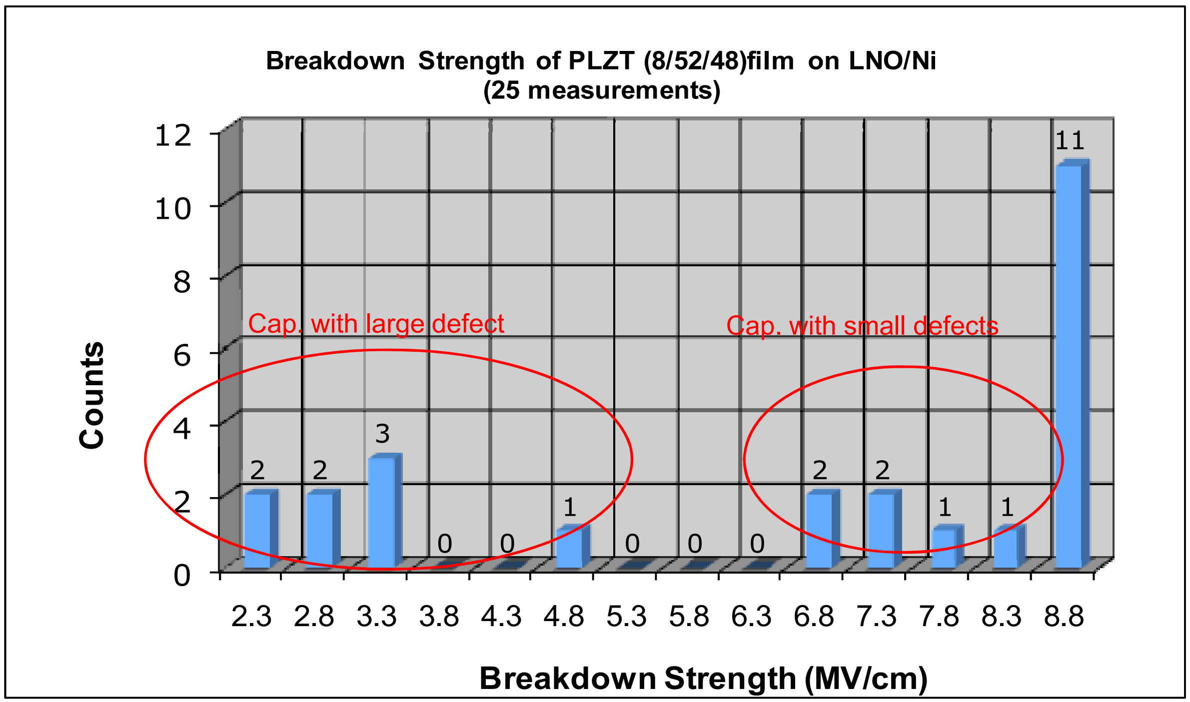
Test condition:

applied voltage: 200~1000V

step time: 0.5 sec

zero time: 1 sec



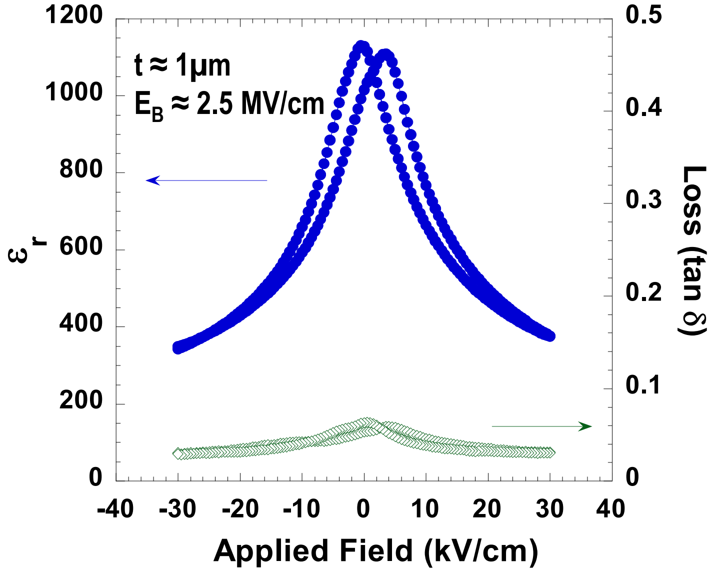


- Controlling the defects through process optimization will yield PLZT films with very high breakdown field (E_b).
- Higher E_b will reduce dielectric layer thickness & cost of the caps for power inverter applications.

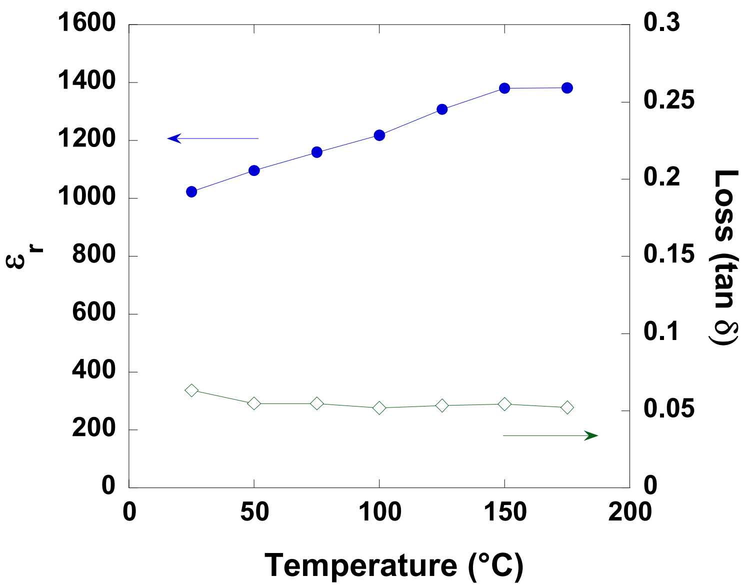
- **Our results show that it is possible to fabricate PLZT film-on-foil dielectric films with E_b >10 MV/cm.**

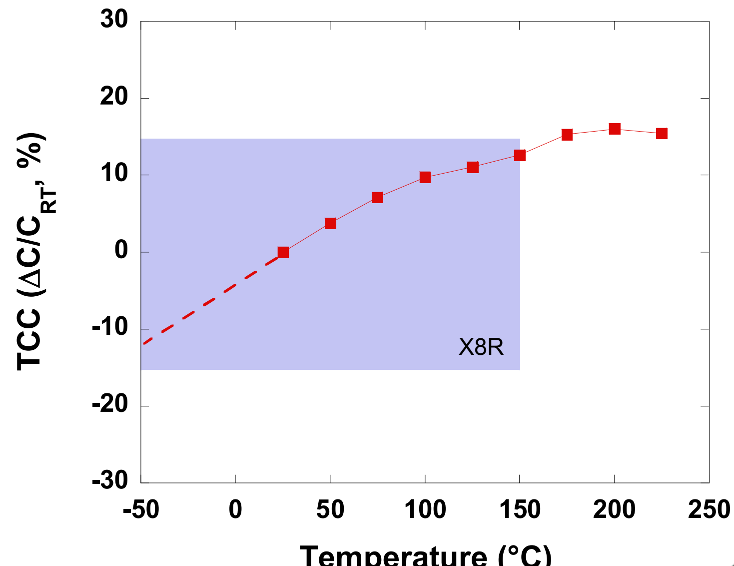
Accomplishments/Progress/Results (Cont.)

PLZT/Cu



- Dielectric constant increased from ≈1100 to ≈1400 and loss factor decreased from 0.07 to 0.05 when temperature was increased from 25°C to 150°C.





Future Work

- Optimize processing conditions to make 1” x 1” size capacitors with uniform properties (minimize defects).
  - substrate polishing, drying of individual layers, pyrolysis and crystallization temperatures, & room environment influence the properties of PLZT films.
  - defects in the substrates translate into defects in the dielectric layers.
- Fabricate thicker films for high-voltage applications (600 V rating, up to 700 V transient in inverters).
- Characterize the dielectric properties as function of bias voltage and temperature, and reliability of film-on-foil dielectrics.
- Investigate benign failure in multilayer architecture (demonstrated benign failure mode in single layer film-on-foil dielectrics).
- Produce prototype film-on-foils for power inverters.

Summary

Developing dielectric films that has potential to reduce size, weight, and cost, concomitant with increased capacitance density & high temperature operation, for capacitors in inverters in electric vehicles.

- Demonstrated dielectric films with k >1200, E_b ≈6.5 MV/cm, and $I_{leakage}$ <10^{-8} A/cm^2.
- Dielectric constant increased and loss factor slightly decreased when temperature increased from 25°C to 150°C, both causing ESR to decrease.
- Showed potential for film-on-foils with E_b >10 MV/cm; high E_b increases capacitance density and reduces amount and cost of capacitors in inverters.
- Measured energy density ≈170 J/cm^3 in a ≈2 μm-thick PLZT film-on-foil.
- Demonstrated graceful failure by self-clearing method in single layer dielectric films.
- Film-on-foil dielectrics were thermally cycled (≈1000 cycles) between -50°C and +150°C with no measurable degradation in k.
- Thin ceramic dielectric on relatively thick Ni substrate is quite strain tolerant.
- A CRADA with Delphi was established to further develop and commercialize this technology.
- Over 30 publications and presentations have been made.