High Temperature Inverter

Ralph Taylor - Principal Investigator
Delphi Automotive Systems, LLC
14 May 2013

Project ID # APE012

Project Overview

Timeline

- Start: January, 2008
- Finish: September, 2013
- 95% complete (thru Feb/13)

Budget

- Total project funding
  - DOE: $5,442k
  - Contractor: $3,380k
- DOE funding to date
  - FY08: $1,731k
  - FY09: $1,271k
  - FY10: $1,122k
  - FY11: $ 688k
  - FY12: $ 140k
  - FY13: $ 247k
  - Total $5,199k

Barriers

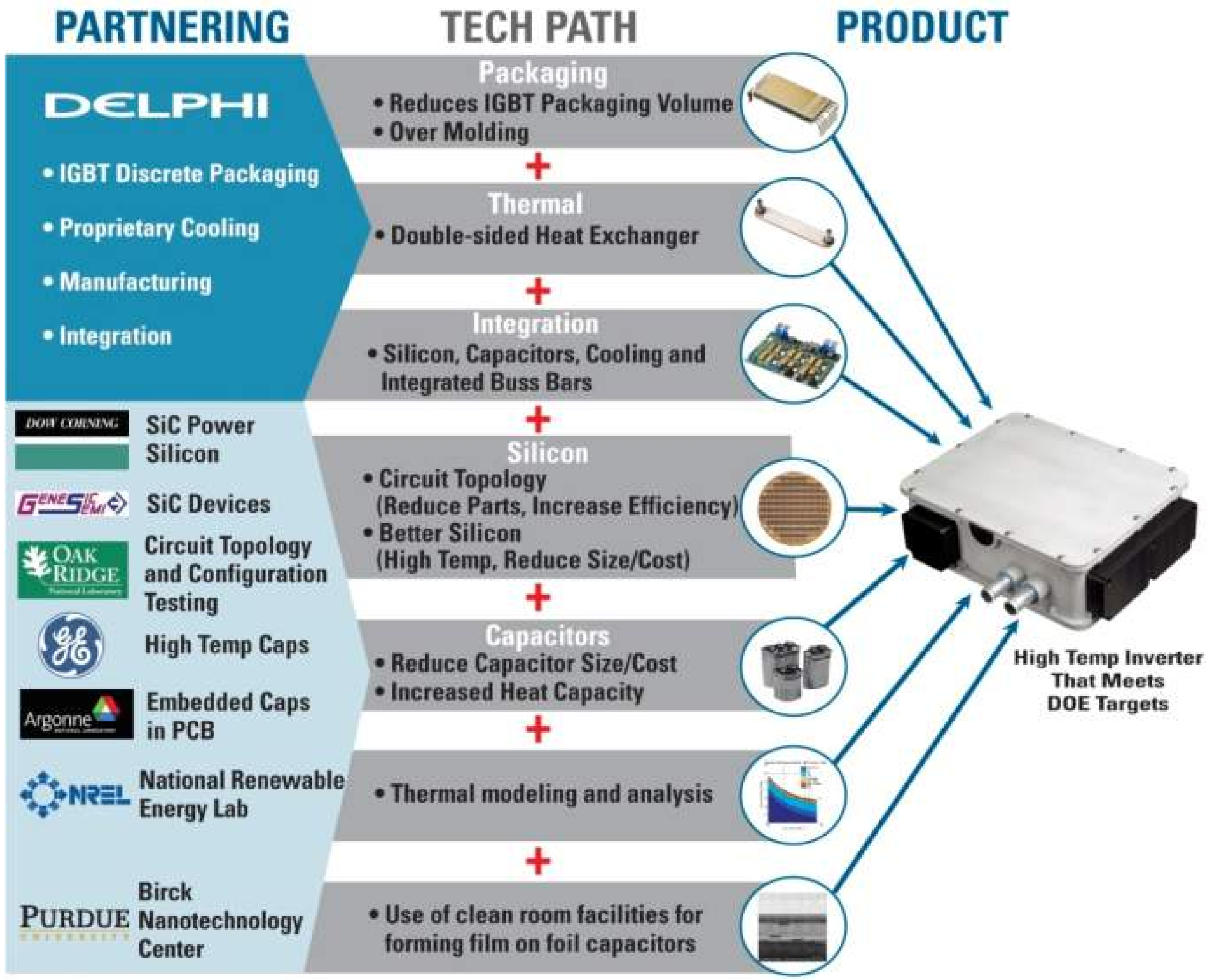
- Reduce system cost by 50% ($275)
  - Compatible with engine coolant (105°C), volume manufacturing, and scalable
- Reduce system volume by 50% (4.6 L)
- Reduce system weight by 50% (4.6 kg)

Partners

- Delphi (project lead)
- Dow Corning/GeneSiC (SiC-on-Si power semiconductor devices)
- GE (film capacitors)
- ANL (film-on-foil capacitors)
- ORNL (system modeling/simulation, power device characterization, system testing)
- NREL (thermal modeling)

DELPHI

Partners/Collaborators



DELPHI

Project Objectives / Relevance

- Overall Objective
  - Develop, test and demonstrate a 30kW continuous, 55kW peak inverter that can operate from the vehicle’s existing coolant system, be 4.6 liters or less in volume, 4.6 Kg’s or less in weight, manufacturable in high volume, meet DOE cost target in quantities of 100,000 units.
- Inverter cost must be reduced by 50%
  - Cost of today’s available propulsion inverters for HEV, PHEV and FCV contributes to a higher cost/price premium for these vehicles, inhibiting consumer acceptance
- Inverter volume & mass must be reduced
  - Volume & mass driven by bulk capacitors and thermal/mechanical packaging
- Manufacturability must be improved
  - Today’s power silicon modules contain too many parts => too many manufacturing steps => quality, reliability and durability challenges, as well as high cost
  - Design must be scalable

DELPHI

Project Objectives / Relevance

- Uniqueness and Impacts
  - Lower thermal resistance packaging with lower device losses enables less silicon
    - Less silicon implies less silicon packaging, lower cost
    - Less silicon packaging and smaller bulk capacitor implies smaller inverter package size and lower cost
  - Smaller Volume – Lower Weight – Easier to Manufacture – Lower Cost

- Objective (March 2012 – March 2013)
  - Determine root cause failure of previous high temperature PEI capacitors
    - Take corrective action, build and test PEI capacitor
    - Integrate PEI capacitor into High Temperature Inverter
    - Execute inverter test plan and provide results to ORNL
  - Investigate process concepts for forming sub-micron PLZT particles
    - Develop a process concept for forming films based on sub-micron PLZT particles

DELPHI

Milestones

Project Duration: FY08 – FY13 **Overall Objective (all years):** Development, Test and Demonstration of a Cost-Effective, Compact, Light-Weight, and Scalable High Temperature Inverter for HEVs, PHEVs, and FCVs
FY 8 - 10 Focus: Develop a cost-effective, compact, light-weight, and scalable High Temperature Inverter for HEVs, PHEVs, and FCVs
Deliverable: Inverter and component specifications; Inverter design; Report on modeling and simulation of various inverter topologies for efficiency and cost with ORNL; Report on WBG vs. Advanced Si to use for costing and performance comparisons with DOW; Evaluations of thermal interface materials and cooling topologies analysis for inverter power stage with NREL.
Go/No Go Decision Point: Inverter designed; new components defined and tested
FY 11 Focus: Design and procure component parts, build and test inverter, verification
Deliverable: Deliver high temperature inverter
Go/No Go Decision Point: Microprocessor and electronic component availability, connector system, PEI DC- link capacitor, 3C-SiC/Si
FY12 Focus: Build and test inverter with PP DC- link capacitor & determine root cause of PEI failures
Deliverable: Test report for low temp inverter & functioning PEI capacitors
Go/No Go Decision Point: Build and test inverter; package and test 3C-SiC/Si diodes; Invite ORNL to do verification testing of the inverter; Deliver the inverter to the DOE
FY13 Focus: Build and test high temperature inverter – Develop process concepts for PLZT
Final Deliverable: High temperature inverter and its test results & report on PLZT process possibilities
Path Forward: Final Report

DELPHI

Approach

- This year, the focus of our work was to understand and fix the problems associated with the GE PEI capacitor and then build a PEI capacitor, such that high temperature testing of our inverter could be completed
  - Failure analysis of PEI capacitors
    - Electrical, thermal, x-ray, material
  - Develop a process FMEA
    - Based on failure analysis, what in the process could cause the problem
  - Discuss potential process issues with suppliers
  - Create a design of experiments to replicate and fix the problem
  - Make DC-link PEI capacitors
  - Build and test a high temperature inverter
- In addition, determine if the PLZT capacitor material that has used chemical solution deposition (CSD) to form capacitors can be formed as sub-micron particles
  - Allows opportunities for lower-cost deposition processes
  - The sub-micron particle based chemistry may allow aerosol, ink jet, electrostatic or other deposition processes to be used for forming capacitors with a few simple process steps.
    - These processes are currently being investigated
    - Work with suppliers to identify process possibilities
  - The CSD process has many deposition and recrystallization steps (not practical)
- Packaging, thermal and integration
  - Build, test and demonstrate an inverter using a PEI DC-link capacitor

DELPHI

Accomplishments:
PEI Capacitors GE

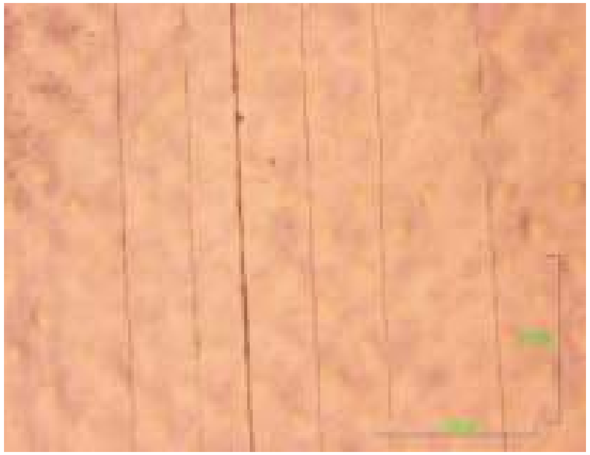
- After a lengthy investigation, a design of experiments (DoE) was proposed and executed at Dearborn Electronics' winding facility
- This DoE showed that one of the process steps can cause arcing to the film
- More capacitors have been formed at Dearborn with newly metalized film
- The metalized film exhibits no failures
- A tested PEI DC-link capacitor was delivered the week before Christmas allowing us to resume our build and test of the high temperature inverter

One lot of Four
Results of 75 caps
All lots similar

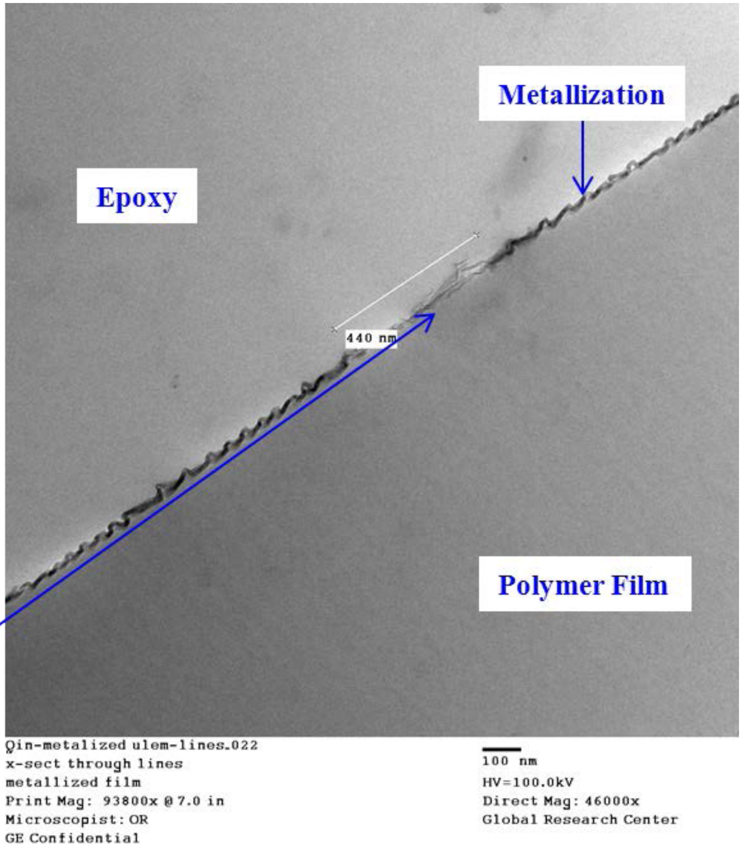
	Capacitance After Lead Attach (μF)	Dissipation Factor After Lead Attach %	ESR @1000 Hz (mΩ)
Mean	16.8	0.61	65
Min	16.2	0.30	29
Max	17.1	1.26	578
Standard Deviation	0.14	0.19	62

DELPHI

Accomplishments:
PEI Capacitors GE (continued)



Scratches on film under high magnification



TEM image of scratch

The energy of the arc was enough to vaporize the metal, but not enough to scratch the underlying film.

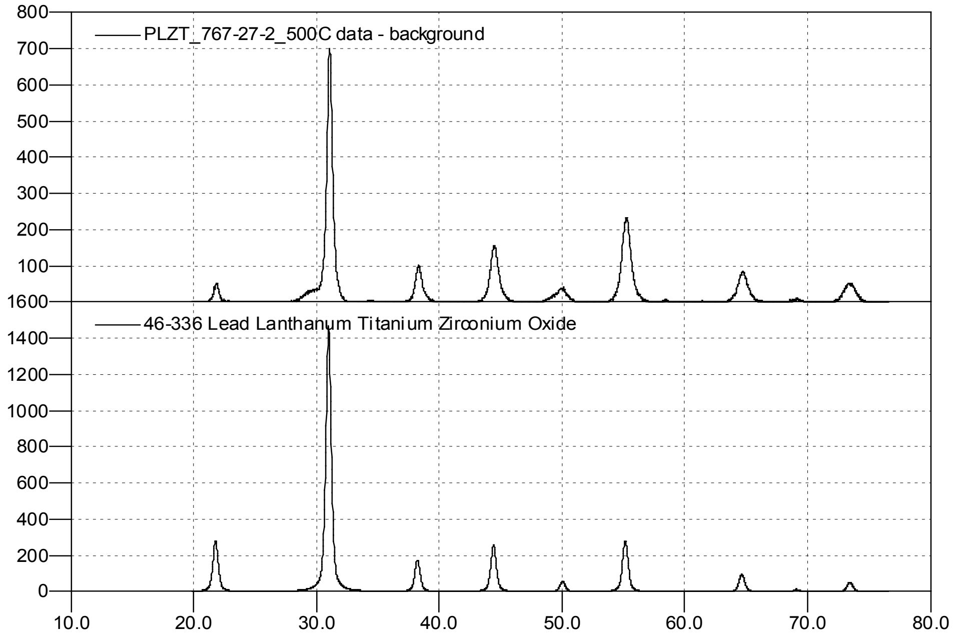
DELPHI

Accomplishments:
PLZT Capacitors Argonne

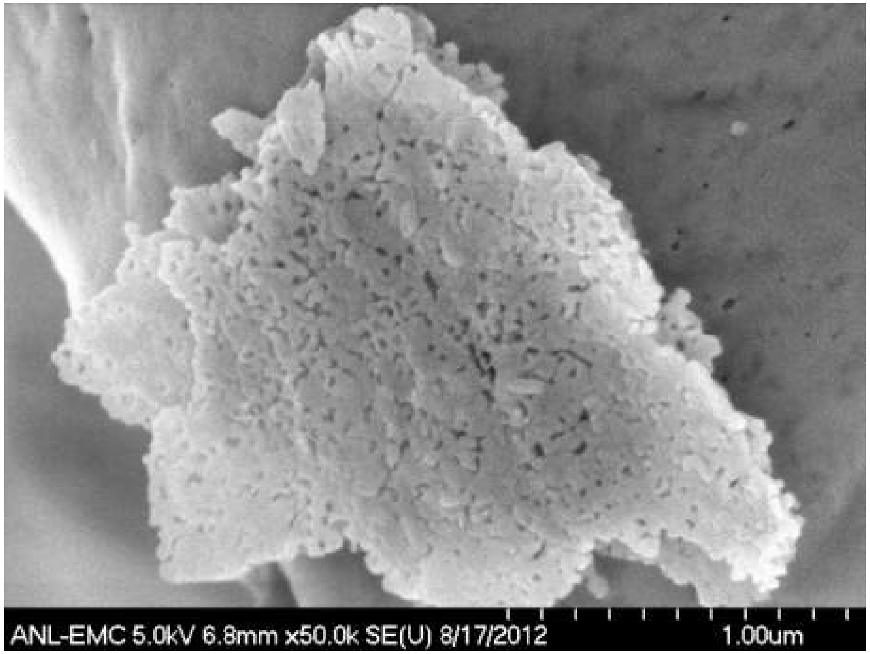
- After continued work with a solution-based PLZT chemistry, it was agreed to focus on ways to form PLZT such that a single step deposition process of PLZT could be used to lower process cost.
- Argonne is developing a combustion synthesis process to form sub-micron PLZT particles.
  - The process has been demonstrated and the sub-micron PLZT particles have the same crystal structure as the bulk material.
- Delphi is working to define a deposition process to form capacitors using Argonne's sub-micron PLZT particles.
  - With and without recrystallization (low temperature vs. high temperature)
  - Wound vs. stacked
  - Aerosol, ink jet, electrostatic and other deposition processes are being evaluated
- Focus is on defining a lowest cost process
  - Started a cost model incorporating what we know about forming sub-micron PLZT particles
  - Working with suppliers to determine process materials
  - Working with suppliers to identify process possibilities
- Current efforts are focused on producing a film to understand sub-micron PLZT material properties.

DELPHI

Accomplishments:
PLZT Capacitors Argonne (continued)



Top: PLZT powder synthesized at Argonne
Bottom: JCPDS 46-336 (PLZT Standard)



SEM picture shows the “flaky” nature of the PLZT powder agglomerates & the primary particles within the agglomerates.

Accomplishments:
Packaging Thermal and Integration

- Demonstrated a non-optimized, scalable solution for multiple applications
  - Built and tested an inverter using the 5 µm PEI DC-link capacitor
    - PP will not meet the temperature or volume target
    - 5 µm PEI will meet 140°C temperature requirement, but does not meet the volume or cost targets
      - 4 µm or thinner PEI has the potential to meet the volume target at lower cost than existing PP cap technology
    - Completed all performance tests both hot and cold
  - Meets DOE performance requirements
  - Scalable: capable of operating over a wide range of applications
    - Capable of 80A to > 460 A/phase output
      - Parts delete and part substitution, Si size, heat sink materials and design, component temperature ratings
  - Utilizes advanced Si with improved heat sink
    - Characterized static and dynamic performance of advanced silicon devices over temperature (25°C and 150°C)
  - Utilizes 105°C engine coolant, 140˚C ambient
    - Dual-side cooled discrete power switches
    - Light weight, high performance heat rails
    - Thermal performance characterized with 105°C coolant
  - Utilizes high performance phase change material
    - Lower thermal resistance junction-to-water
  - Utilizes scalable high current connection system
    - Connections are on the box lid
    - Only need to change the lid for different connectors as opposed to the entire housing

DELPHI

Future Work

- Continue the development of process concepts for forming films using sub-micron PLZT particles
  - Select suppliers for capacitor materials
  - Select capacitor manufacturer to work with
  - Complete an initial costing of the proposed PLZT capacitor concept materials and process
- Provide final report

DELPHI

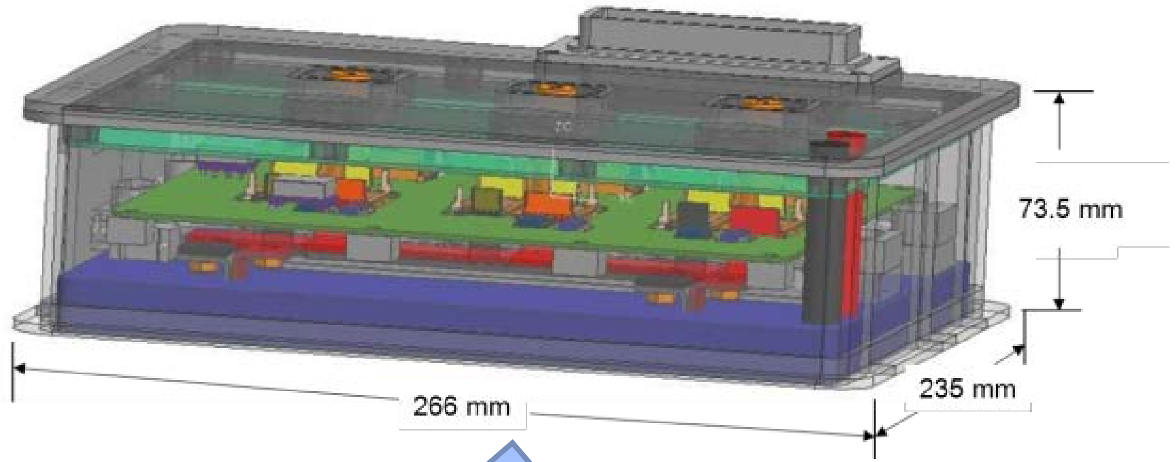
Summary

- Inverter was built and tested using a high temperature PEI capacitor
  - Testing was verified by ORNL
  - Hot and cold test results were provided to ORNL
  - This completes the test plan provided by ORNL
  - Inverter meets DOE performance requirements
- An inverter design, based on work done under this program, is going to production
- Thank you to the DOE Vehicle Technologies Program for your support and funding for this program

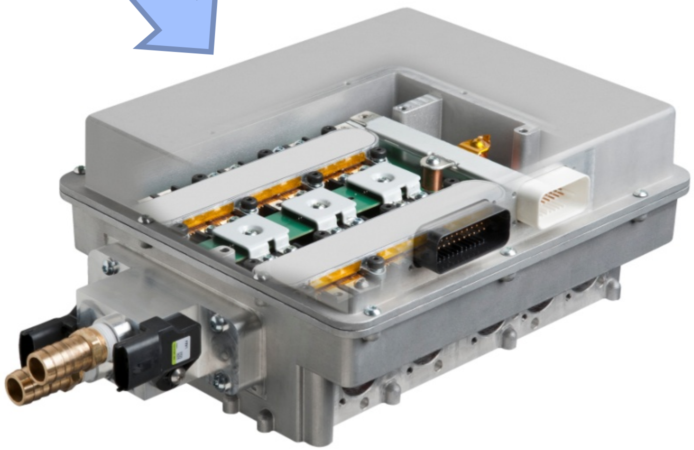
DELPHI

Summary (cont'd)

DOE PEEM Inverter with controller



Technologies developed in DOE PEEM program are now in production planning cycle



DELPHI