U.S. DEPARTMENT OF ENERGY

OAK RIDGE NATIONAL LABORATORY
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Power Device Packaging

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2012 U.S. DOE Hydrogen and Fuel Cells Program and Vehicle Technologies Program Annual Merit Review and Peer Evaluation Meeting

Project ID: APE023

Overview

Timeline

- Start Date: Oct. 2009
- End Date: Sept. 2014
- 70% Complete

Budget

- DOE Share – 100%
- FY10 received: $480K
- FY11 received: $650K
- FY12 received: $672K

Barriers

- Existing inverters are twice the cost of the DOE 2020 target. Power modules make up 50% of the inverter's cost
- State-of-the-art (SOA) technologies have limitations in electrical, thermal, and reliability performance, as well as high manufacturing costs.

- **Targets:**
  - 40% cost reduction and 60% power density increase of the power module, in line with DOE power electronics 2020 targets.

Partners

- **ORNL Team Members:** Puqi Ning, Andy Wereszczak, Randy Wiles, Laura Marlino
- **The University of Tennessee:** Fred Wang

Objective

The fundamental efforts of this project are to:

- **Identify the limitations and shortcomings with existing device packaging approaches;**
- **Develop new packaging concepts for improved electrical, thermal performance, manufacturability, and reliability;**
- **Complement other power electronics research efforts within the Vehicle Technology Program.**

FY12

- **Evaluate industry SOA power modules:** Packaging performance, material, processing and structure analysis.
- **Planar_Bond_All (PBA) power module development**
  - **Packaging process optimization:** Material/structure, cost-effectiveness manufacturing**.**
  - **Prototype module fabrication:** Integration of advanced processing techniques.
  - **Module testing and analysis:** Electrical, thermal, properties measurement and analysis.
- **Provide packaging support for other VTP APEEM projects:** Fabrication of customer-specific power modules.

Milestone

- **Sept. 2011**

  - Selected advanced packaging candidate technologies.
- **Go No/Go Decision Point**: Determine if prototype PBA technology could potentially meet the performance and power density targets.
- **Sept. 2012**

  -Test PBA modules to confirm improvements in electrical and thermal performance.

  -Provide prototype modules for Segmented Drive Inverter Project (APE004) and Wide Bandgap Project (APE003).
- **Go/No Go** – Determine if PBA modules can meet the targets on cost and reliability.

Approach

Overall Strategy

- **Benchmark existing power device packaging technologies, including package configuration, materials characterization, processing, and thermal and electrical performance evaluations. Determine the "weak links".**

- **Develop new packaging approaches through simulation and experiments to improve power module electrical, thermal, thermo-mechanical performance and manufacturing cost-effectiveness.**

- **Apply packaging expertise to provide customer-specific power modules to VTP projects.**

Status of Milestone

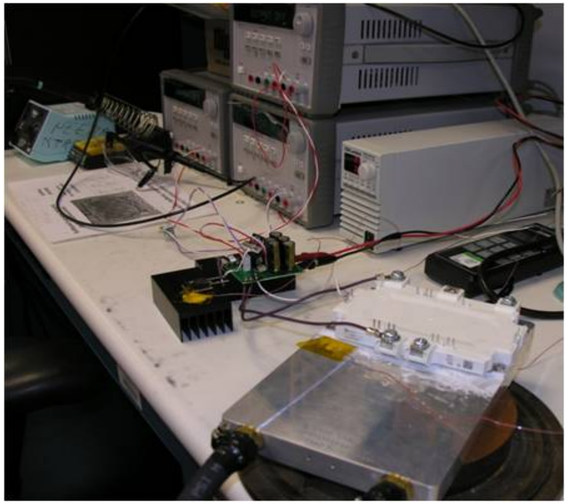
- **FY11 PBA prototype completed**

- **FY12 - PBA optimized module fabricated; Testing is underway;**

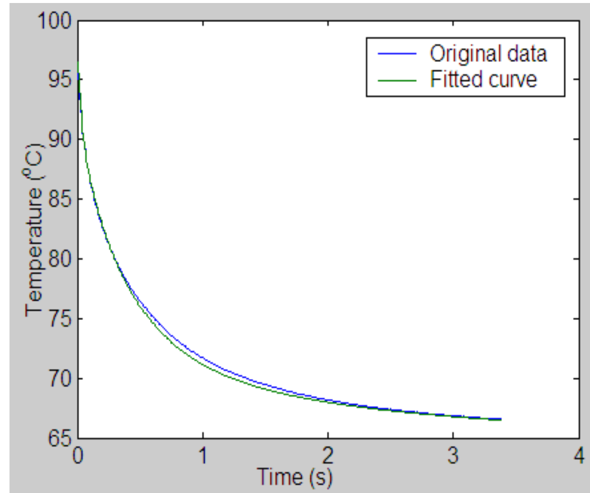
  - Customer modules delivered.

FY11/12 Technical Accomplishments

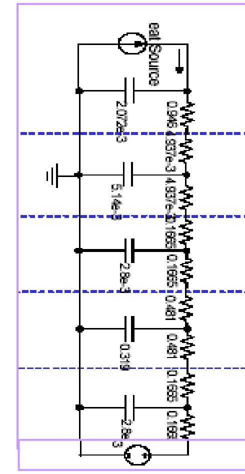
Benchmark: Thermal Performance Characterization of SOA Modules



Infineon® HybridPack1™ under test

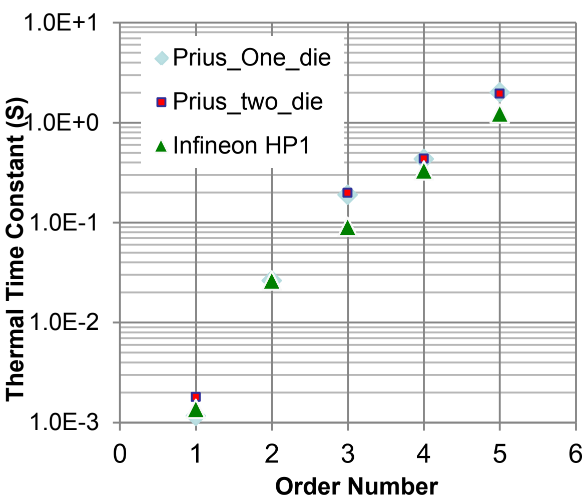


Junction temperature cooling down curve

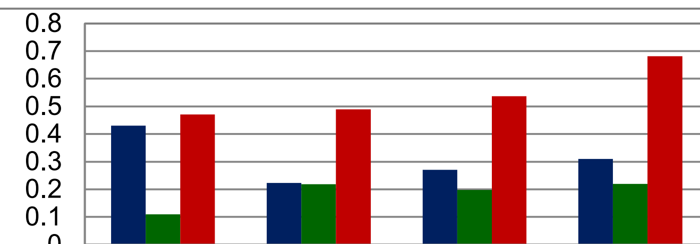


Thermal model

Thermal Parameters



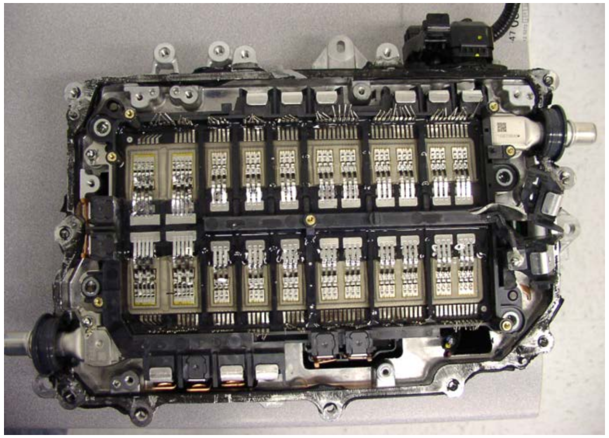
Thermal Resistance Comparison



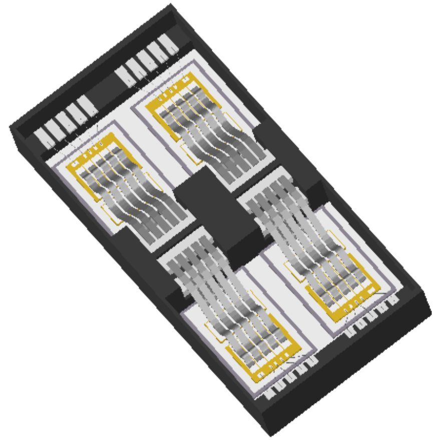
	ToyotaPrius10 _OneDie	ToyotaPrius10 _TwoDie	InfineonHP1	NissanLeaf
Thermal Resitance (C/W)	0.43	0.22	0.27	0.31
Die area (10xcm2)	0.11	0.22	0.20	0.22
Specific Thermal resitance (Cm2.C/W)	0.47	0.49	0.54	0.68

FY11/12 Technical Accomplishments

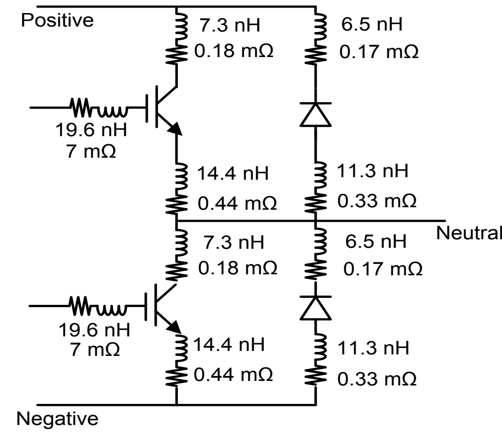
Benchmark: Electrical Performance Characterization of SOA Modules



Prius 2010 Module

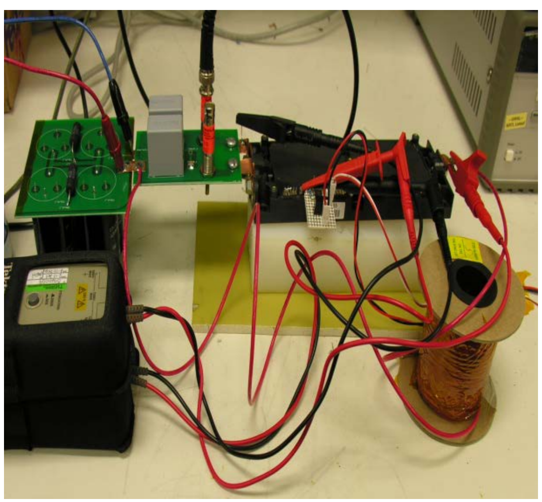


3_D Electromagnetic Model

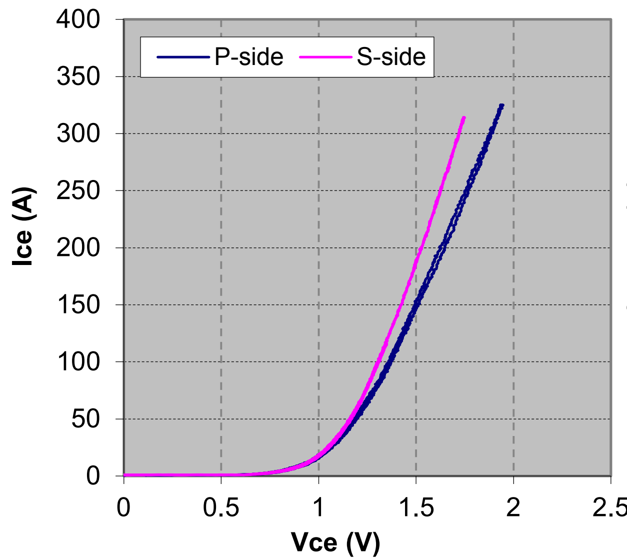


Lump element model of parasitic electric parameters

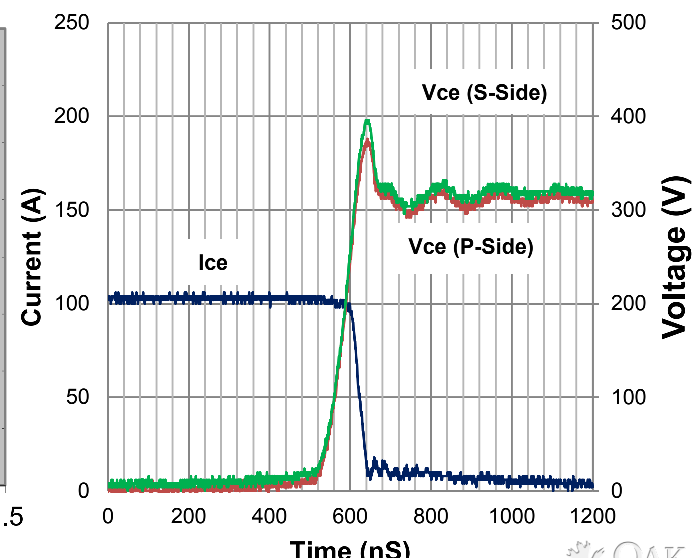
Nissan LEAF under Test



IGBT I-V Curve

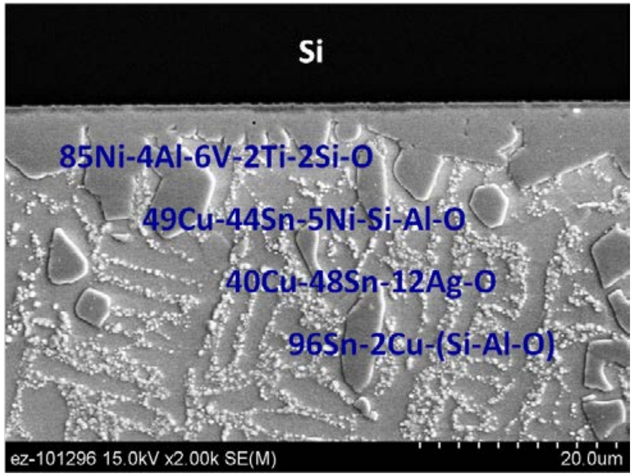


IGBT Switching Curve

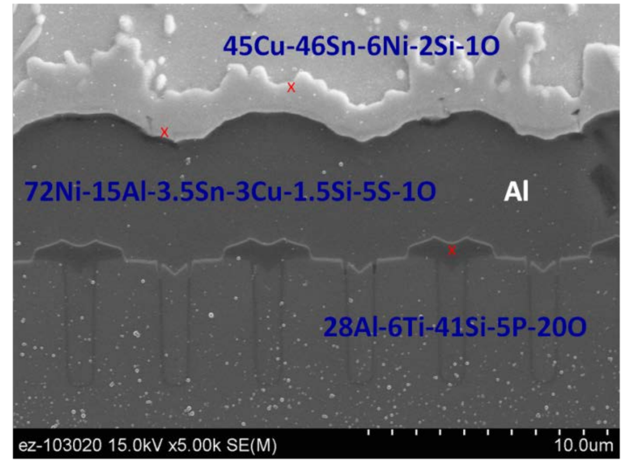


FY11/12 Technical Accomplishments

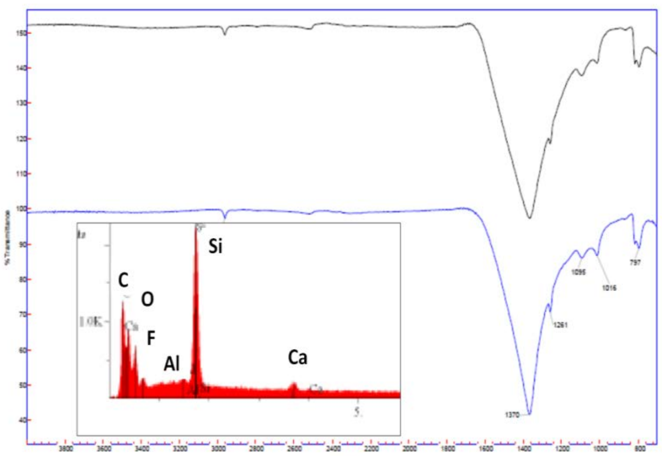
Benchmark: Micro-structural analysis of packaging structures/materials



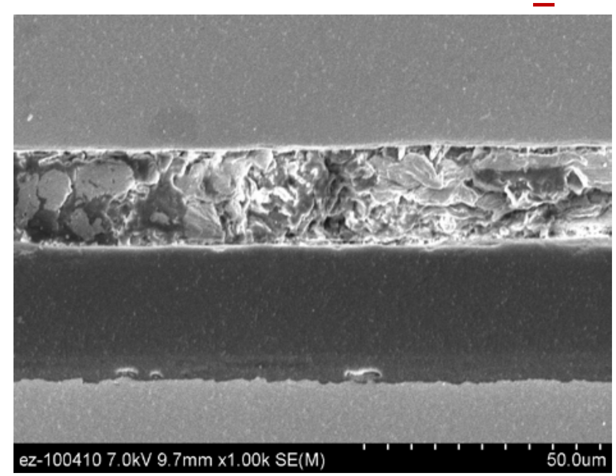
Die attach solder layer in Infineon HP1



Metallurgical compositions on top of IGBT die in Mitsubishi TPM_II



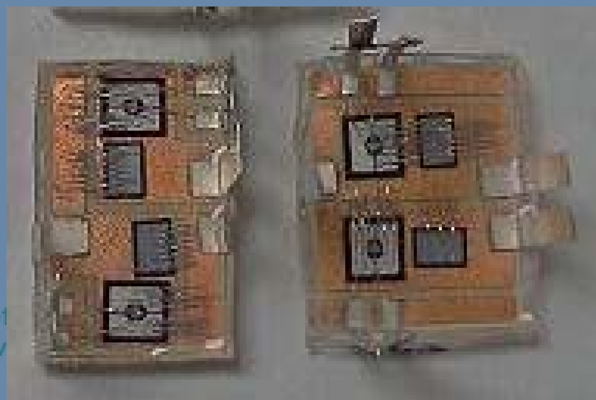
Insulator sheet in Nissan LEAF™ module



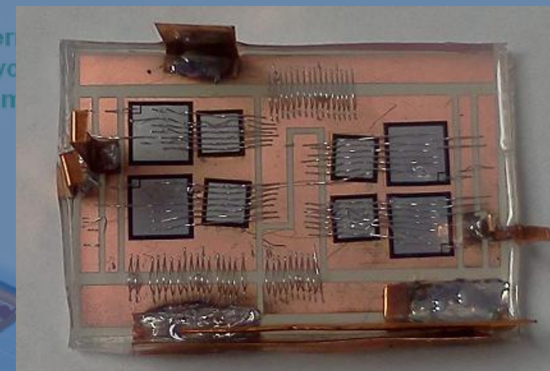
Polyimide bond line

FY11/12 Technical Accomplishments

Prototype: Customer-specific power modules



High power density integrated traction machine drive



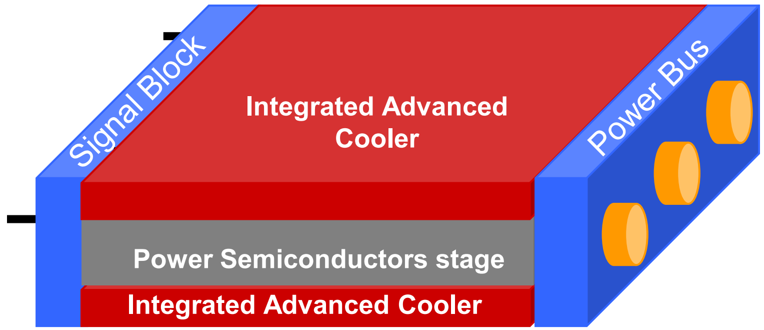
Reduced stray inductance power module

Segmented drive Module

HT Power SiC diode package.

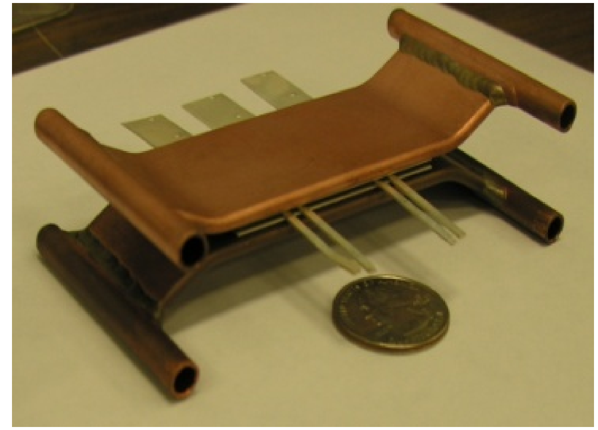
FY11/12 Technical Accomplishments

Develop: Planar_Bond_All power module



❖3-D planar Electrical Interconnection ❖Symmetrically Mechanical Structure

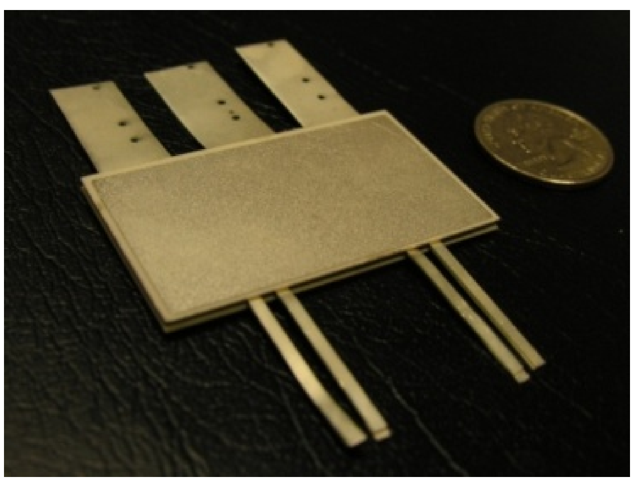
❖Integrated, Double Sided Cooling ❖Cost-effective Manufacture



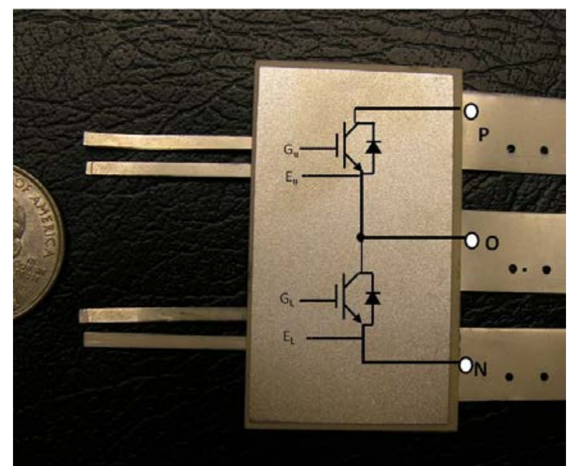
Advanced Power Module Concept

Planar_Bond_All Power Module Prototype

Planar Bond Power Stage



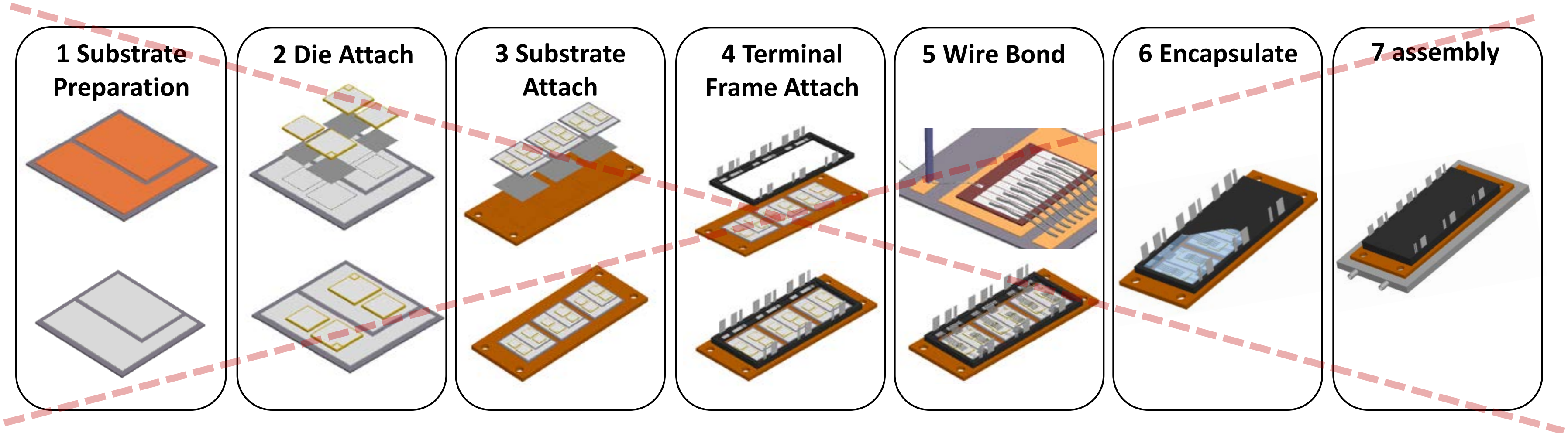
Electrical Connection



Patent Pending: serial number 61/509312

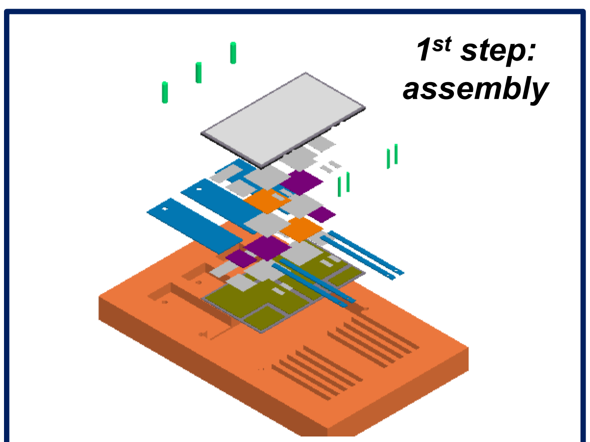
FY12 Technical Accomplishments

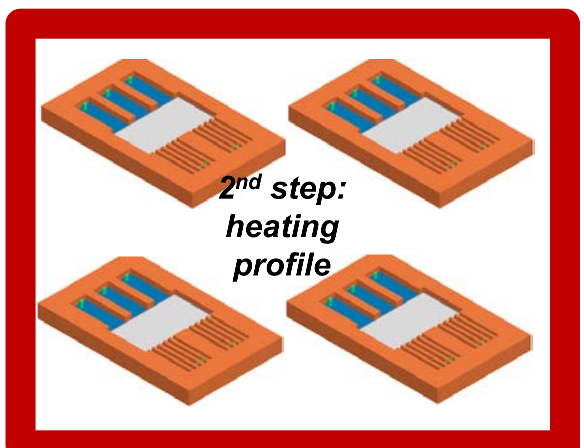
Develop: Advanced manufacturing process



Wire Bond Packaging

Planar_Bond_All





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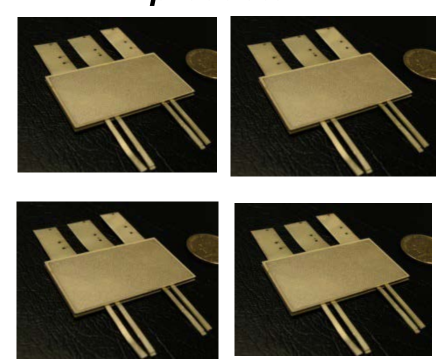
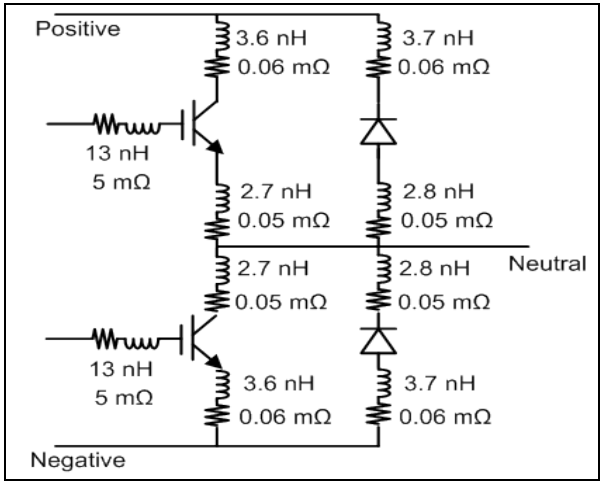


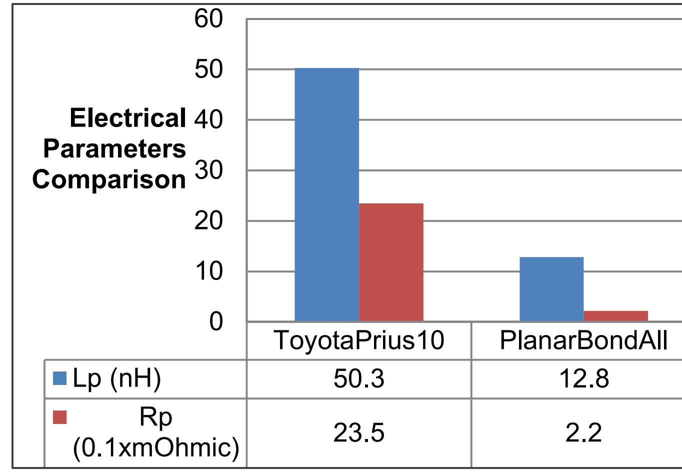
Patent Pending: serial number 61/509312

FY12 Technical Accomplishments

Develop: Analysis of electrical performance of PBA module

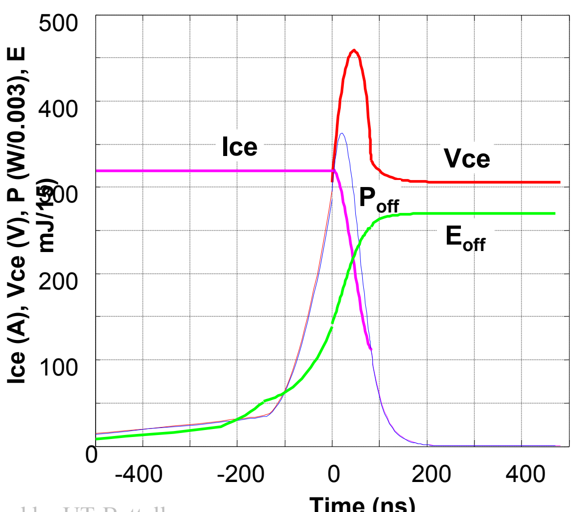


Lump element model of PBA module

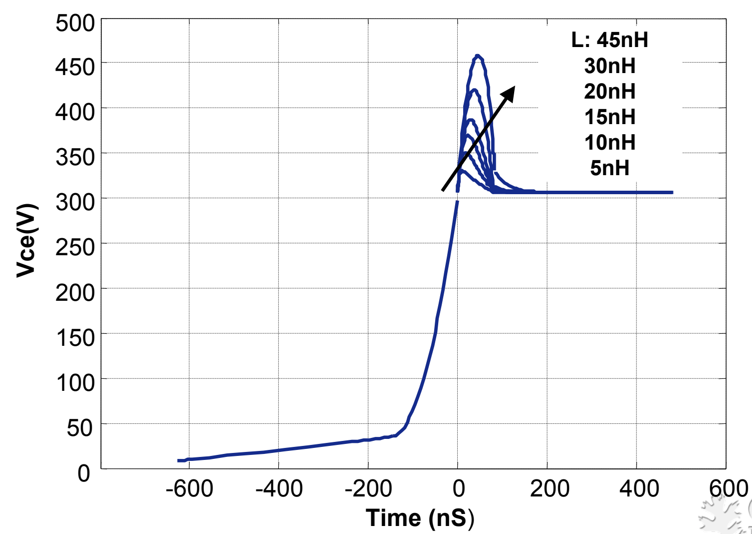


Parasitic parameters comparison

Simulation of IGBT switching

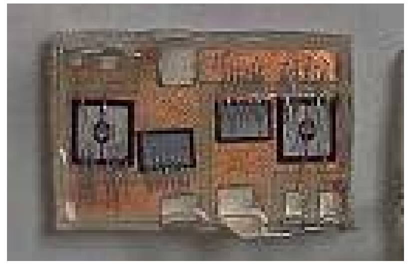


Voltage overshoot vs. parasitic inductance



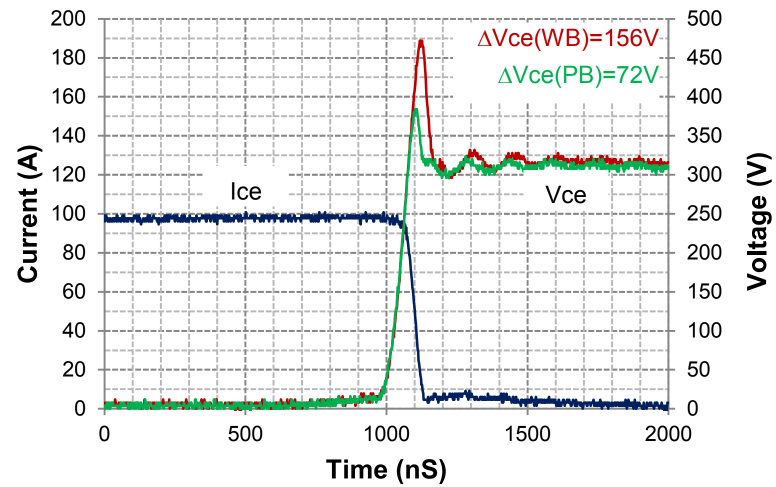
FY12 Technical Accomplishments

Develop: Analysis of electrical performance of PBA module



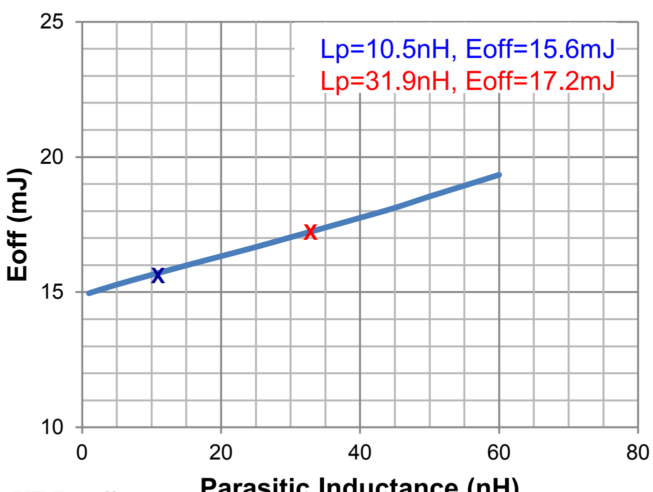
Inductance (nH)	Experimental Value	Calculated Value
Planar Bond_Lower IGBT	10.5	6.3
Wire Bond-Lower IGBT	31.9	23.5

Comparison: PBA vs. wire bond module

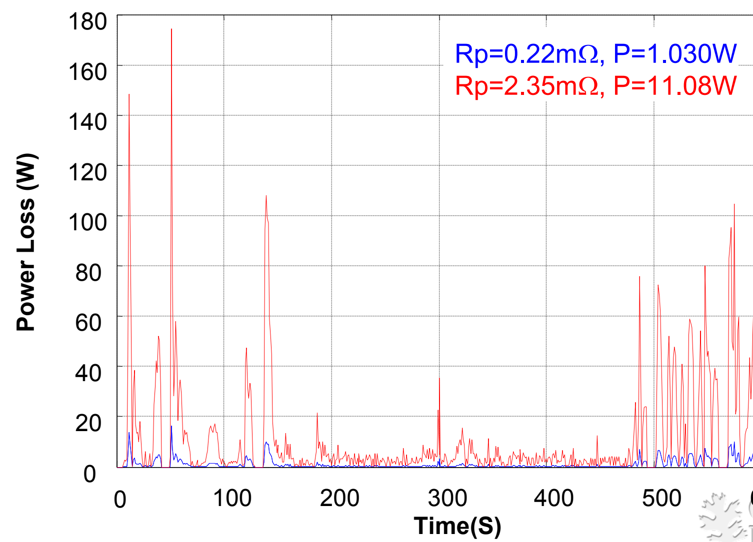


Voltage overshoot: PBA vs. wire bond

Switching loss: PBA vs. wire bond

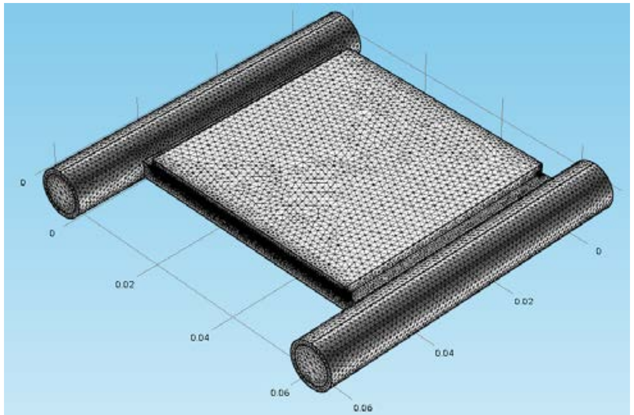


Conduction loss: PBA vs. wire bond

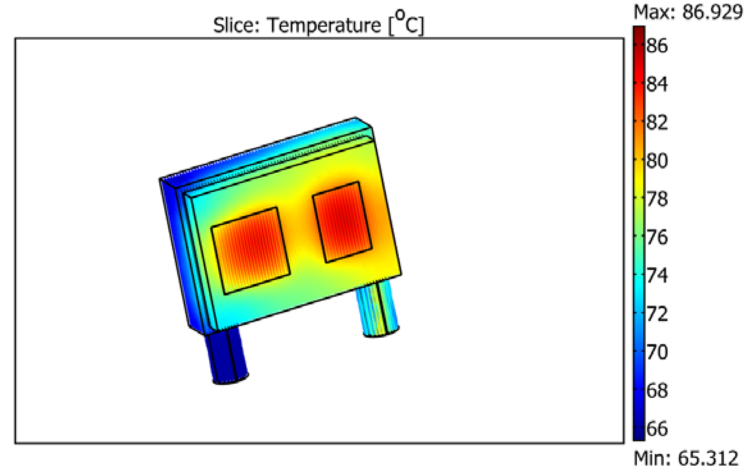


FY11/12 Technical Accomplishments

Develop: Analysis of thermal performance of PBA module

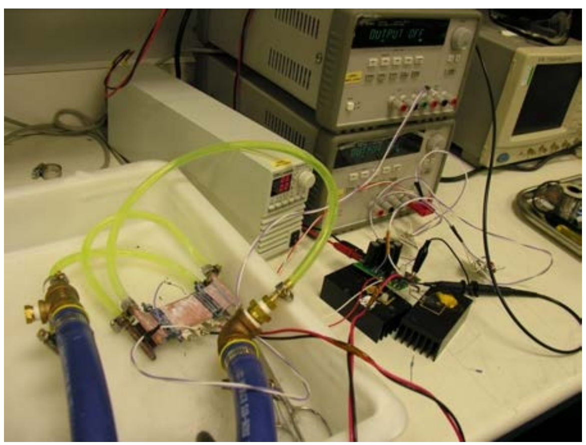


3-D Thermal Model of PBA module with mini-cooler



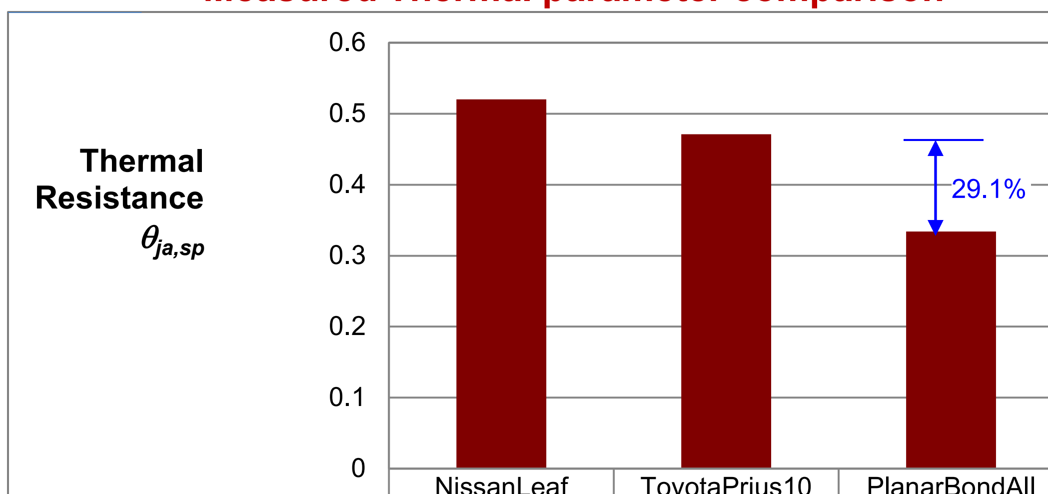
Temperature distribution with cooling

PBA module under thermal test



$$\frac{\$}{kW} \propto \frac{S_{Die\ Area}}{P} = \frac{\eta \bullet \theta_{ja,sp}}{(T_j - T_a)}$$

Measured Thermal parameter comparison

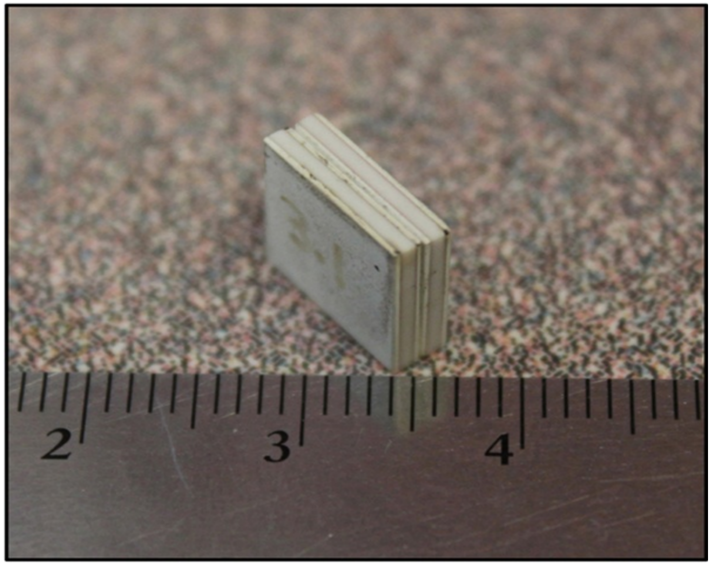


	NissanLeaf	ToyotaPrius10	PlanarBondAll
Specific Thermal resitance (Cm2.C/W)	0.52	0.471	0.334

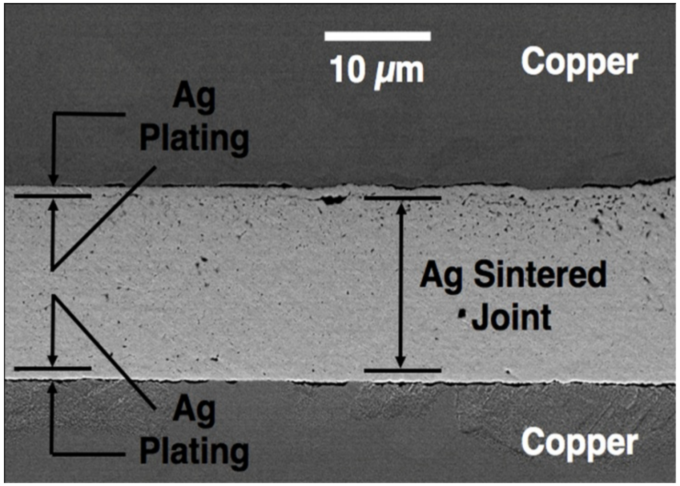
FY12 Technical Accomplishments

Develop: New bonding material and processing

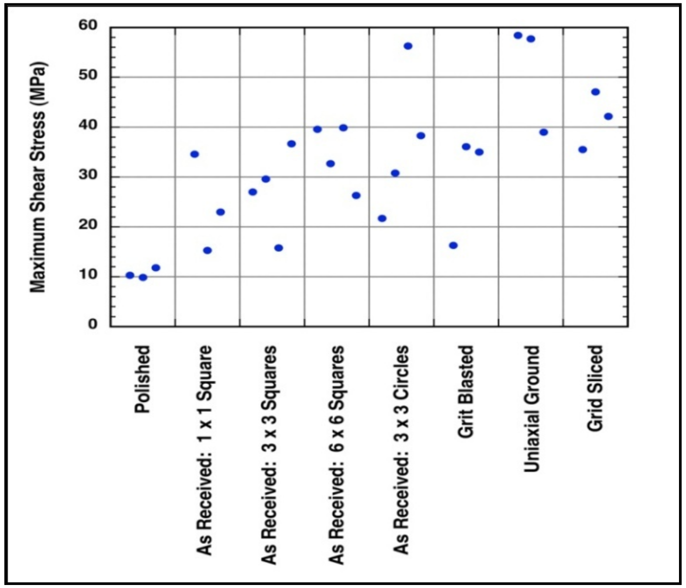
Ag Bonded DBC Substrates



Cross sectional View of Bond Line



Bond Strength vs. Topography



Bond Line View After Tear Down

Collaboration and Coordination

- **NREL**
  - Will use ORNL supplied modules to develop reliability parameters
- **ORNL Materials Science and Technology Division**
  - Leveraged DOE VTP Materials Program
  - Coordinated research to address packaging materials needs
- **University of Tennessee**
  - Assisted in benchmarking commercial packages
- **Virginia Tech University**
  - Collaborated on die attach material and power electronics module packaging

Future Work – FY12

- Complete development of PBA processing portfolio
  – Complete the die top electrode design and fabrication process;
  – Complete the insulation processing for solderable front metal (SFM) power semiconductor switches;
  – Assemble all individual steps into one processing run;
  – Finish the electrical and thermal performance tests.
- Continue to benchmark packaging technologies (performance, materials and processes)
- Continue to support new power electronics module development

Future Work – FY13 and Beyond

- Enhance reliability of PBA concept
  - Perform thermo-mechanical design and simulation of advanced planar bond module packages;
  - Implement cost-effective materials and structures into PBA power modules;
  - Conduct simulations and preliminary reliability tests of packages.
- High temperature module packaging development
  - Incorporate advanced bonding material/processing techniques;
  - Investigate new encapsulate, thermal materials;
  - Evaluate the high temperature effects of power module on cost, efficiency and reliability, including Si, SiC and GaN power semiconductors.
- Continue to benchmark SOA technologies as needed (module performance, materials evaluation and processing)
- Provide packaging support for other projects

Summary

- **Developed PBA power module packaging technologies and fabricated power modules resulting in,**
  - **Decreased package thermal resistance by 30%;**
  - **Decreased package parasitic electrical inductance by 3/4th, and electric resistance by 90%;**
  - **Reduced the major packaging manufacturing steps from five (5) to two (2);**
  - **Achieved more than 30% volume, and weight reduction.**
- **Benchmarked SOA automotive power module**
  - **Nissan LEAF module: electrical, thermal test, insulator sheet analysis;**
  - **Toyota Prius 2010 module: thermal, and microstructure;**
  - **Infineon HybridPack1: thermal, and microstructure;**
  - **Mitsubishi TPM II: semiconductor and package microstructure.**
- **Delivered customer-specific power modules,**
  - **Segmented drive inverter modules (FY12);**
  - **HDITMD inverter modules (FY11);**
  - **High power SiC diode modules (FY12);**
  - **Low inductance wire bond modules (FY11).**