DC-link Capacitors

A Summary of the Work Performed Under DoE Programs

DE-EE-00006433, DE-EE-00006438, and DE-AC02-06CH11357

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A joint effort by

Delphi, Argonne, GE, Sigma and the
U.S. Department of Energy Vehicle Technologies Office

March 3rd, 2018

DELPHI
Innovation for the Real World

When this presentation was completed our company name was Delphi.

At the beginning of this year the powertrain organizations of Delphi; Gas, Diesel and Electrification were spun off into a new company, we became

Delphi Technologies

Why the Emphasis on DC-link Capacitors?

- Delphi designs, manufactures and sells automotive power electronics
  - Inverters, converters, chargers, battery management systems ....
- The power electronics volume is driven by the size of the passive components (capacitors and inductors) and the thermal management necessary to keep all of the electronic components (e.g., the power module, as well as the passives), sufficiently cool during the demanding operating conditions in an automotive environment.
  - DOE EETT roadmap 2013
- "*Today the package of a motor inverter is mainly driven by the size of the capacitor, the busbars, the terminal box and the filter components*."
  - Plikat, Mertens, Koch, Volkswagen AG, Corporate Research, 2013
- Delphi worked with the DOE and our partners to reduce the cost, size and weight of today's capacitor technology
  - With emphisis on the DC-link capacitor and it's commercialization

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Challenges and Opportunities with Today's DC-link Capacitors

- Today's EDV inverters have migrated to Polyproplene (PP) DC-link capacitors
- PP DC- link capacitors are costly
  - A lower cost capacitor requires:
    - Less time in process
    - New manufacturing process
    - Or both
    - A reusable design concept
- PP DC-link capacitors are large (~1 liter) and heavy (~1 kg)
  - A smaller lighter capacitor requires
    - Dielectric material with a higher dielectric constant
    - Thinner dielectric material
    - Or both
- PP DC-link capacitors have a limited operating temperature range
  - 85˚C with some time spent at 105˚C ambient
    - Higher temperature requires a new dielectric material

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Why aren't the Challenge's Being Addressed by the Film Capacitor Industry?

- The film capacitor industry is fragmented with no one entity willing to make the investment for new material development
- Today's PP DC-link capacitor supply chain
  - Today's PP DC-link capacitors utilize extruded and biaxially-oriented film produced and metallized by just a handful of film OEMs worldwide
  - The metallized PP film is then distributed to 100s of capacitor manufacturers who wind, test, and package the DC-link capacitors, which are then supplied to the inverter manufacturers.
  - Capacitor OEMs have no control of the PP dielectric; instead they can specify and control:
    - Width and length of the capacitor
    - Wound round vs. wound flat and stacked parts
    - Metallized electrode thickness and design
    - Capacitor package
  - As a result, most capacitor manufacturers produce very similar products and there is limited opportunity for innovation
  - Each DC-link capacitor for EDV applications is a custom design for a particular inverter

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DOE Role via its Vehicle Technologies Program

- Develops technologies, not vehicles
- Explores multiple technologies
  - For the power electronics applications, it is necessary to consider semiconductor switches, capacitors, magnetics, packaging, as well as new topologies.
- Pursue parallel paths
  - To meet the very challenging technical targets, high-risk concepts must be considered and pursued. Likewise, to reduce the overall risk of technical failure, it is necessary to pursue more than one path toward each objective.
- Ensure technology transfer

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DOE Research Area

- ***Research Area: Capacitors***
  - Capacitors typically represent one of the larger cost components of an inverter, accounting for a major portion of the inverter's volume and weight
  - Materials that offer improved dielectric properties, higher temperature capabilities and low equivalent series resistance (ESR) are needed to reduce the DC-link capacitor's size and the inverter's overall volume
  - Polymer-film capacitors are used in most HEVs today, but currently cannot tolerate temperatures for future applications that will require 150°C
    - Many current polymer-film capacitors typically are rated at 85°C, but more expensive, larger volume ones are available that can operate up to 105°C
    - Ceramic capacitors have excellent performance characteristics, but cost, reliability, and achieving a benign failure mode remain issues

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DOE Capacitor Programs

- In 2013, Argonne National Lab, General Electric and Sigma Technologies were each awarded separate DOE programs to pursue DC-link capacitor technologies, to achieve the DOE targets
  - 3 unique approaches
  - Delphi was a partner in each of these programs
    - Delphi co-manages the project with each partner
    - Includes determining the DC-link capacitor specifications, shape, external connections, packaging, integration into an inverter and testing

Argonne National Lab

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Innovation for the Real World

Argonne's Approach

- New dielectric material
  - PLZT: Pb-La-Zr-Ti-O
  - High temperature > 200˚C
- Much higher dielectric constant,
  - ~80 (vs. 2.2 for PP)
- New manufacturing process
  - Aerosol Deposition (AD)
- Incorporates innovative electrode design to achieve benign failure
- PLZT films have properties suitable for application in high-temperature inverters – meeting the goals for temperature & volumetric efficiency
- Focus: develop a process to synthesize sub-micron powders and optimize AD to deposit PLZT on metallized polymer film substrates

Argonne's Approach

- Basic research demonstrated a spin-coating process can produce PLZT films that satisfy high-temperature and volumetric requirements for advanced capacitors
- However, the spin-coating process is not a practical process for mass production of large area capacitors
  - Spin-coating deposition thickness = 0.15 µm/layer
  - Thickness of dielectric required >6 µm for voltage breakdown strength
  - ~40 layers (6 µm / 0.15 µm/layer)
  - Recrystallization or annealing time/layer = ~20 minutes/layer
    - ~20 minutes/layer x 40 layers = ~800 minutes (= too much time)
- Aerosol Deposition (AD), a high-rate, room-temperature film deposition process, is being developed at Argonne to reduce capacitor cost
  - Development work at Argonne using an Aerosol Deposition (AD) process demonstrated a thick film can be prepared at room temperature in significantly shorter time (10 min vs. ≈ 5 days by spin-coating)
  - AD approach combines the superior attributes of PLZT-based high-temperature capacitors and a high-rate deposition process

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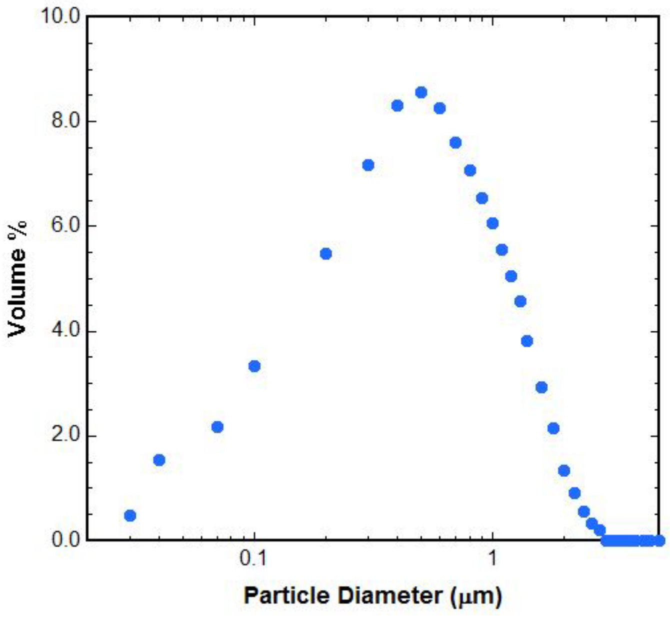
Argonne's Approach

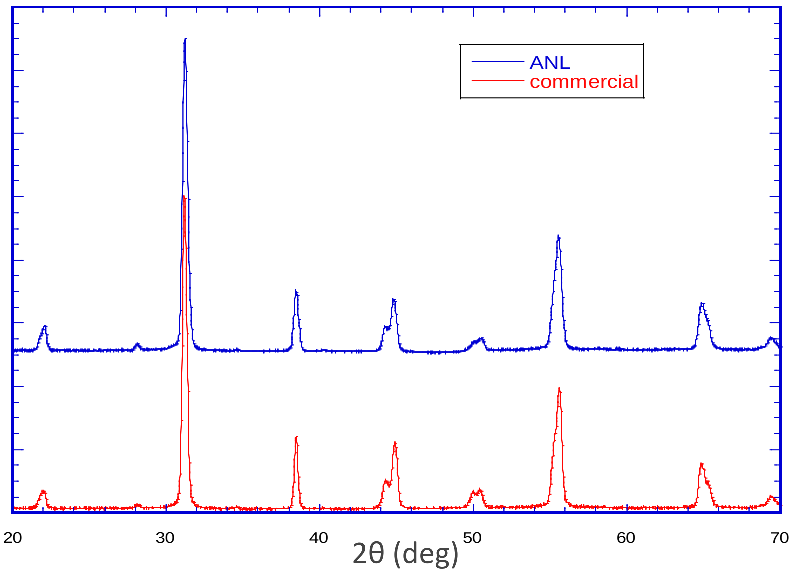
- Manufacturers of conventional multilayer ceramic capacitors (MLCC) may not be the most logical manufacturers for the PLZT-based capacitor
  - MLCCs are made by co-firing of dielectric tapes and electrodes
  - MLCCs don't have benign failure feature
- The process being developed in this project is more akin to today's process used for making polymer film caps
- Argonne's PLZT capacitor has the potential to be wound
  - 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
- In the event that production of wound capacitor rolls is not practical, a stacked multilayer design will be adopted

Argonne's PLZT Powder Synthesis Process

- Synthesis of sub-micron PLZT powder
  - Prepare aqueous solution containing fuel, oxidant, and cations
  - Lead nitrate, lanthanum nitrate, zirconyl nitrate, titanium isopropoxide, citric acid and ammonium nitrate are used in the combustion synthesis process
  - Heat solution on hot plate to initiate combustion that is completed after only 2-3 min.

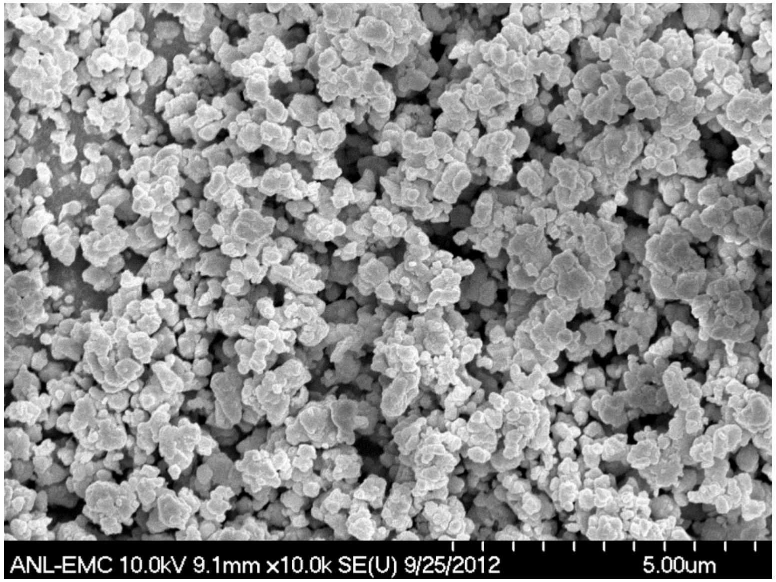


Particle Size Distribution

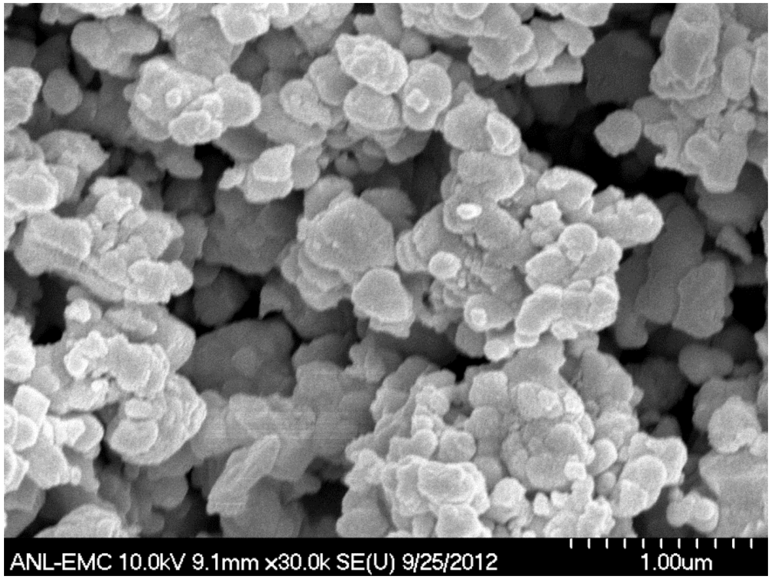


XRD of Argonne's Synthesized PLZT Powder and a Commercial PLZT Powder

Test Results

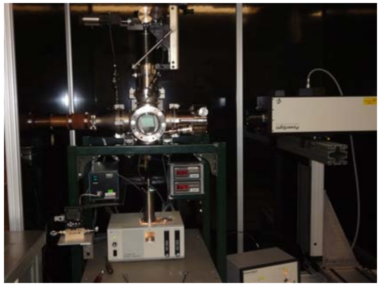


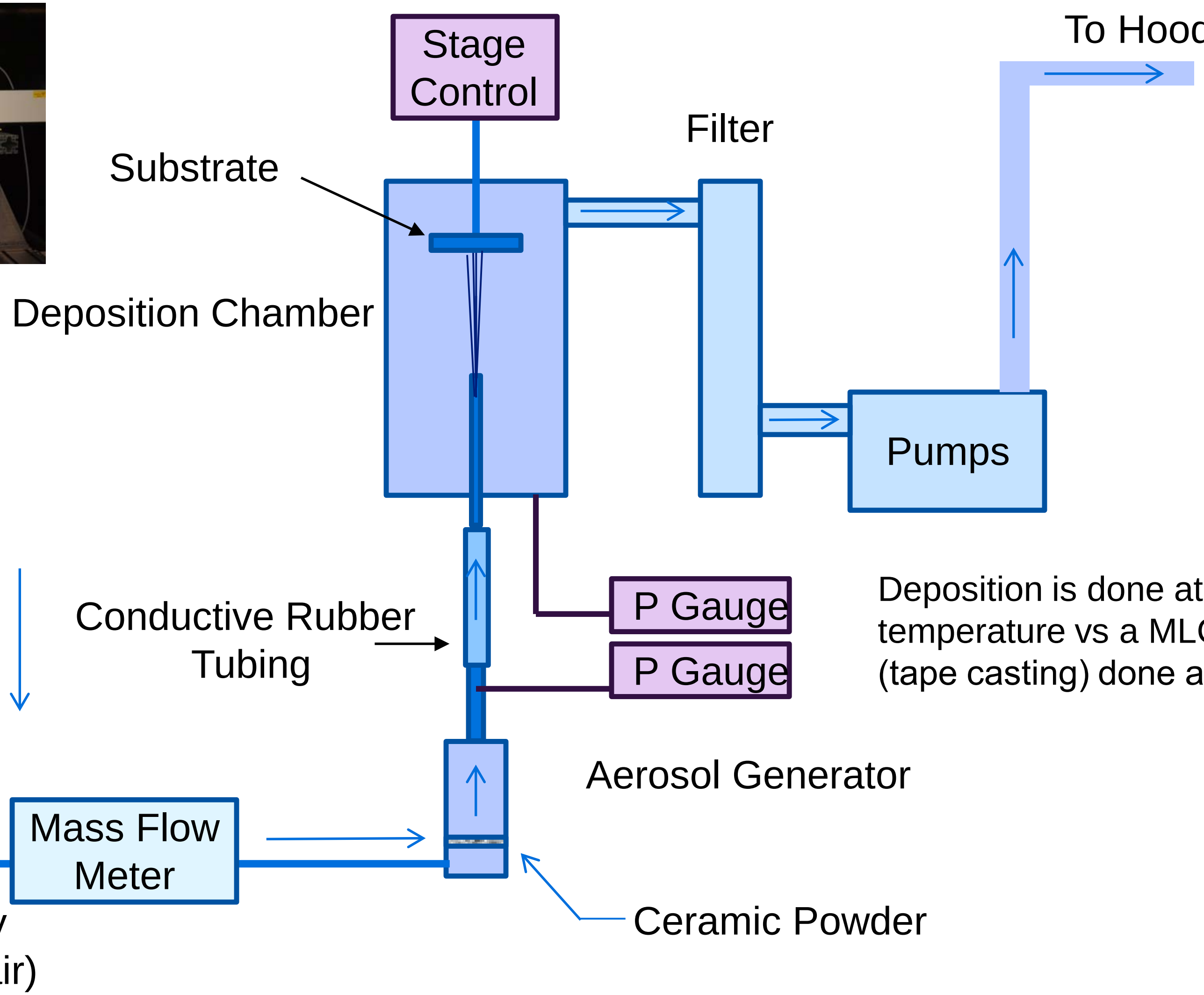
SEM of the agglomeration of PLZT Powders



SEM showing range of particle sizes

Argonne's Aerosol Deposition (AD) Process

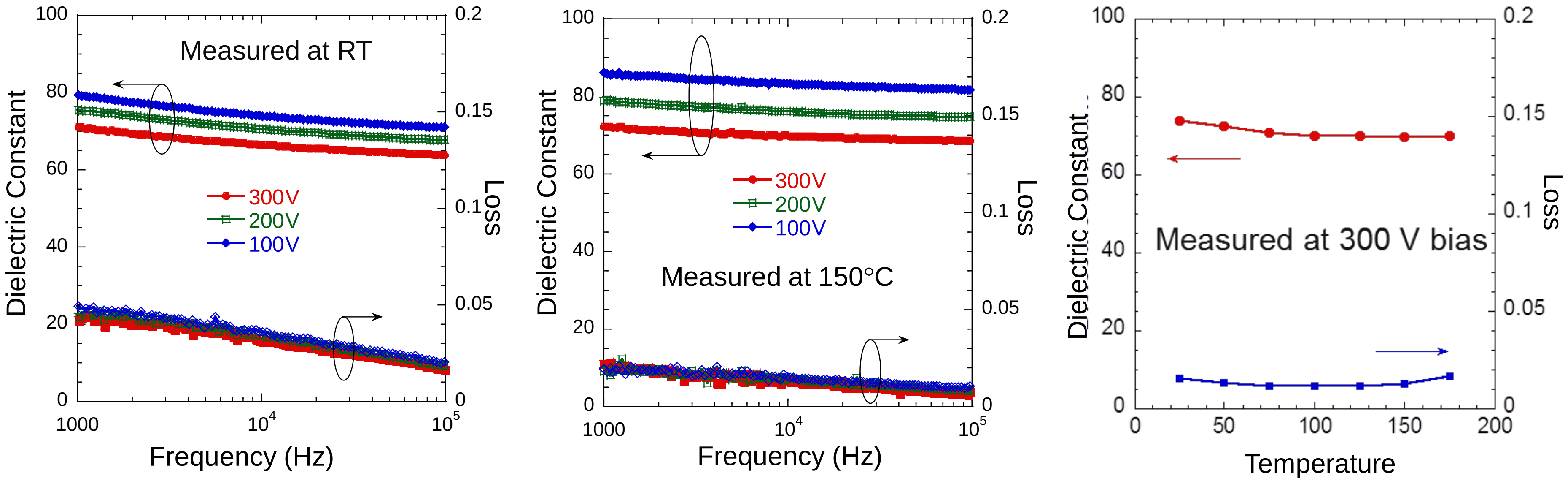




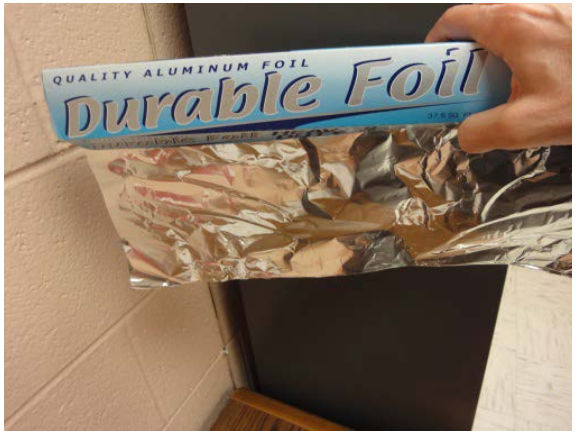
Deposition is done at room temperature vs a MLCC process (tape casting) done at >1000˚C

Test Results

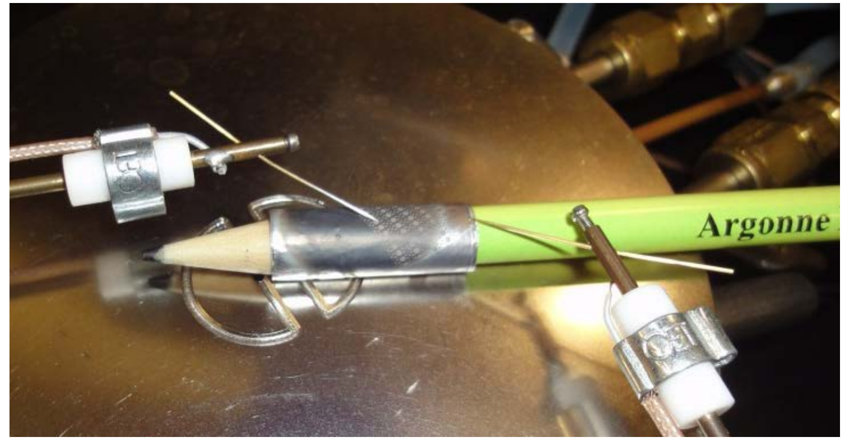
- PLZT film made by high-rate AD process has high dielectric constant and low loss over the operational ranges for temperature, voltage, and frequency



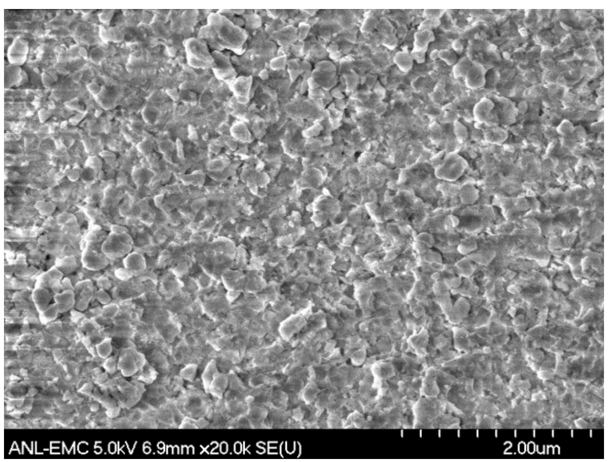
Dielectric properties



Al foil

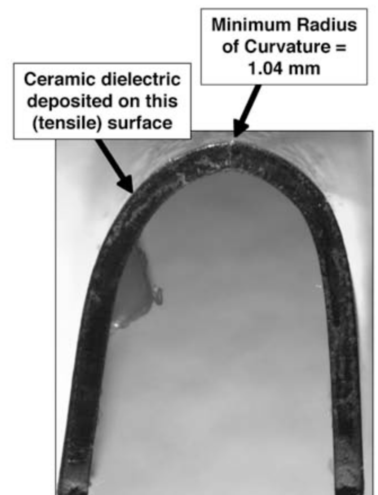


PLZT layer with patterned top electrode on Al foil



SEM of as-deposited film surface

AD process has the potential to produce wound ceramic PLZT capacitors



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

Technology Evaluation and Analysis
Potential Product / Process Advantages

- Argonne transferred their aerosol deposition process to Sigma
- Sigma in turn made their own aerosol deposition system and nozzle designs
- The Sigma aerosol deposition process allowed for higher speed particle deposition and higher velocity deposition
  - More vacuum, denser dielectric on a faster moving substrate
- Forms a flexible ceramic substrate with no external heating
  - Parts can be wound
- Process demonstrated that sample parts are can be made larger in size and could be formed faster
  - Scalable (not optimized)
- While this process is still in infancy the dielectric's high dielectric constant, low DF offer the potential for a lower cost smaller size DC-link capacitor
  - Or embedded capacitors

Technology Evaluation and Analysis

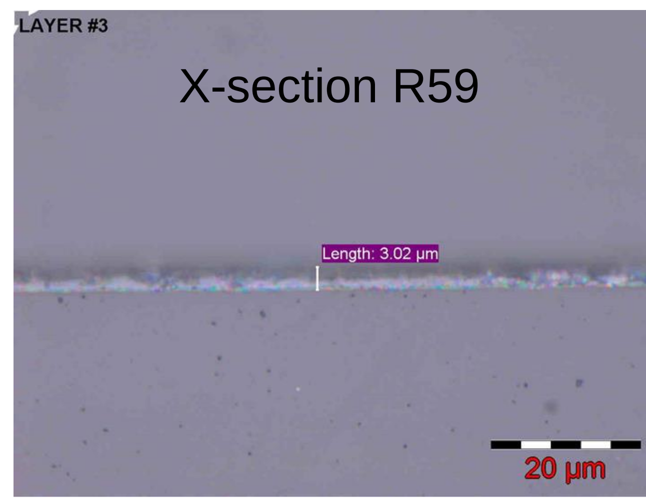
Keysight Fixture	Date	Serial Number	Temperature	Endpoint	Capacitance 10kHz nF	Dissipation Factor 1kHz Percent	Dissipation Factor 10kHz Percent	ESR Keysight Ω	ESR Frequency Keysight E4990A MHz	Rs 10kHz Ω	Rs 20kHz Ω	Rs 30kHz Ω	Rs 40kHz Ω	Rs 50kHz Ω	Rs 60kHz Ω	ESL Keysight E4990A nH	ESL Keysight Frequency MHz	Dk
42942A	1/24/2017	R56	-40 C	0	372.59	1.794	8.630	1.71	2.719	3.69	3.49	3.42	3.38	3.36	3.34	40.72	10	42.1
42942A	1/23/2017	R56	Room	0	392.97	3.170	11.200	2.21	2.828	4.54	4.21	4.10	4.04	4.01	3.98	37.03	10	44.4
42942A	1/25/2017	R56	140 C	0	465.71	18.400	19.300	2.27	1.792	6.61	5.15	4.74	4.55	4.44	4.36	83.20	10	52.6
42942A	1/24/2017	R57	-40 C	0	635.71	1.520	4.840	0.62	1.412	1.21	1.09	1.05	1.03	1.01	1.00	40.75	10	28.7
42942A	1/23/2017	R57	Room	0	666.41	2.772	5.910	0.61	1.656	6.45	1.41	1.20	1.14	1.11	1.09	31.59	10	30.1
42942A	1/25/2017	R57	140 C	0	774.48	12.410	10.780	0.81	0.877	2.22	1.60	1.43	1.35	1.31	1.28	83.73	10	35.0
42942A	1/24/2017	R58	-40 C	0	0.01	-0.610	0.198	1190.00	2.52	4.84K	-14.8K	9.09K	10.6K	7.05K	4.46K	-39.99	10	0.0
42942A	1/23/2017	R58	Room	0	0.01	5.090	2.430	0.34	74.58	57K	34K	18K	14K	11K	8.5K	-97.01	10	0.0
42942A	1/25/2017	R58	140 C	0	584.85	13.890	14.940	25.92	0.95	4.37	3.46	3.21	3.10	3.04	3.00	91.70	10	119.0
42942A	1/24/2017	R59	-40 C	0	466.26	1.640	6.490	1.47	1.79	2.21	2.05	1.99	1.97	1.96	1.95	37.67	10	21.1
42942A	1/23/2017	R59	Room	0	490.64	2.950	8.290	1.70	1.76	2.69	2.41	2.33	2.28	2.26	2.24	38.24	10	22.2
42942A	1/25/2017	R59	140 C	0	564.21	13.110	14.010	2.09	1.113	3.95	3.12	2.89	2.79	2.73	2.70	82.51	10	25.5

Dielectric Constant for R59

Capacitor L: 6.2” W: 0.625”

PLZT Thickness
from Delphi x-section: 2.5-3.22 µm

Dielectric Constant:
Delphi Measured Thickness: 63-76



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General Electric

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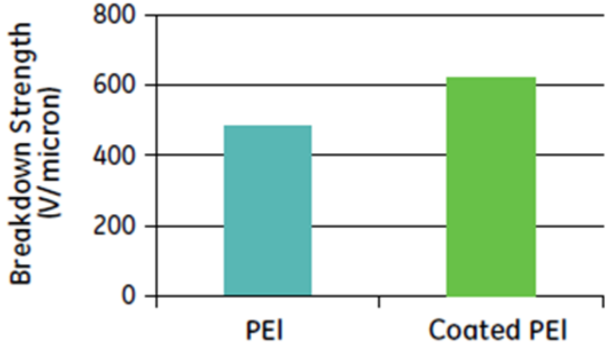
Innovation for the Real World

GE Approach

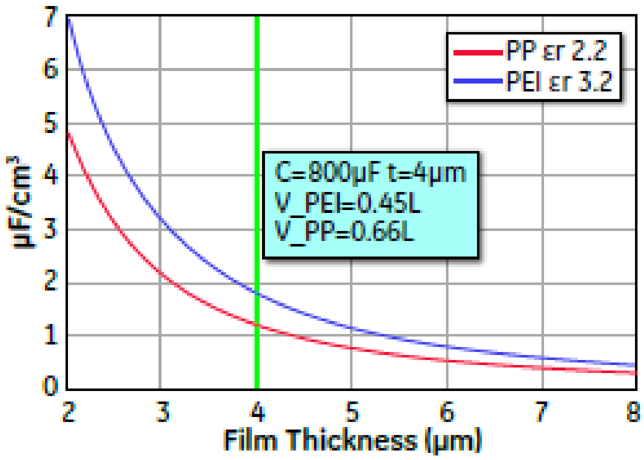
- New dielectric material: Extruded Polyetherimide (PEI)
  - MPI/Setsu extruders
  - High temperature capable film >200˚C
  - Higher dielectric constant (3.2 vs. 2.2 for PP)
- New manufacturing process: Extrusion of PEI
  - Extrude it thinner
  - Using extrusion manufacturers in the US and Japan
- Adapting the existing metalization and OEM capacitor manufacturing operations
  - Bollore' for metalization
  - DEI, ECI and Kemet for capacitor manufacturing

GE Approach

- Enhance dielectric strength via inorganic coating of PEI films for smaller volume capacitors
  - Coating materials from Materion

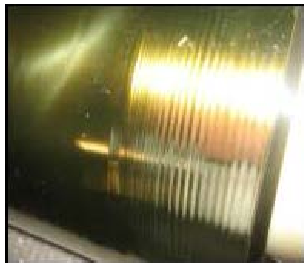


- Capacitance density increases with decreasing film thickness, leading to smaller capacitor volume

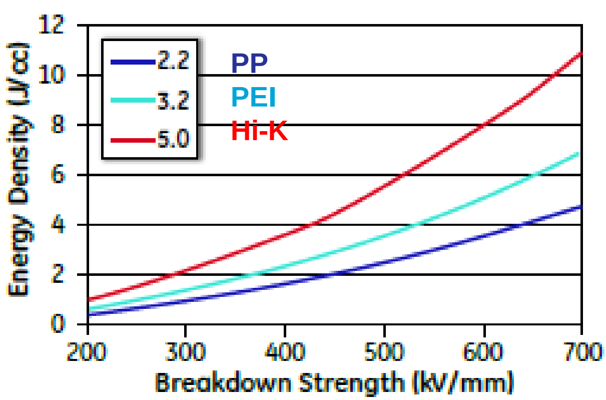


GE Approach

Continuous Improvement



13 µm 2005 | 6 µm 2008 | 5 µm 2009-2014 | 3 µm 2014+



- Wrinkles minimized
- Thickness consistency improved

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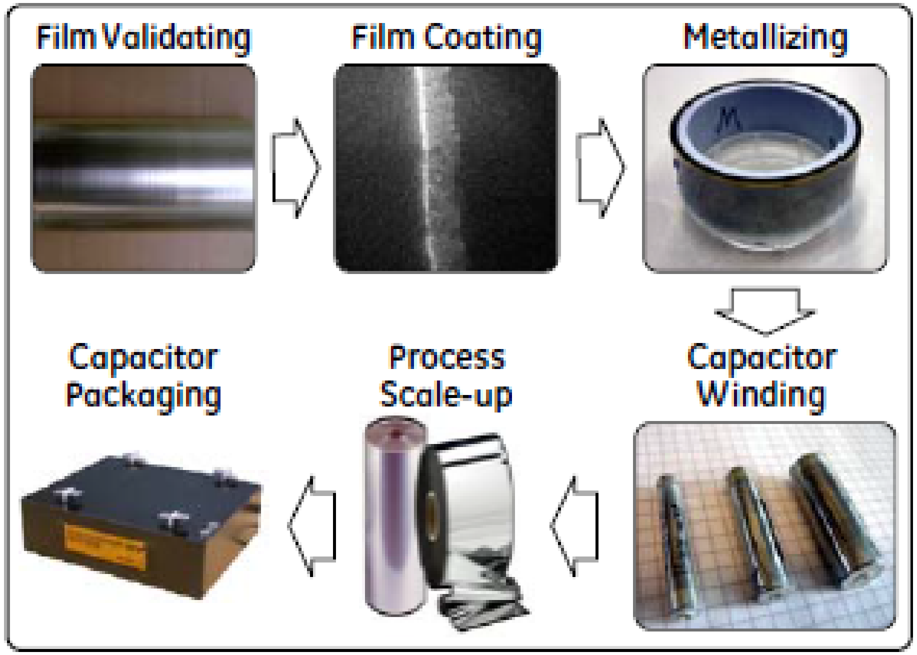
Challenges

- Processing cost of thinner films
- Nano-coating process continuity
- Winding difficulty
- Wrinkle and static free thin films are hard to extrude
- Film extrusion is being done in Japan
  - Film availability on a large scale may be a concern



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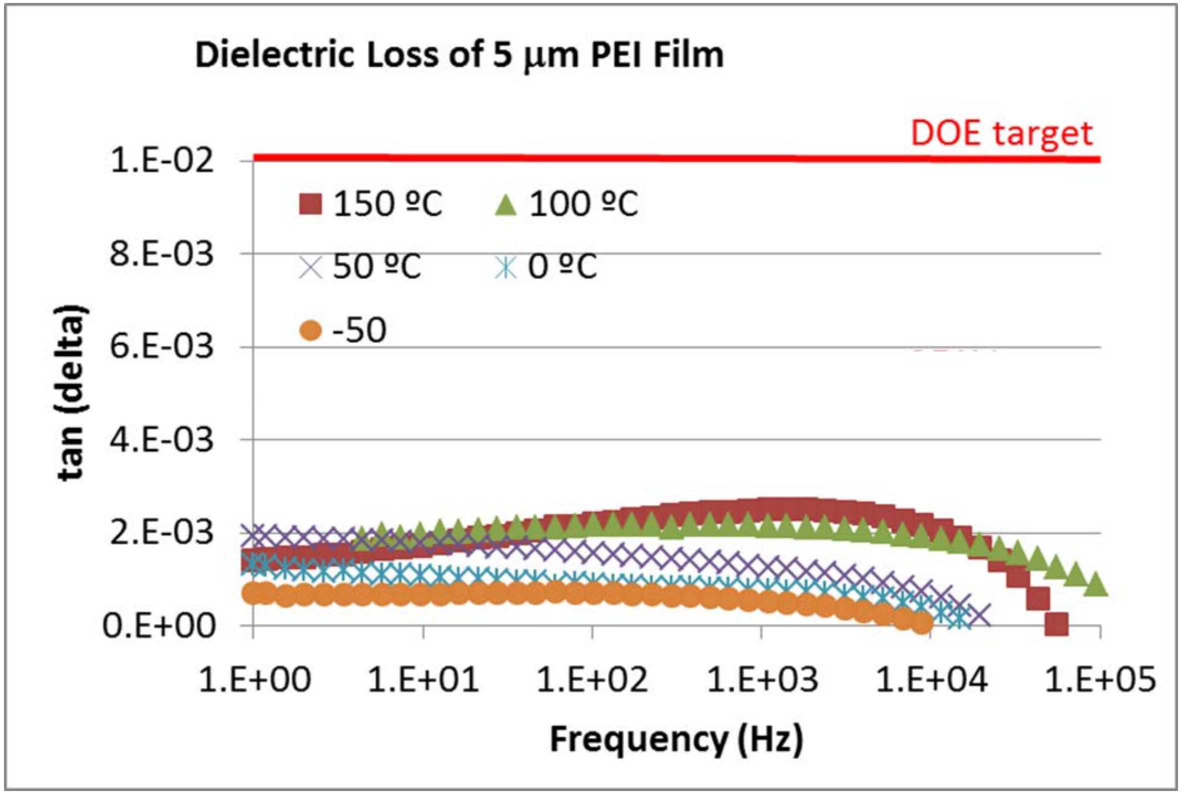
GE Material Properties

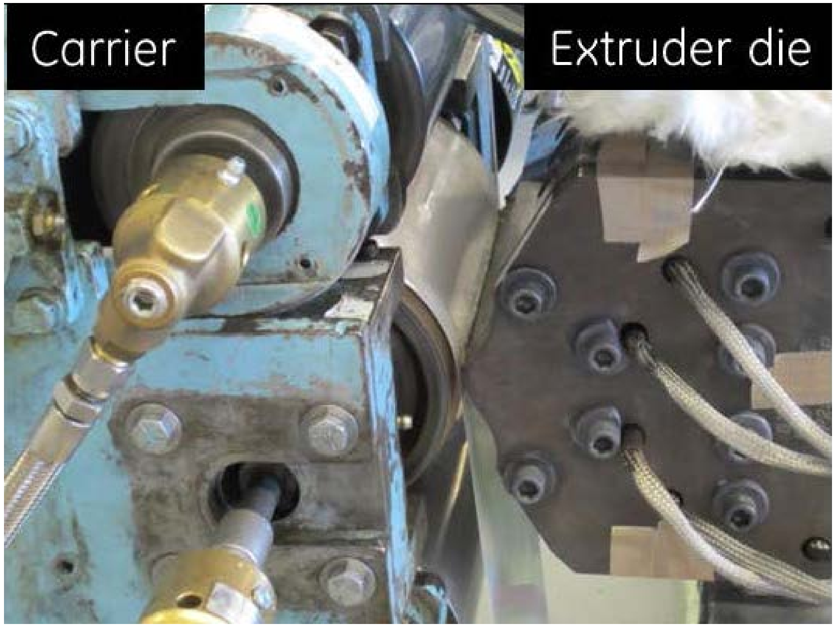
Dielectric constant remains 3.16 - 3.20 in the range of temperature and frequency of measurements



Extruded film exhibits low dielectric loss and stable dielectric constant

GE Process

New Extrusion Mechanism-Carried Films



Controlling screw speed, film take-up speed of carrier, die lip gap and temperature, carrier etc.

Film wrinkle issues avoided by using a carrier

GE Process

Carrier Treatment and Performance

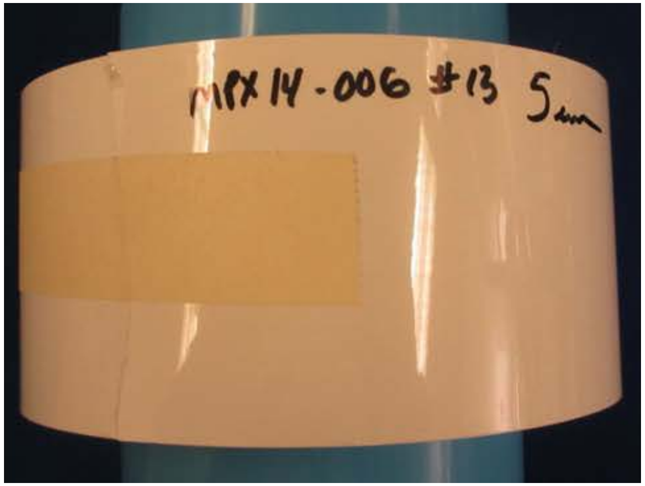
Thinner-Cheaper
Know how

Two carriers developed for good adhesion and delamination.

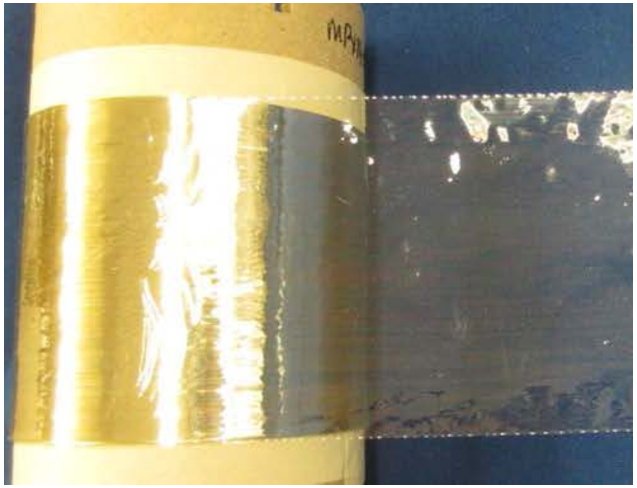
GE Process

Slitting and Delamination

After Slitting



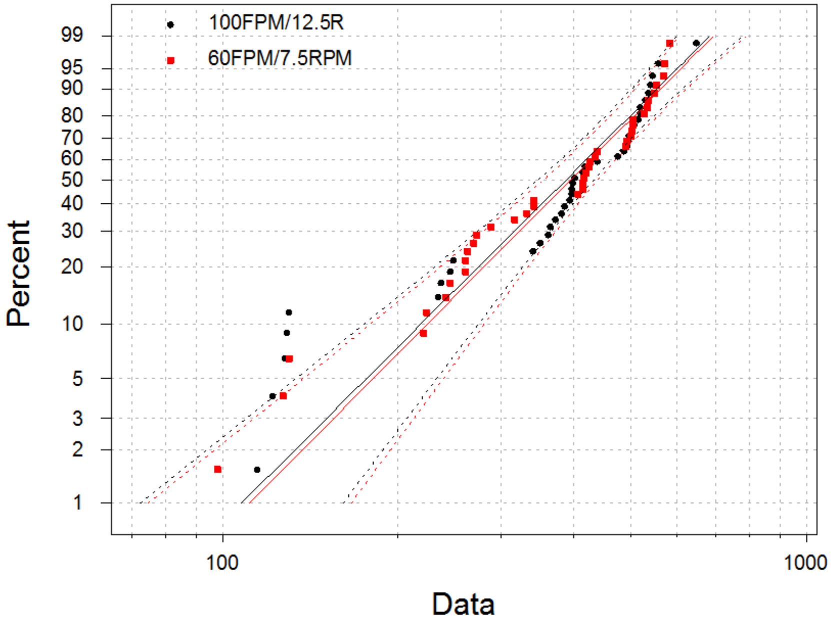
After Delamination

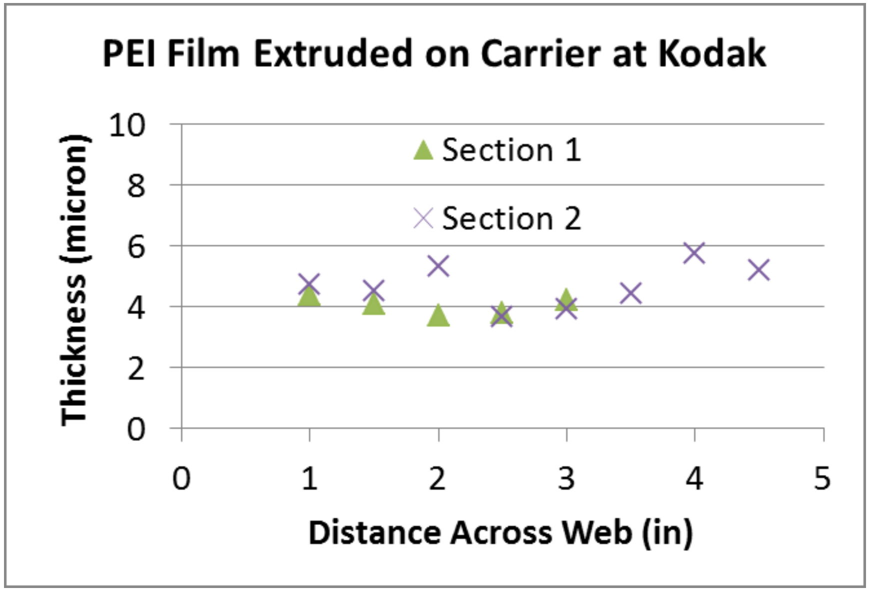


All film processing appears to be feasible

Test Results

Properties of PEI Films Released from Carrier

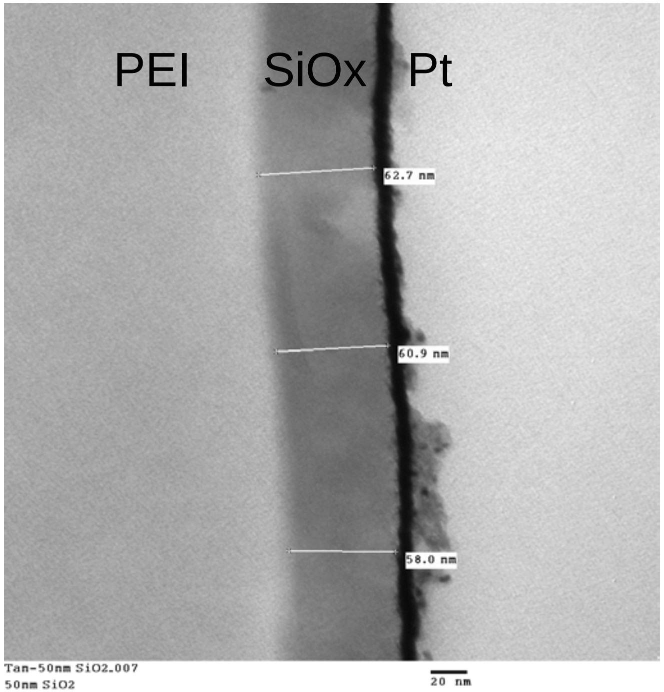


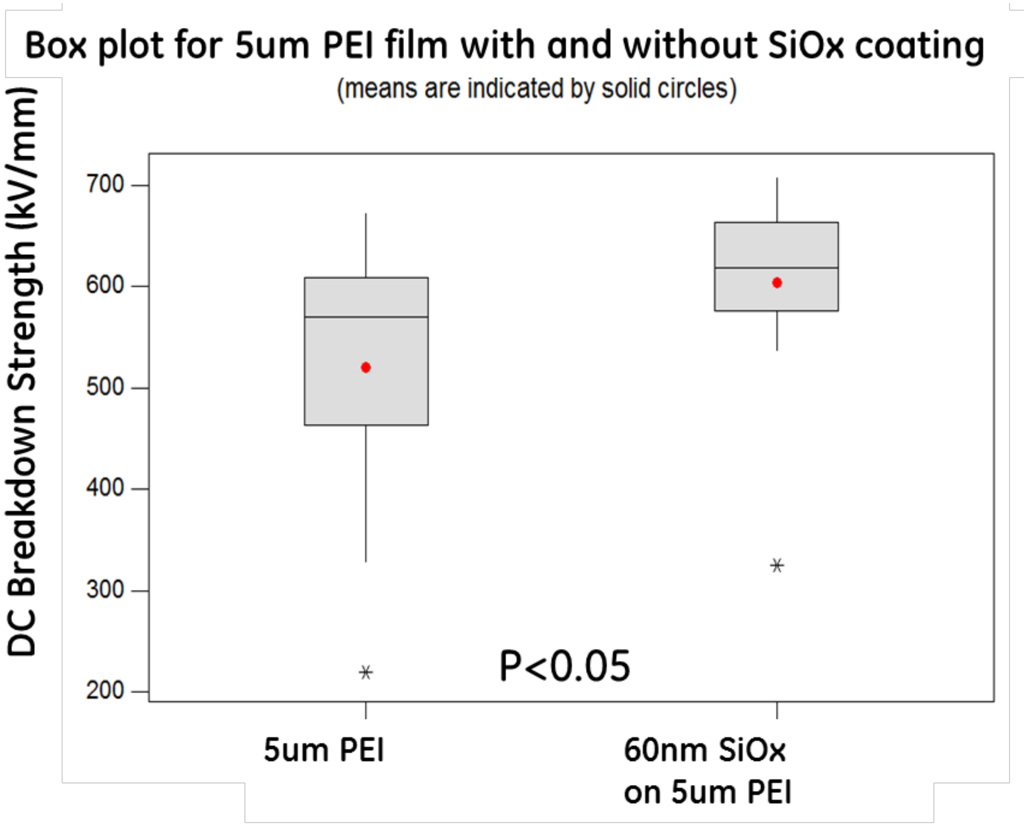


Thinner film shows lower breakdown strength (458.2 kV/mm for 5 μm, 574.1 kV/mm for 10 μm, beta~9)

Test Results

- Roll-to-Roll Oxide Coating Demonstrated on 5 μm Film by Sputtering





Coating on free-standing film remains to be challenging

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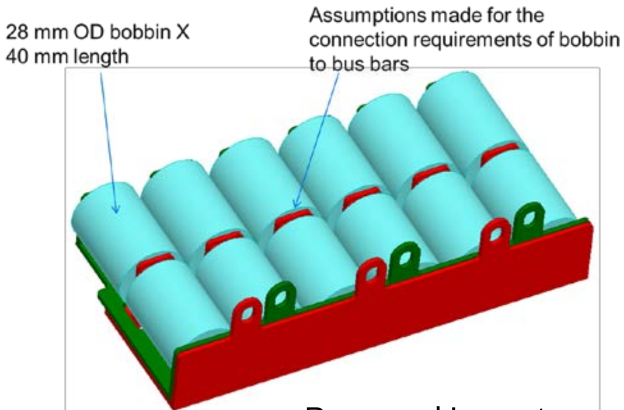
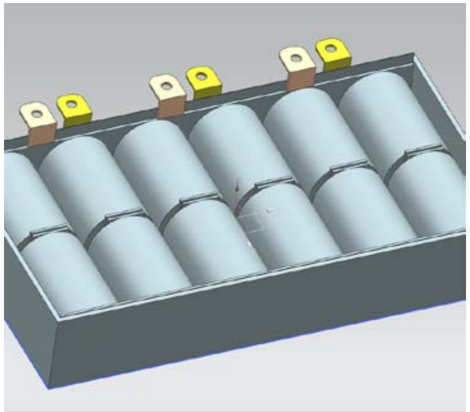
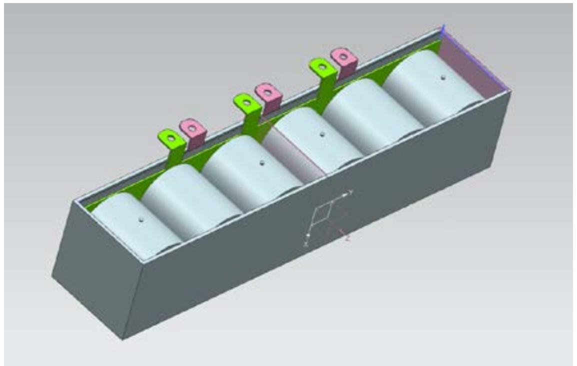
Technology Built (Packaging)



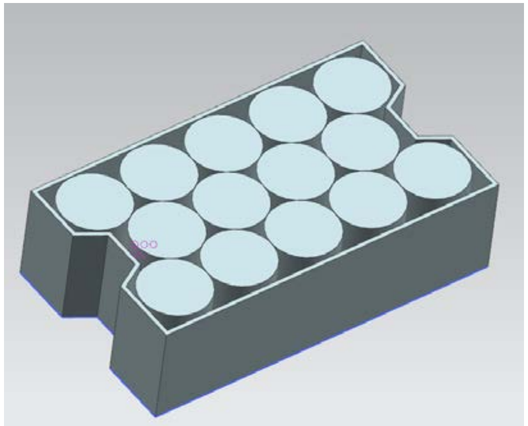
Proposed Layout



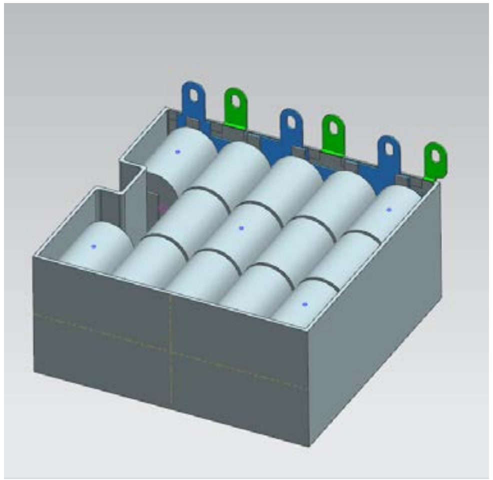
Twelve, 4µm, 25µF bobbins to make a 300µF capacitor



Six, 4µm, 50µF bobbins to make a 300µF capacitor



Fourteen, 3.5µm, 50µF bobbins to make a 700µF capacitor



Twenty Eight, 4µm, 25µF bobbins to make a 700µF capacitor

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Potential Product

Go From

GE/Delphi 800 μF PEI Capacitor
5 μm film, 17μF bobbins
Weight ~ 5.2 kg
Volume ~ 3.3 l

To

GE/Delphi 700 μF PEI Capacitor
3.5 μm film, 50μF bobbins
Weight ~ 1.65 kg
Volume ~ 0.78 l

Today

Commercial PP 700 μF Capacitor
2.5 μm film
Weight ~ 1.1 kg
Volume ~ 0.7 l

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Risk Assessment

- Extruders having difficulty making a PEI film thinner than 4µm
- Extruded film has film quality issues
  - Wrinkles, pits, lower breakdown strength, static cling
  - Breakdown strength is good using a point measurement (ball)
  - Breakdown strength drops when using a surface measurement (plate)
    - Possibly due to pits
      - Pits may be related to monomer
- Some extruded film is coated (SiO_2 …)
  - Improves breakdown strength
    - Possibility of µcracks
- Metalizers having difficulty
  - Non uniform metalization
    - Due to wrinkling, film tension, adhesion, pits, static cling
  - Film resistance to low
    - Clearing issues
      - Target 20Ω/□
- Difficult to wind capacitors
  - Due to wrinkling and static cling
- Over time the extruders, metalizers and winders are getting better

Risks Assessed

- Film is being coated with another thinner film to promote self healing and improve breakdown strength
  - Process did not scale
- PEIs surface finish during extrusion needs to be addressed
  - Overshadowed by the coating process, Extrusion process needs more time
    - Film characteristics were constantly changing
      - Wrinkles and static
- Potential incompatibilities with existing capacitor manufacturing processes
  - Suppliers need more time to adapt their process to the new film
  - Film needs to be stable
- Cost of extrusion and coating
  - Can cost of manufacturing PEI film equal the cost of manufacturing PP film, such that the higher cost of the PEI film is offset by packaging efficiencies, higher dielectric constant and a simplified thermal system?
    - More work is needed by the cap suppliers on how to work this new film
- Commercially extruded 5µm PEI film was announced as available at last years PCIM Europe

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Sigma Technologies

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Innovation for the Real World

Sigma's Approach

- Thinner dielectric
  - Target 650 nm
    - Non self supporting film
- Higher Dielectric Constant
  - >3
- New Dielectric Material
  - Amorphous high breakdown strength dielectric
    - >1000 V/µm for a 0.5 µm dielectric, 1000-layer capacitor
    - highest ever recorded for a polymer capacitor and higher than the intrinsic strength of thicker polymer films (450 – 700 V/µm)
  - Dissipation factor < 0.01
  - Operating temperature (Top) range of -40˚C < Top < 140˚C

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Sigma's Approach

- Sigma dedicated more than 10 years developing the Polymer Multi Layer (PML) capacitor technology before licensing it to two multinational capacitor OEMs
- Sigma developed the material and process technology and built production equipment for producing the mother capacitor material
- Surface mount low voltage PML capacitors are now used in common consumer electronic devices such as digital cameras, LED and LCD TVs, audio amplifiers and others
- After developing the lower voltage PML capacitor technology, Sigma has spent several years working on higher voltage PML capacitors

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Sigma's Approach

- Adapting the existing PML manufacturing process for forming low voltage caps
  - Transformational and potentially disruptive technology
    - Liquid monomer and Al wire are converted in a single step into mother capacitor material
      - Dielectric thickness ≤ 650 nm
    - Eliminates extrusion manufacturing and metalizing by outside suppliers
      - All aspects of capacitor manufacturing are controlled by the capacitor OEM
      - Capacitor manufacturer has the opportunity to innovate and create application specific products with different polymer dielectric materials
- Sigma has developed a solid-state PML capacitor comprising 1000's of radiation cured polymer dielectrics and Al electrodes
  - Forms large area nano-laminate ("mother capacitor") that is segmented into individual capacitors
    - Having a prismatic shape with low ESL and ESR
    - Benign failure mode
    - Low cost materials and process

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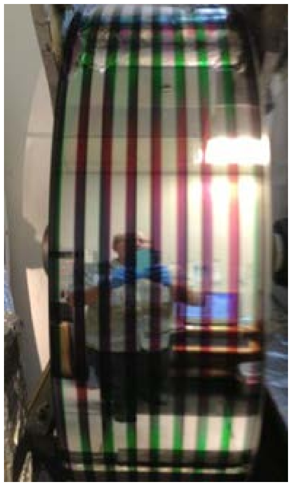
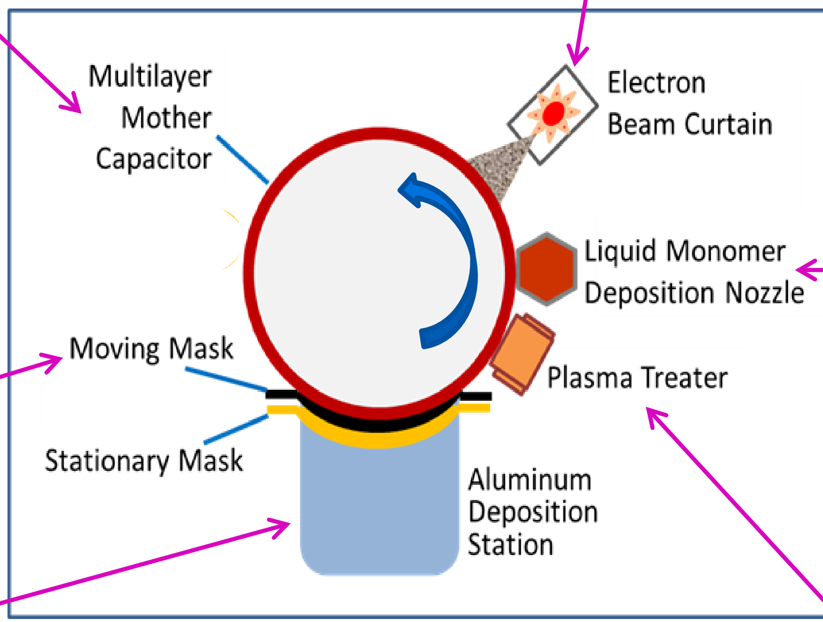
PML Process



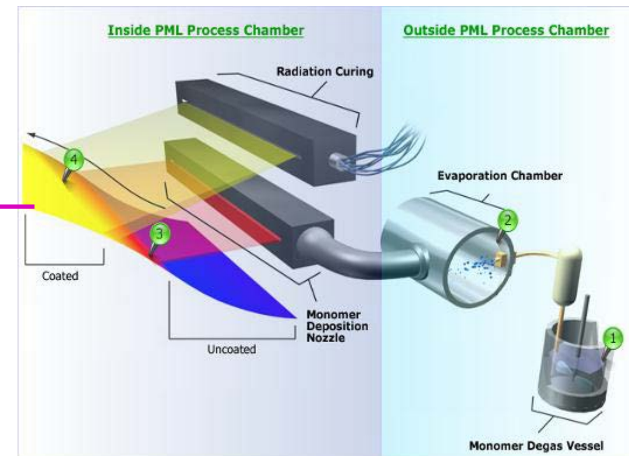
A mask is moved. Patterns heavy edge and body

Al is evaporated onto the monomer (body and heavy edge)

4 Monomer condenses on the drum and is cross-linked with an electron beam



3 Due to a difference in pressure, between the monomer environment and the drum, the vapor is supersonically deposited on the cooled rotating drum

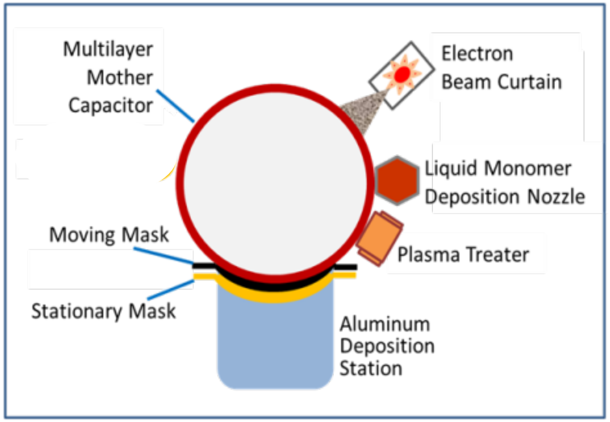


1-2 Monomer is melted – metered – atomized, then flash vaporized

Al is then plasma treated

PML Process

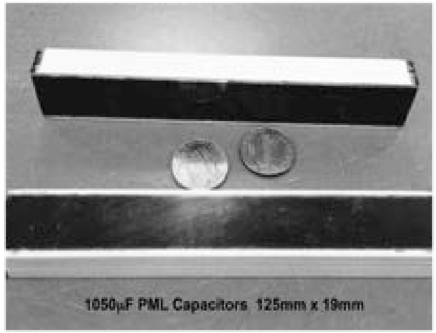
- The mother capacitor is sawed, pressed and dried, diced, etched, ashed, arc-sprayed, terminated, tested, and packaged

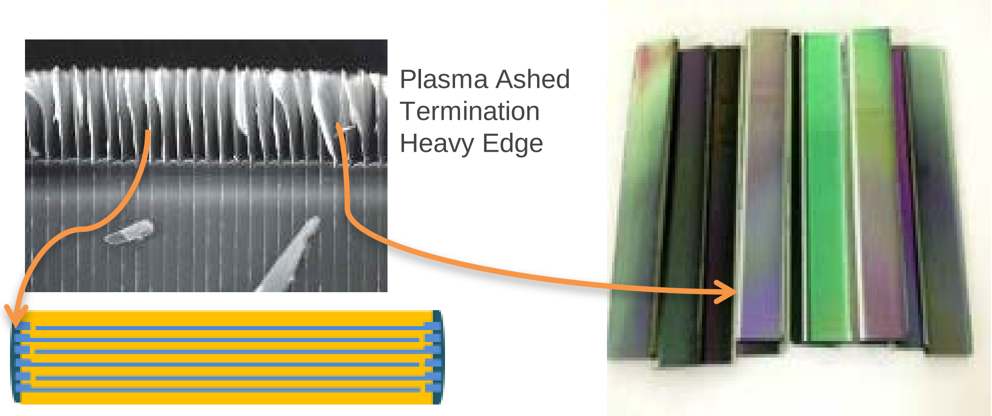


PML Capacitor Process Schematic

10ft long Mother Capacitor Material On Process Drum

12” x 12” Card After Vacuum Heat Bake

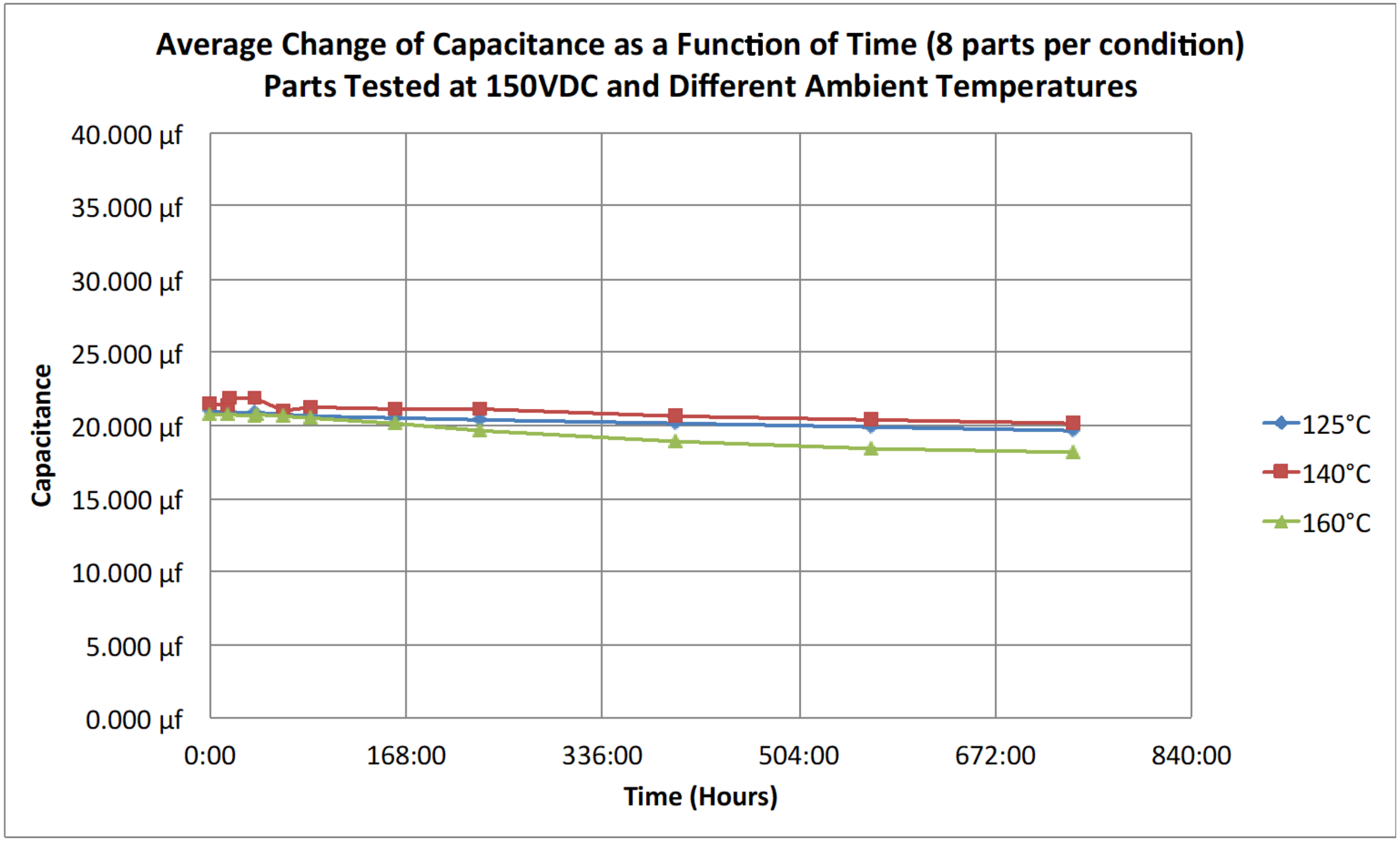




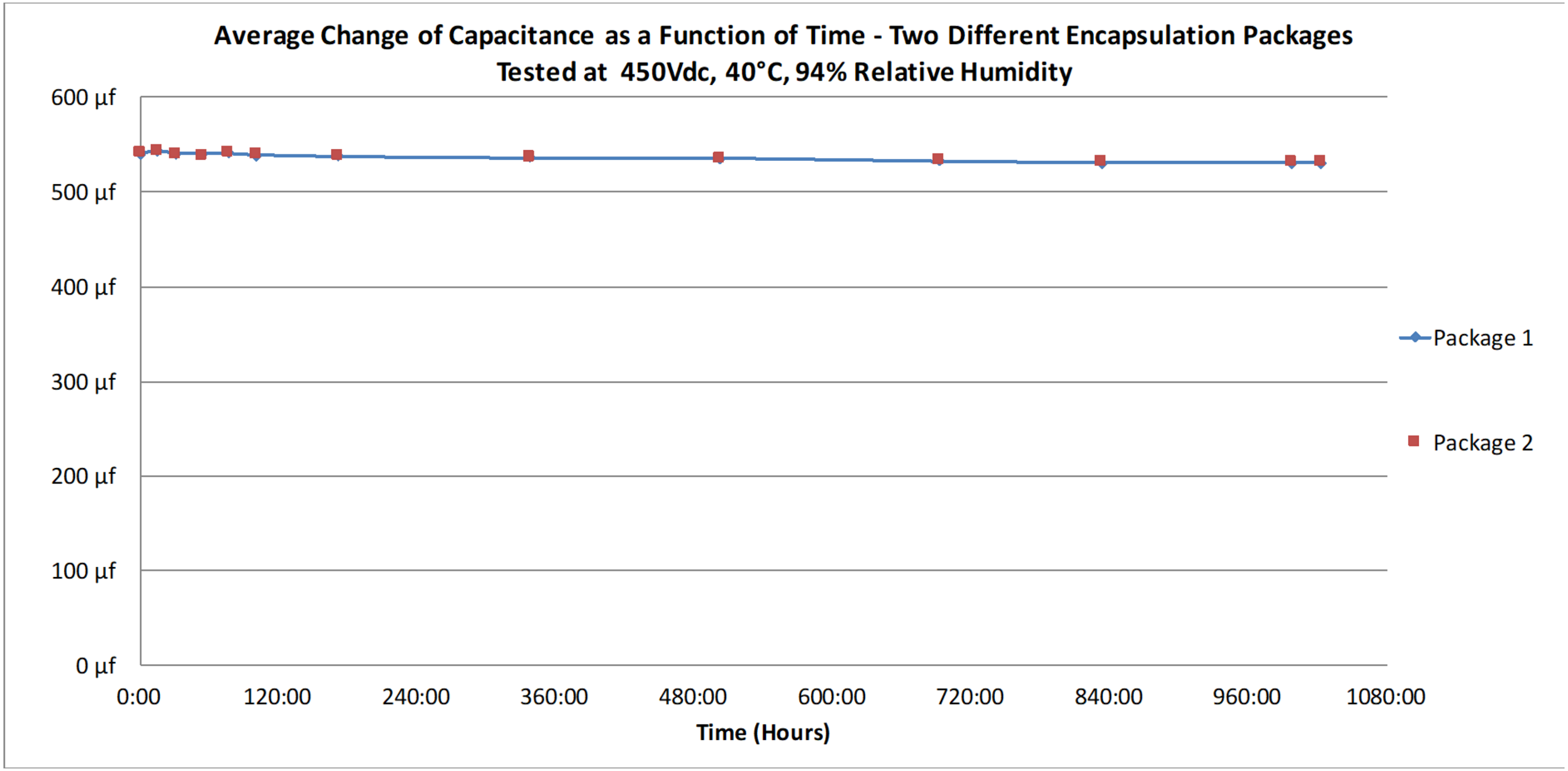
Arc Sprayed Termination

Thermal Test

Life Test of Unpackaged, Partially Passivated PML Capacitors



Bias Humidity and Temperature Test



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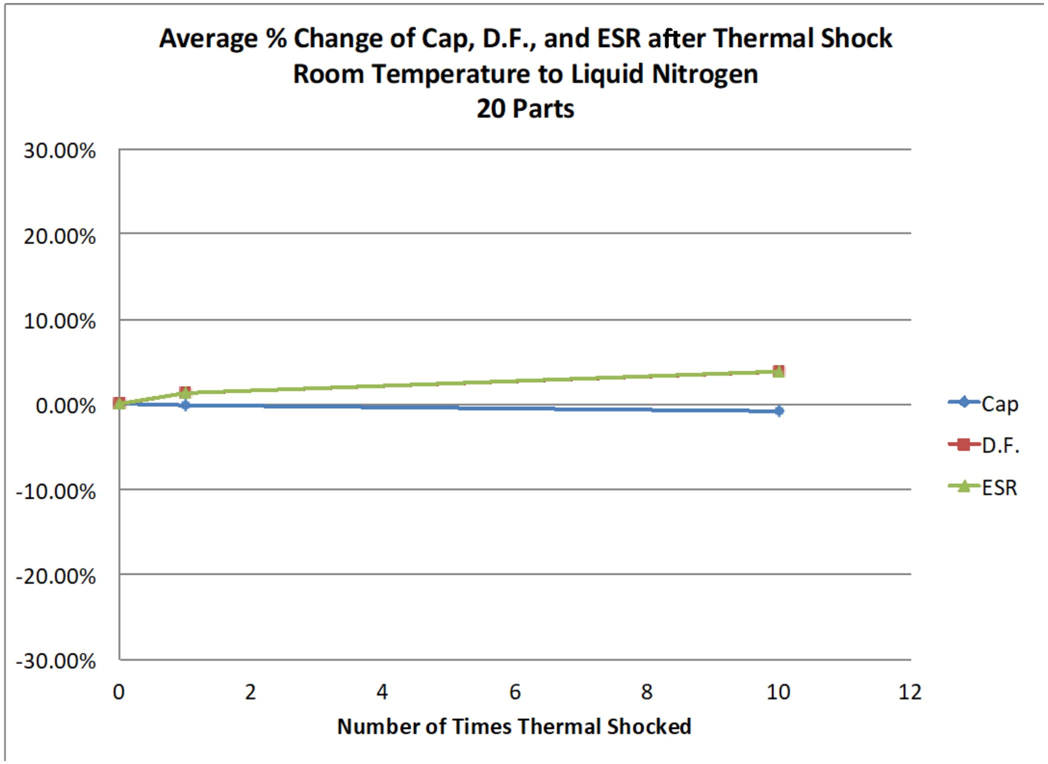
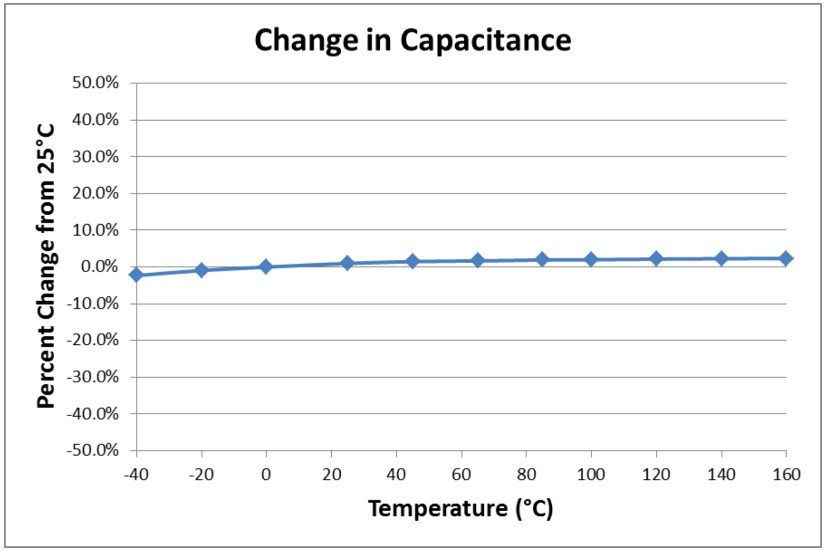
Thermal Shock

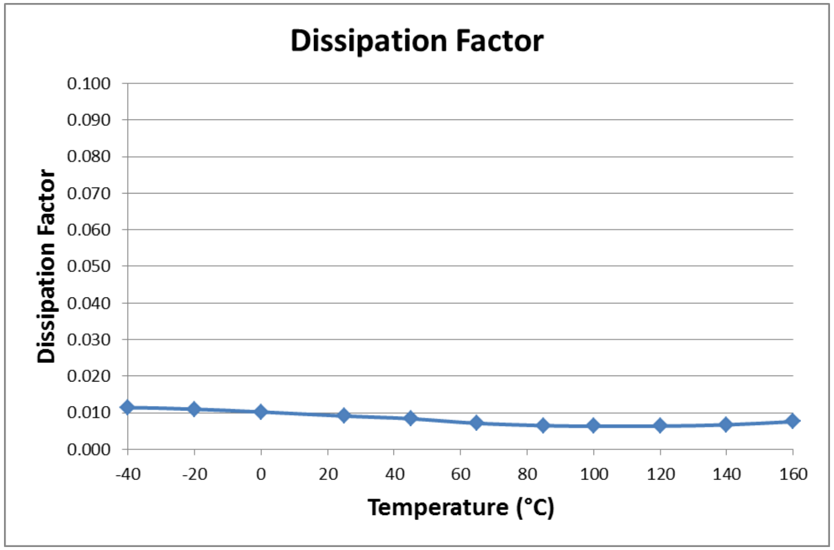
Thermal Shock Test Room Temperature to Liquid Nitrogen 25°C to -196°C Temperature Change 221°C



PML Dielectric for Gen1 Capacitors

Capacitance and Dissipation Factor Stability of GEN1 Dielectric





A self-healing, thermally stable polymer dielectric was developed with a glass transition temperature (Tg) >180˚C

Energy Density

ENERGY DENSITY OF GEN1 PML CAPACITORS

TARGET: 3X ENERGY DENSITY OF MPP CAPACITORS

Dielectric Thickness = 650 nm

	GEN1 Rating	Potential GEN2
Hipot Voltage 240V (3X = 720V)	V_{rated} = 150V 3X = 450V	V_{rated} = 175V 3X = 525V
Energy Density of Individual Capacitors (J/cc)*	**0.59**	**0.80**
Energy Density of Three Capacitors in Series (J/cc)**	**0.49**	**0.65**

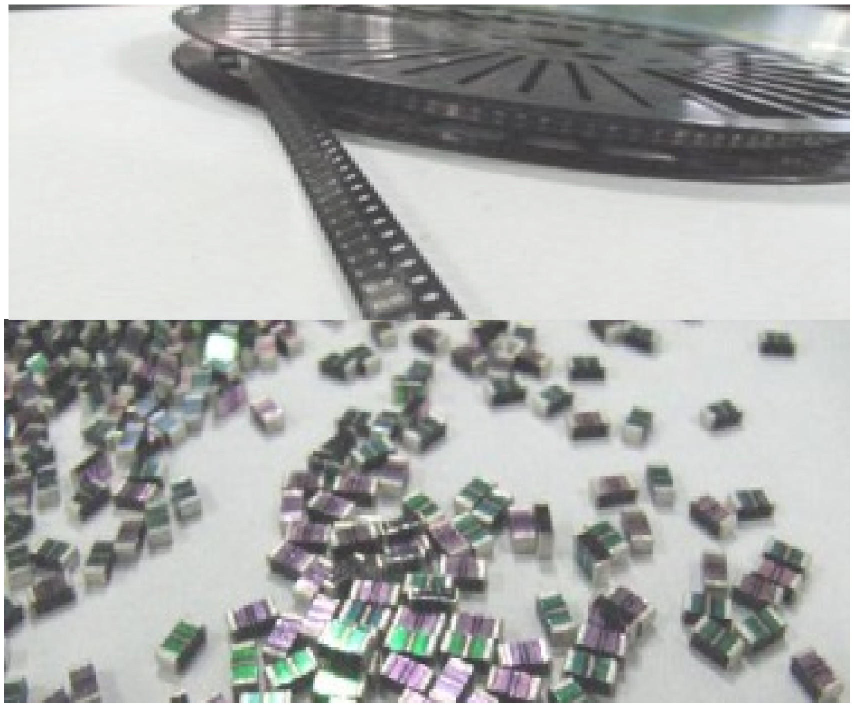
* Capacitors as currently produced

** Energy density of packaged DC-link Capacitor

Energy Density of Current Metallized PP Capacitors Used by Leading US Inverter OEM is 0.09 J/cc

PML Capacitors

Commercially Available PML Low Voltage Capacitors for Consumer Electronic Applications



NanoLam™ is a trademark of **"PolyCharge"** a capacitor spinoff from Sigma Technologies that will manufacture DC-link Capacitors

NanoLam™ Capacitors*

NanoLam™ (HV PML) DC-link Capacitor Comparison with State-of-the-Market Metallized PP Capacitor

- Left: 350 µF- 400V - $600V_{peak}$ - 105˚C metallized PP capacitor comprising multiple wound units internally connected
- Right: 350 µF- 450V - $650V_{peak}$ - 140˚C PolyCharge NanoLam™ Capacitor (unpackaged)

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DOE Acknowledgements & Disclaimer

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DELPHI

When this presentation was completed our company name was Delphi.

At the beginning of this year the powertrain organizations of Delphi; Gas, Diesel and Electrification were spun off into a new company, we became

Delphi Technologies