High Dielectric Constant Capacitors for Power Electronic Systems

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Project Duration: FY04 to FY14

DOE Vehicle Technologies Program
Advanced Power Electronics and Electric Motors R&D
FY12 Kickoff Meeting

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USDRIVE
DRIVING RESEARCH AND INNOVATION FOR VEHICLE EFFICIENCY AND ENERGY SUSTAINABILITY

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The Problem

- **The DC bus capacitors are currently the largest component of electric drive vehicle (EDV) inverters.**
- **Current polymer film capacitors have temperature limitation for under-hood operation.**

Capacitor development will reduce the size & increase the temperature of operation of one of the largest components in the inverter: the DC bus capacitor

Capacitors have a significant influence on inverter lifetime, reliability, and high temperature operation. They have direct impact on overall size & cost of inverters.

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Project Overview

Research Focus Area: Power Electronics

Sub focus area: DC bus capacitors

Overall Project Objective

- Develop ceramic dielectric films that have potential to reduce size, weight, and cost, concomitant with increased capacitance density & high temperature operation, for capacitors in electric drive vehicle inverters. The purpose of this project is to build & test a prototype capacitor capable of meeting DOE-OVT requirements.

Addresses Targets

- This project directly addresses the temperature, size, and cost specifications required for DC bus capacitors. The performance of presently available capacitors degrade rapidly with increasing temperature and they occupy significant fraction of the inverter volume (≈35%), weight (≈25%), and cost (≈23%).

Uniqueness and Impacts

- Our approach uses inexpensive high-temperature ceramic dielectric films that are either stacked on or embedded into printed wiring board (PWB) to meet DOE-OVT requirements for future power inverters.

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Description of Technology

- Our approach is to develop high-dielectric-constant, high-temperature ceramic (Pb-La-Zr-Ti-O, PLZT) films on base-metal foils ("film-on-foil") that are either stacked on or embedded directly into the PWBs.
  - Integration of base-metal (Ni, Cu) electrodes provides a significant cost advantage over noble metal electrodes that are used in conventional multilayer capacitors.
  - PLZT 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.

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 Pb-La-Zr-Ti-Oxide (PLZT) dielectric

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

Component

Stack on or embed coated foils directly into printed wire board for power electronics in EDVs

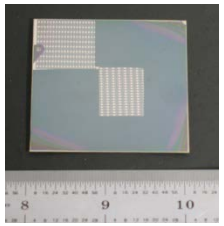
Advantages

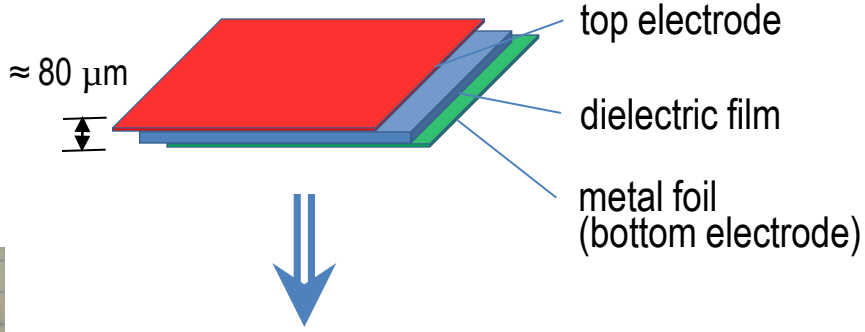
Reduces component footprint

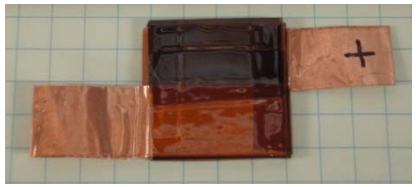
Shortens interconnect lengths

Reduces parasitic inductive losses & electromagnetic interference

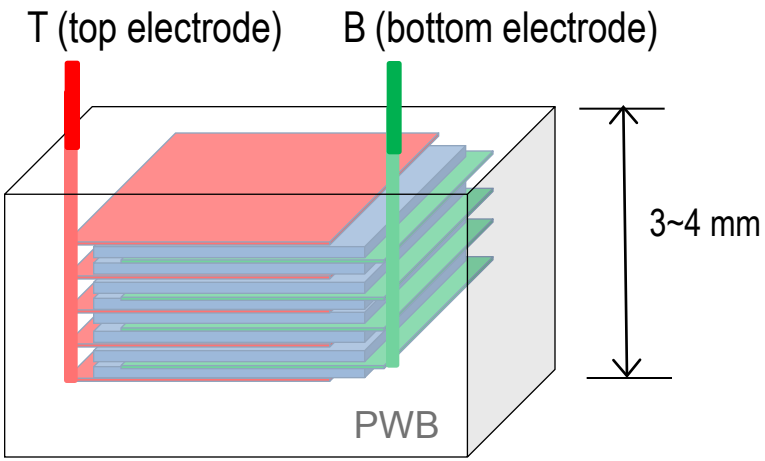
Film-on-foil capacitor (FoF)







Stack of three FoFs

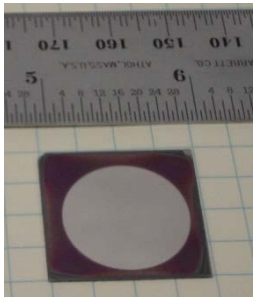


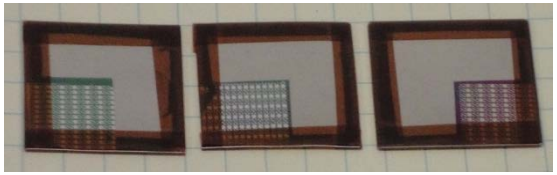
PWB Embedded capacitor with interconnections

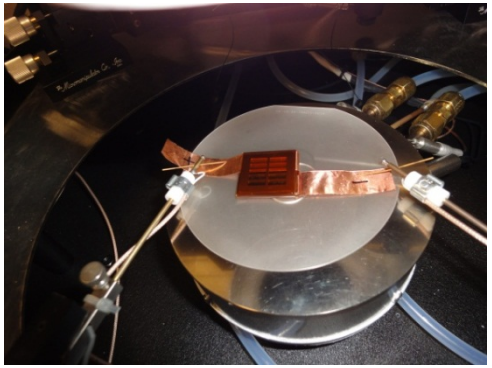
Reliability is improved because the number & size of interconnections are reduced. Solder joints that are most susceptible to failure are no longer needed.

Accomplishments to Date

- Fabricated ≈5 μF capacitor by stacking three 1” x 1” film-on-foils (Capacitance density of 4 μF/cm^3).
- Fabricated & measured a 20-mm diameter film-on-foil (≈0.7 μm-thick PLZT) with capacitance of ≈5 μF (at the FY10 kickoff meeting we reported maximum capacitance of ≈0.9 μF).
- Demonstrated film-on-foil dielectrics with k >1300, breakdown field > 2.6 MV/cm, and leakage current <10^{-8} A/cm^2.
- Measured k ≈120, loss factor ≈0.008 at 300 V bias, and energy density ≈85 J/cm^3 on a ≈3.0 μm-thick film-on-foil (for comparison, k of polymer films are ≈6).
- Dielectric films are thermally cycled (about 1000 cycles) between -50 C and +150 C with no measurable degradation in k.
- Demonstrated graceful failure mode by self-clearing method in single layer film-on-foil dielectrics.
- Thin ceramic dielectric on relatively thick Ni substrate is quite strain tolerant (measured at ORNL by Andy Wereszczak).
- A CRADA with Delphi has been established; samples have been provided to Delphi for testing.
- Over 45 publications and presentations have been made. One patent was issued & two Patent Applications were filed.



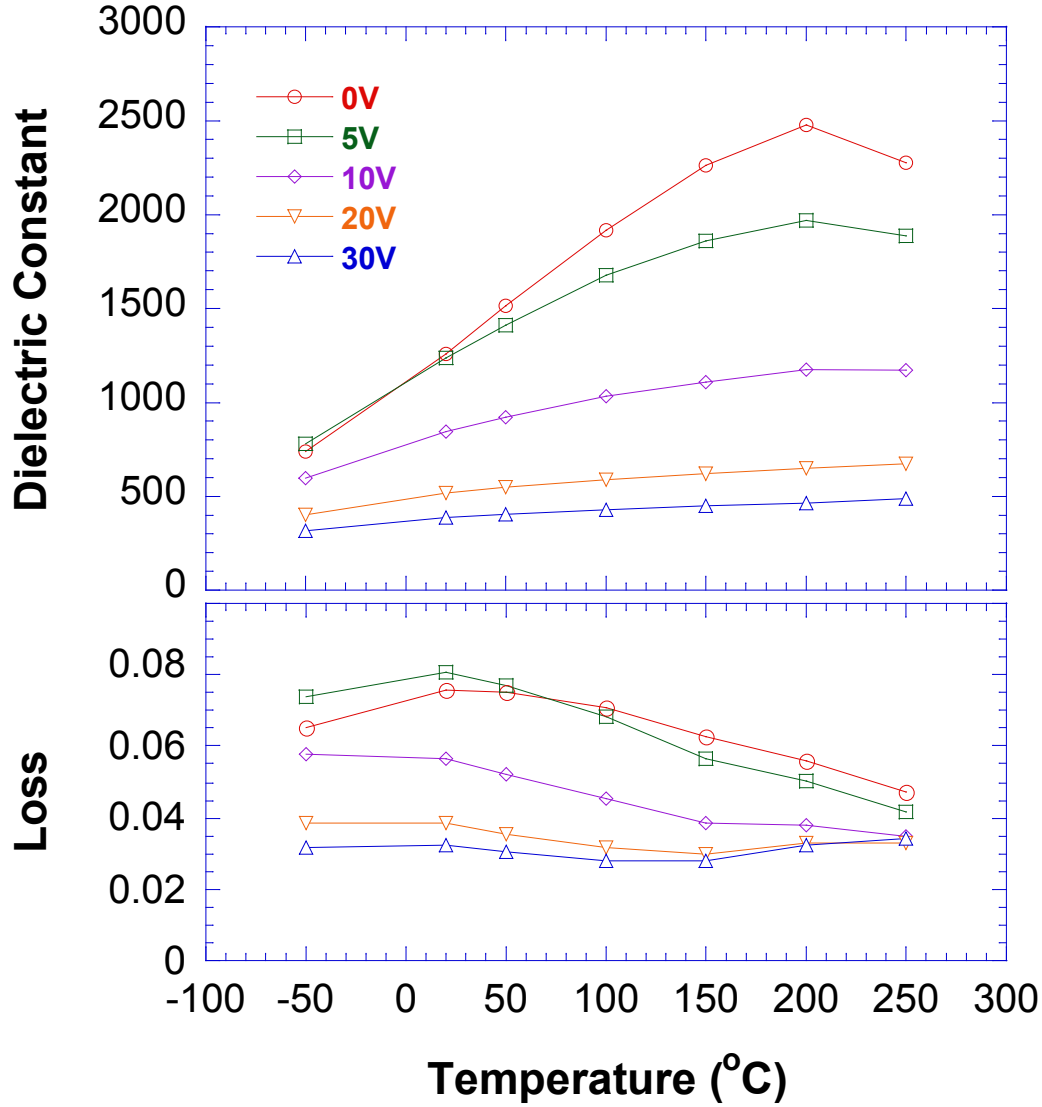




Capacitance: ≈5 μF
Capacitance density: ≈4 μF/cm^3

Accomplishments to Date (Contd.)

Temperature Dependent Dielectric Properties of PLZT Film-on-Foils under bias fields



Measured k ≈120 & loss ≈ 0.008 (0.8%) @ 300 V bias at room temperature on a 3 µm thick PLZT on Ni-foil

- **Dielectric constant (capacitance) increases and loss decreases with temperature (-50 to +150 C).**
- **ESR = DF/2πfc (DF = loss factor; f = frequency; c = capacitance).**
- **ESR will decrease and the ripple current capability will increase with temperature.**

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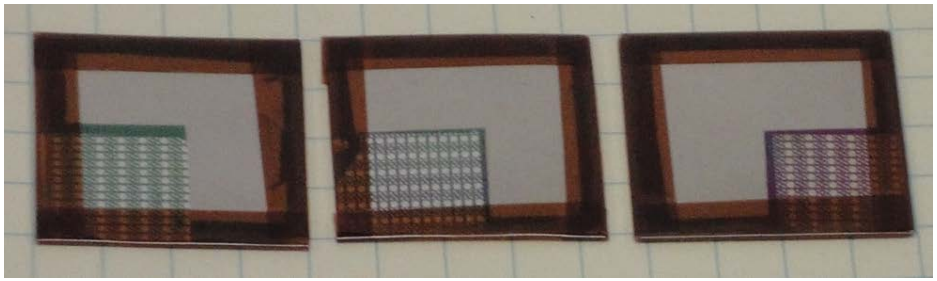
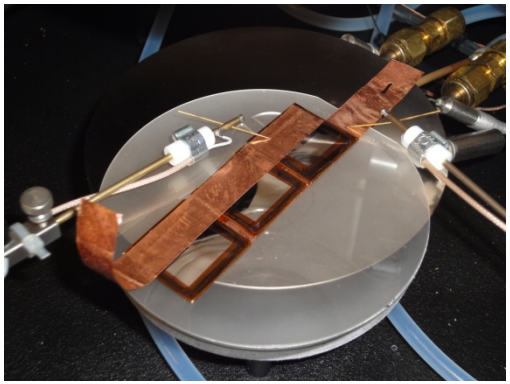
Prototype Multilayer Capacitor with Leads





For the fabrication we used:

- Three foils that were tested ≈1/4th area using small-size electrodes
- Ni foil thickness ≈400 μm
- Cap. of individual foils ≈1.7 μF
- Four Cu shims (thickness ≈120 μm)
- Two Cu ribbons (thickness ≈80 μm)
- Only ≈3/4th area of the film-on-foils

25 mm x 25 mm x 2 mm;
Measured capacitance ≈5 μF
Cap. density (unbiased) ≈4 μF/cm³

Calculation of the Volume of 1000 μF/450 V Cap:

- Volume will be 0.55 L if ≈80 μm thick Ni foil & ½ oz. Cu ribbon (≈20 μm) is used.
- Volume can be reduced to 0.2 L if ≈5 μF films are used.

Volt (V)	K
300	120 (measured)
450	80
600	60

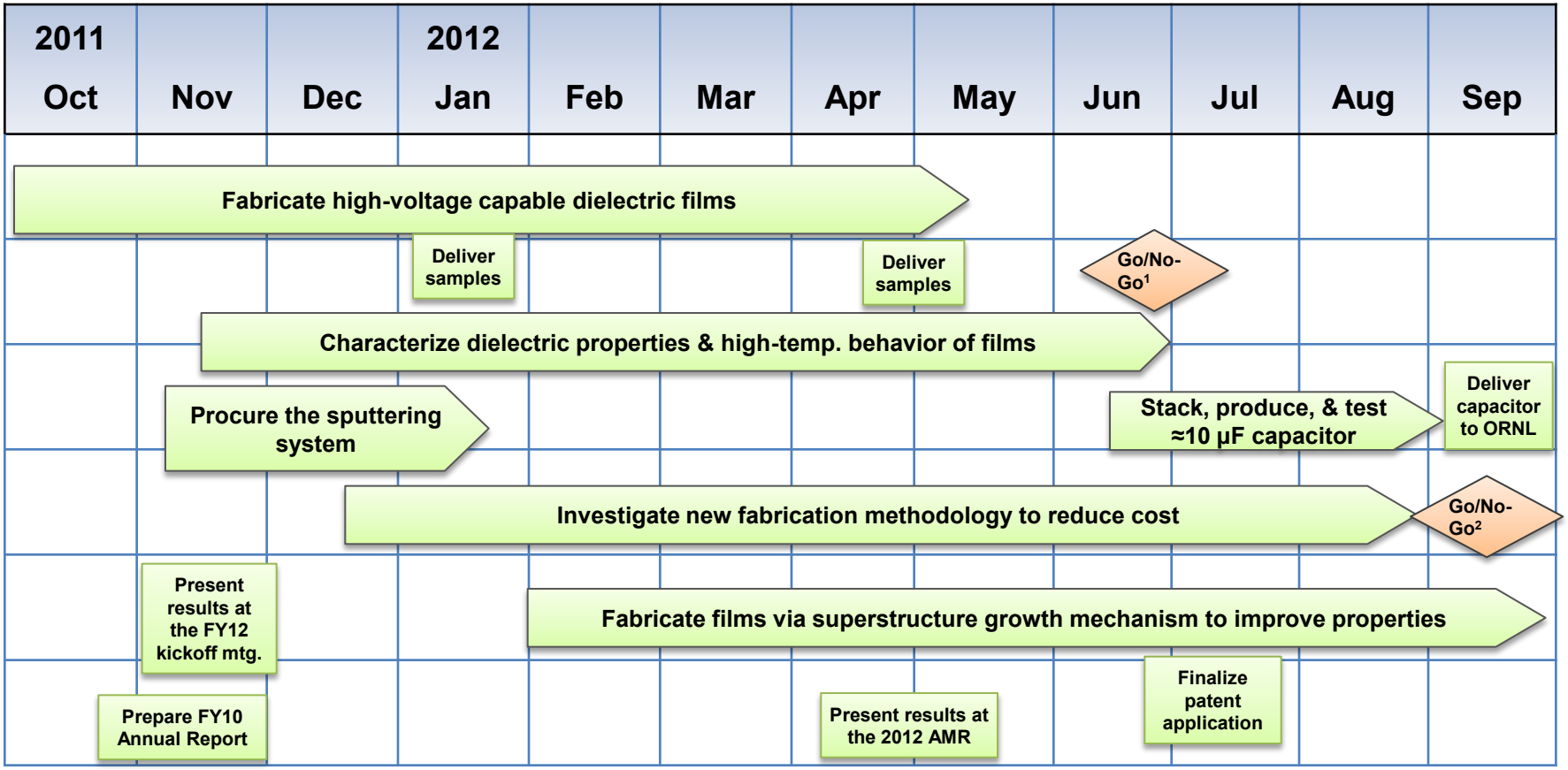
- DOE-OVT DC Bus Capacitor Goal ≤0.6 L
- Volume and capacitance of current polymer film capacitor module in Camry ≈2.6 L (2,098 μF) & Lexus LS 600h ≈4.0 L (2,629 μF). Ref: ORNL/TM-2007/190 & ORNL/TM-2008/185 reports.

FY12 Approach

The primary emphasis of FY12's effort is toward advancing the proven laboratory scale film-on-foil technology and fabricating a ≈10 μF, high-voltage (operating voltage 450 V) capable capacitor.

- Optimize processing conditions to produce high-voltage capable film-on-foils with uniform properties on 1" x 1" and larger substrates
  - Better quality substrates (chemical-mechanical polishing - CMP)
  - Pyrolysis and crystallization conditions (humidity control, organic removal, rapid thermal annealing)
  - Cleaner environment
- In collaboration with Penn State, characterize the dielectric properties & high temperature behavior of high-voltage capable film-on-foils
- Stack high-voltage capable film-on-foils, produce a ≈10 μF capacitor with termination, and characterize the properties of the capacitor
- Investigate new fabrication methodology (sol-gel with nano-particle seeds and aerosol deposition) to reduce the capacitor cost
- Fabricate film-on-foils with improved breakdown strength and reduced loss via novel superstructure film growth mechanism
- Identify industrial partner to manufacture multilayer capacitors

FY12 Approach and Challenges



Go/No-Go Decision Point:
1. Do the dielectric films have sufficient quality to produce a ≈10 μF/450 V capacitor?
2. Down-select the fabrication methodology for further development.

Challenges/ Barriers: Controlling defects in films, incorporating graceful failure in multilayers, and making the fabrication process economically attractive. Defects are mitigated by use of CMP substrates, control of crystallization conditions, and use of superstructure during film growth. Graceful failure in multilayers can be accomplished by "pre-zapping" individual films & using phase-transition electrodes. Aerosol deposition & sol-gel methods have the potential to minimize processing steps and yield thicker films at a higher rate.

FY12 Approach Highlights

At the end of FY12 we will have:

- **Produced high-voltage capable dielectric films on 1” x 1” and larger area foils.**
- **Fabricated a high voltage capable ≈10 μF multilayer capacitor with end-termination.**
- **Provided a multilayer capacitor to ORNL for testing.**
- **Identified fabrication methodology to reduce capacitor cost.**

Beyond FY12

- **FY13**
  - **Fabricate and characterize several ≈10 μF capacitors**
  - **Provide the ≈10 μF capacitors to ORNL, Penn State, and industrial partner for testing and validation**
  - **Connect sufficient numbers of ≈10 μF caps and produce an assembly with capacitance ≈100 μF**
  - **Develop fabrication methodology to reduce capacitor cost**
  - **Projected Go/No Go Decision Point: Depends on ORNL test results & techno-economic analysis by industry**
- **FY14**
  - **Fabricate high-voltage capable dielectric films via improved fabrication methodology and characterize the properties**
  - **Fabricate and characterize a multilayer capacitor with termination using the 2nd generation dielectric films**
  - **Transfer the technology for industrial manufacturing of caps for power inverters for automotive applications**

Selected Publications, Presentations, Patents

1. Fabrication and Characterization of Ferroelectric PLZT Film Capacitors on Metallic Substrates, B. Ma, M. Narayanan, S. Tong, U. Balachandran, *J. Mater. Sci., 45, 152, 2010*.
2. Development of PLZT Dielectrics on Base-Metal Foils for Embedded Capacitors, U. Balachandran, D. K. Kwon, M. Narayanan, B. Ma, *J. European Cer. Soc., 30, 365, 2010*.
3. Improved Dielectric Properties of Lead Lanthanum Zirconate Titanate Thin Films on Copper Substrates, M. Narayanan, B. Ma, and U. Balachandran, Mater. Lett., 64, 22, 2010.
4. Dielectric Spectroscopy of $Pb_{0.92}La_{0.08}Zr_{0.52}Ti_{0.48}O_3$ Films on Hastelloy Substrates with and without $LaNiO_3$ Buffer Layers, M. Narayanan, B. Ma, U. Balachandran, and W. Li, J. Appl. Phys. Lett., 107, 024103, 2010.
5. Dielectric Properties and Energy Storage Capability of Antiferroelectric $Pb_{0.92}La_{0.08}Zr_{0.95}Ti_{0.05}O_3$ Film-on-Foil Capacitors, B. Ma, D. K. Kwon, M. Narayanan, U. Balachandran, *J. Mater. Res.*, 24, 2993, 2009.
6. Chemical Solution Deposition of Ferroelectric Lead Lanthanum Zirconate Titanate Films on Base-Metal Foils, B. Ma, D. K. Kown, M. Narayanan, and U. Balachandran, *J. Electroceram.*, 22, 383, 2009.
7. Fabrication of Antiferroelectric PLZT Films on Metal Foils, B. Ma, D. K. Kwon, M. Narayanan, U. Balachandran, *Mater. Res. Bull.*, 44,11, 2009.
8. Dielectric Strength and Reliability of Ferroelectric PLZT Films Deposited on Nickel Substrates, B. Ma, M. Narayanan, U. Balachandran, *Mater. Lett.*, 63,1353, 2009.
9. Leakage Current Characteristics and Dielectric Breakdown in Antiferroelectric $Pb_{0.92}La_{0.08}Zr_{0.95}Ti_{0.05}O_3$ Film Capacitors Grown on Metal Foils, B. Ma, D. K. Kwon, M. Narayanan, and U. Balachandran *J. Phys D: Appl. Phys.*, 41, 205003, 2008.
10. Dielectric Properties of PLZT Film-on-Foil Capacitors, B. Ma, D. K. Kwon, M. Narayanan, and U. Balachandran, *Mater. Lett.*, 62, 3573, 2008.
11. Deposition of Sol-gel Derived PLZT Thin Films on Copper Substrate, M. Narayanan, D. K. Kwon, B Ma, U. Balachandran, *Appl. Phys. Lett.*, 92, 252905, 2008.
12. Ceramic Capacitor Exhibiting Graceful Failure by Self-Clearing Method for Fabricating Self-Clearing Capacitor, D. Y. Kaufman and S. Saha, U.S. Patent 7,099,141, Aug. 29, 2006.

Questions