Advanced Packaging Technologies and Designs

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Oak Ridge National Laboratory

U.S. DOE Vehicle Technologies Office
2015 Annual Merit Review and Peer Evaluation Meeting

June 10, 2015

Project ID: EDT049

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Overview

Timeline

- Start – FY15
- End – FY17
- 17% complete

Budget

- Total project funding
  - DOE share – 100%
- Funding received in FY14: $650K
- Funding for FY15: $600K

Barriers

- Existing standard automotive inverter designs with Si and conventional module packaging technologies will likely not meet the DOE EDT 2022 cost, size, and efficiency targets.

Targets Addressed

- 40% cost reduction and 60% power density increase of the power module, to meet the EDT 2022 targets for power electronics.

Partners

Industry: CREE, Remtec, Masterbond, USDRIVE Members, etc.

ORNL Team Members: Curt Ayers, Andy Wereszczak, Steven Campbell, Randy Wiles

NREL: D. DeVoto, P. Paret

UTK: Fred Wang, Fei Yang

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Project Objective and Relevance

- **Overall Objective**
  - Develop advanced packaging technologies, especially for wide bandgap (WBG) power electronics: advancing automotive power modules, and power inverters, in electrical performance, cooling capability, thermo-mechanical performance, and manufacturability, resulting in comprehensive improvements in cost-effectiveness, efficiency, reliability, and power density of electric drive systems.
  - Provide packaging support for other VTO projects for systemic research, utilizing superior attributes of WBG-based power devices in electric drive systems.
- **FY15 Objective**
  - Develop packaging technologies and highly integrated SiC power modules for automotive inverters/converters with lower thermal resistance, small electrical parasitic parameters, and highly efficient manufacturability enabling 30% cost reduction and 40% power density increase.

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Milestones

Date	Milestones and Go/No-Go Decisions	Status
June 2014	Go/No-Go decision: -Determine if all-SiC modules will meet the targets of cost and power density	Simulation results met the proposed targets
Sept 2014	Milestone: -Develop advanced all-SiC phase leg power module rated at 100A/1200V prototypes	Delivered the prototypes and evaluated successfully
March 2015	Milestone: -Design multi-functional integrated SiC converter/inverter modules and packaging technologies.	Completed the module designs
June 2015	Go/No-Go decision: -Determine if developed packaging technologies meet EDT 2022 power electronics targets of cost and power density, then optimize the design and process.	On Track - Prototypes will be fabricated and evaluated

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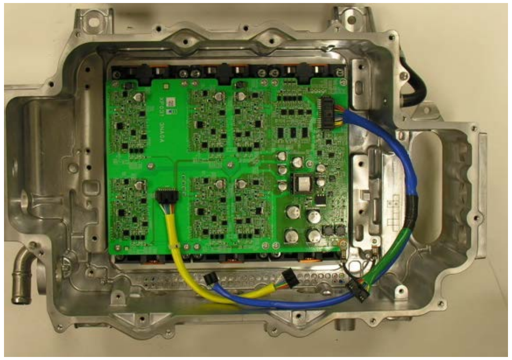
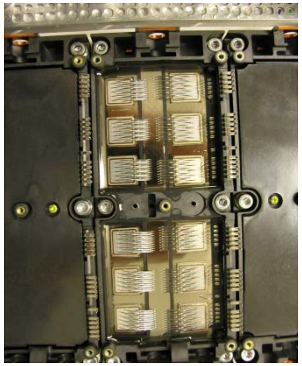
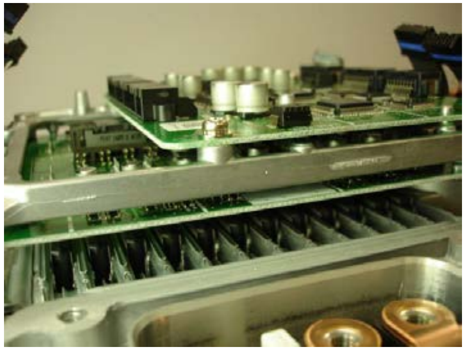
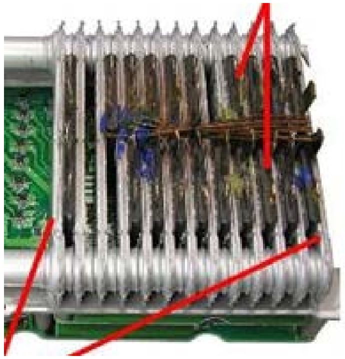
Problem to be Addressed

State of the Art (SOA)

Power Modules in Nissan LEAF Electric Drive Inverter

Power Modules in Toyota Electric Drive Inverters

- Existing standard automotive inverters designs with Si will likely not meet the DOE EDT 2022 cost, efficiency and density targets.
- SOA power module and inverter/converter packaging technologies have limitations in electrical, thermal, and thermo-mechanical performance, as well as manufacturability.

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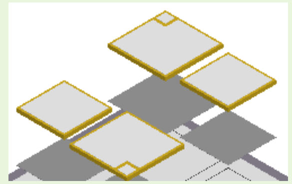
Approach
Strategy to Address Limitations of SOA

- Replace Si devices with their SiC and GaN counterparts to promote their accelerated adoption in power conversion systems

- Develop innovative power packaging techniques to utilize the superior attributes of WBG power semiconductors



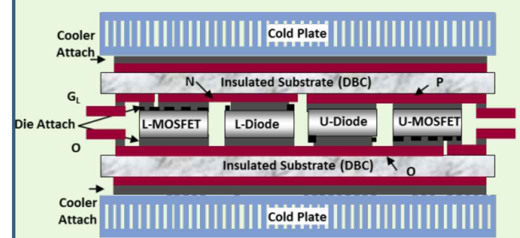
WBG (SiC, GaN) Power Devices

✓ High Current Density and Low Losses

✓ Fast Switching

✓ High Temperature

Integrated Power Module



Cost Reduction

Power Density Increase

Power Efficiency Improvement

Planar-Bond-All (PBA) Packaging

- ❑ Optimized Electrical Interconnection
- ❑ Highly Efficient Heat Transfer
- ❑ Multi-functional Structural Integration
- ❑ Low Cost Manufacturability

Reduce Feature Parameters

- ✓ Pcon, Psw, Plp, Prp: Power losses
- ✓ θ_{ja}: Thermal resistance
- ✓ Lp, Rp, Cp: Parasitic electrical impedance
- ✓ A, Manufacture cost
- ✓ ΔCTE, Thermal expansion Mismatch

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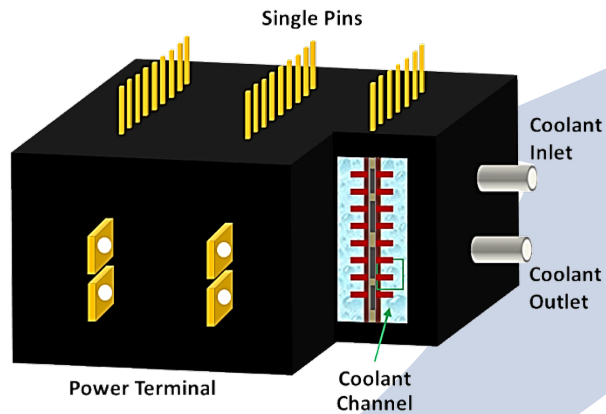
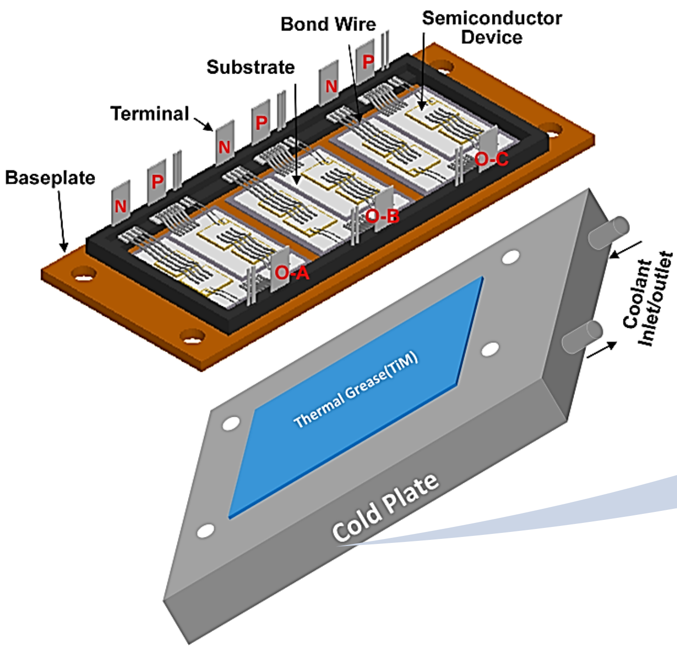
Approach
Strategy to Address Limitations of SOA



- **Cost**
- **Efficiency**
- **Power Density (Weight, Volume)**

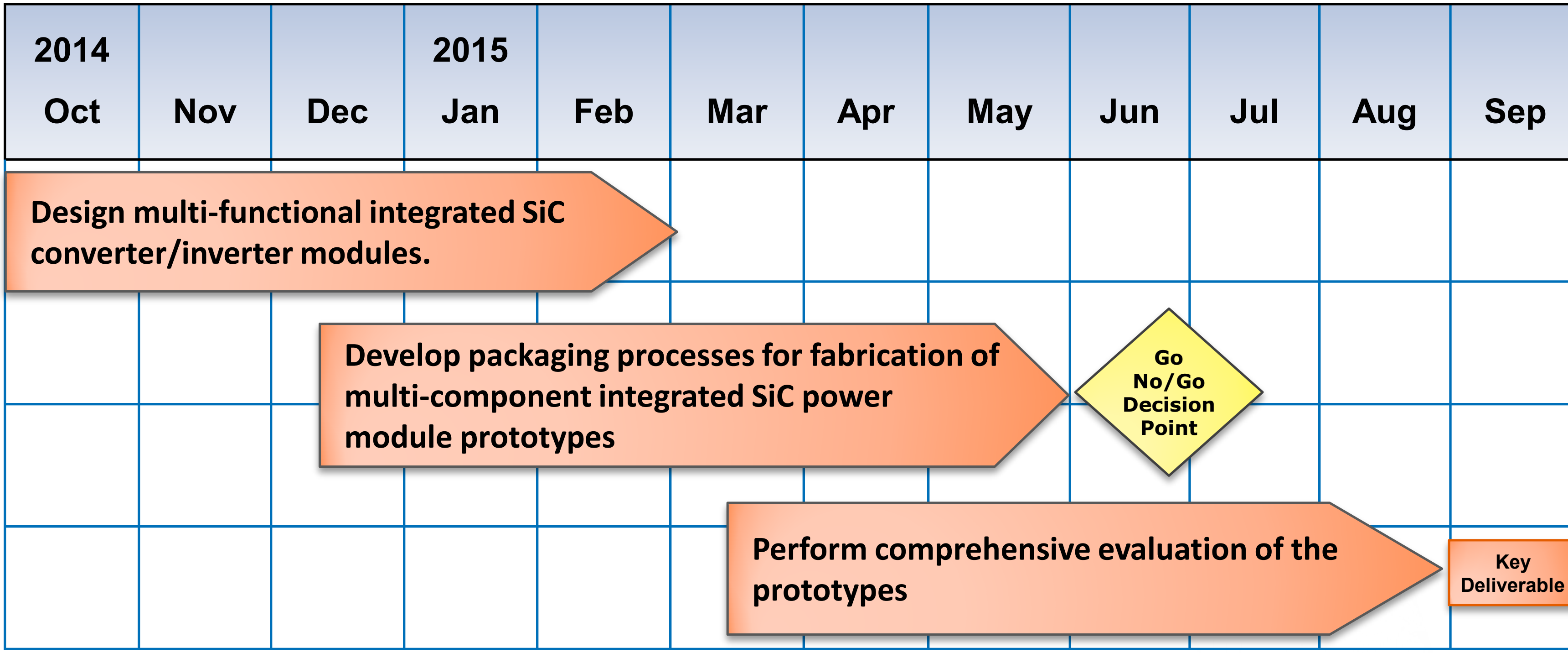


Integrated Packaging

- ❑ Multi-functional Integration
- ❑ Building Block
- ❑ Advanced Manufacturability
- ❑ Superior Performance

Hierarchical Packaging

Approach FY15 Timeline



Go No/Go Decision Point: Determine if developed packaging technologies meet EDT 2022 power electronics targets of cost and power density, then optimize the design and process.

Key Deliverable: Highly functional integrated SiC multi-phase converter module prototypes.

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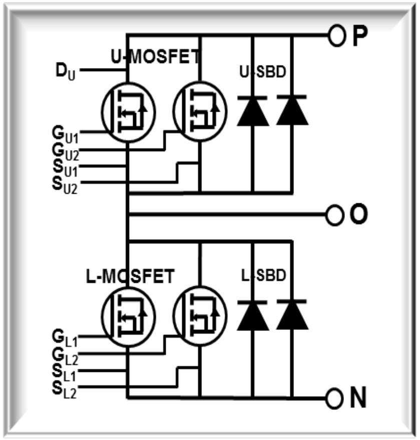
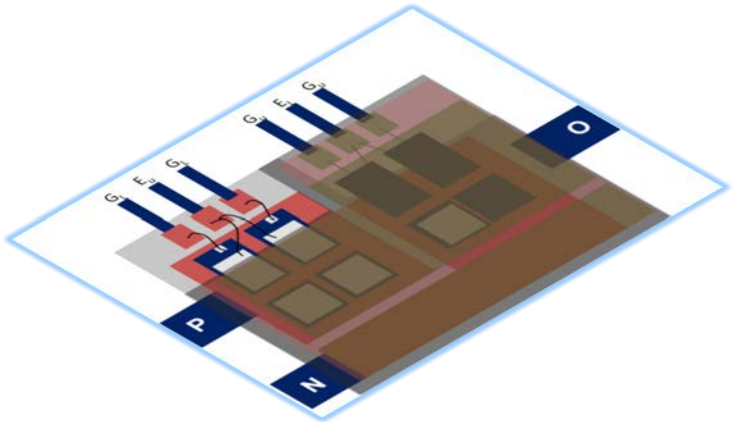
Technical Accomplishments – FY14

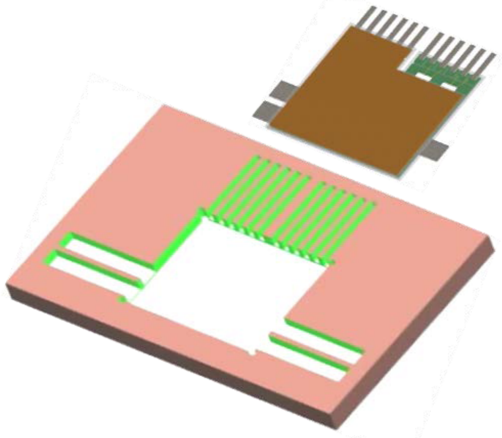
Completed SiC Planar-Bond-All (PBA) Module Packaging Design and Fabrication



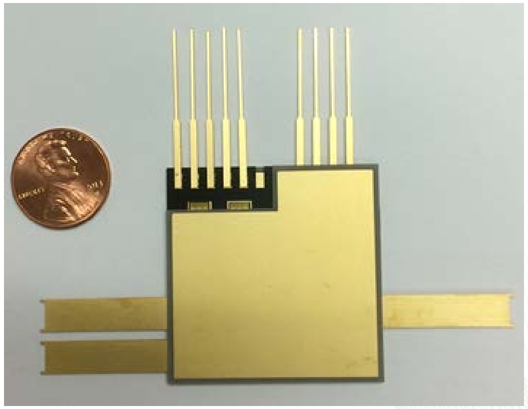
Electrical Diagram of an all-SiC 100A/1200V Phase Leg Module



3-D Power Interconnection in PBA Structure



Schematics of Jig and SiC PBA Package



100A/1200V all-SiC Phase-leg PBA Module

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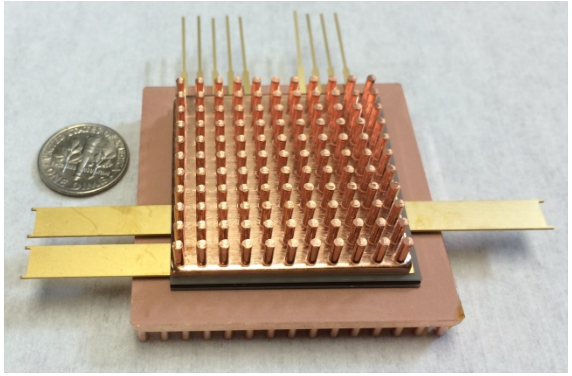
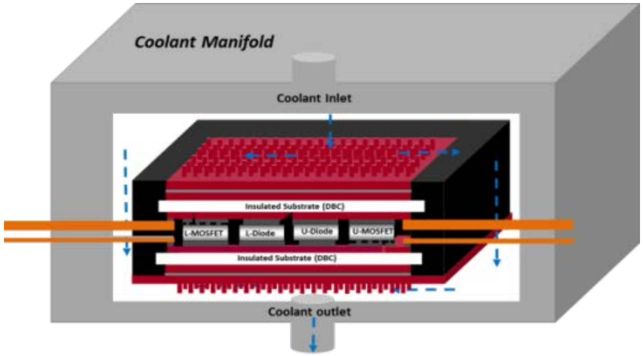
Technical Accomplishments – FY14

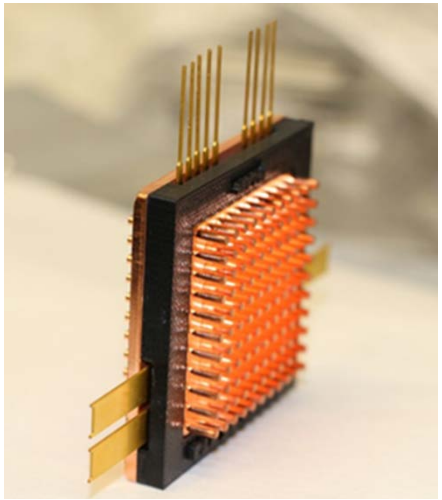
Built Double-Sided Cooling of SiC Planar-Bond-All (PBA) Module



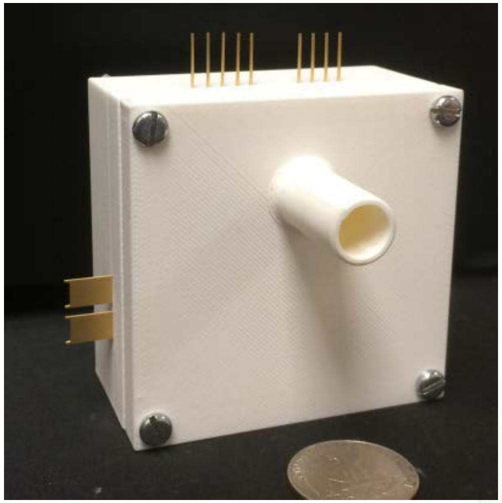
SiC PBA Module with Dual Pin-fin Baseplates



Double sided (Liquid) Cooling Design



Double Sided Air Cooling Assembly



Integrated Double Sided Liquid Cooling Assembly

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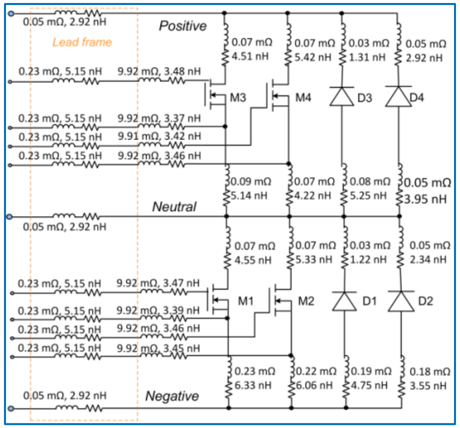
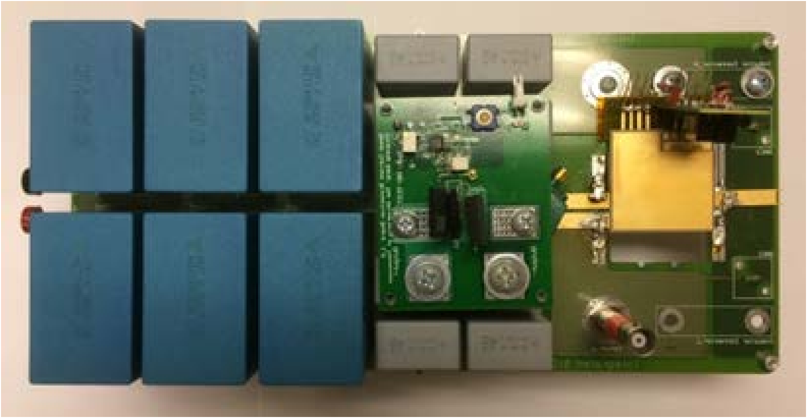
Accomplishments to Date – FY 14/15

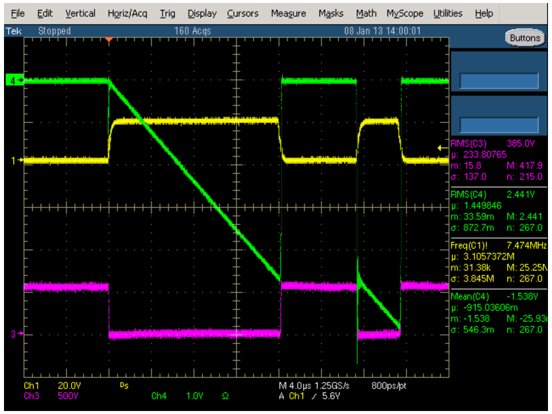
Completed Electrical Characterization of SiC-PBA Module



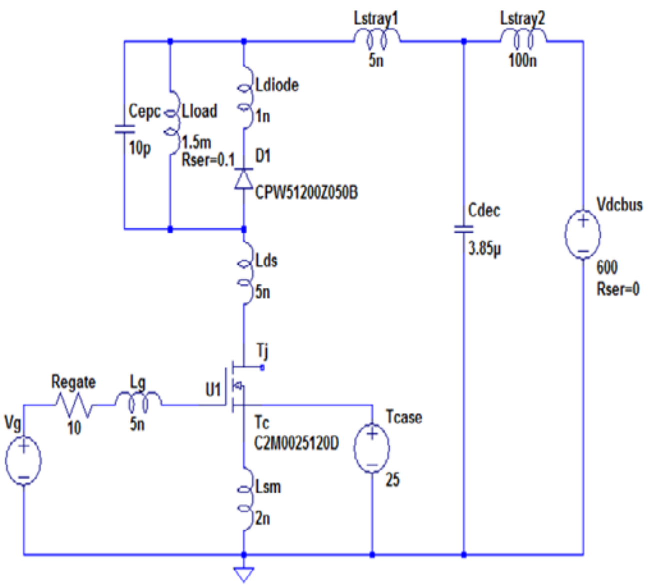
Lumped Parasitic Element Model

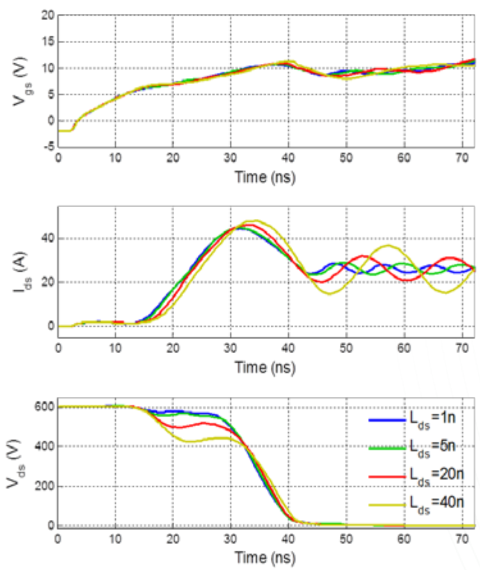


Test Setup for Parameter Characterization

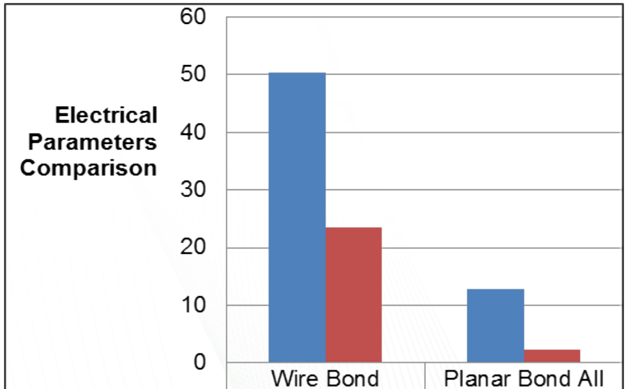


SiC Device Switching Waveforms





Electrical Performance Simulation



	Wire Bond	Planar Bond All
Lp (nH)	50.3	12.8
Rp (0.1xmOhmic)	23.5	2.2

75% reduction of Lp
90% reduction of Rp

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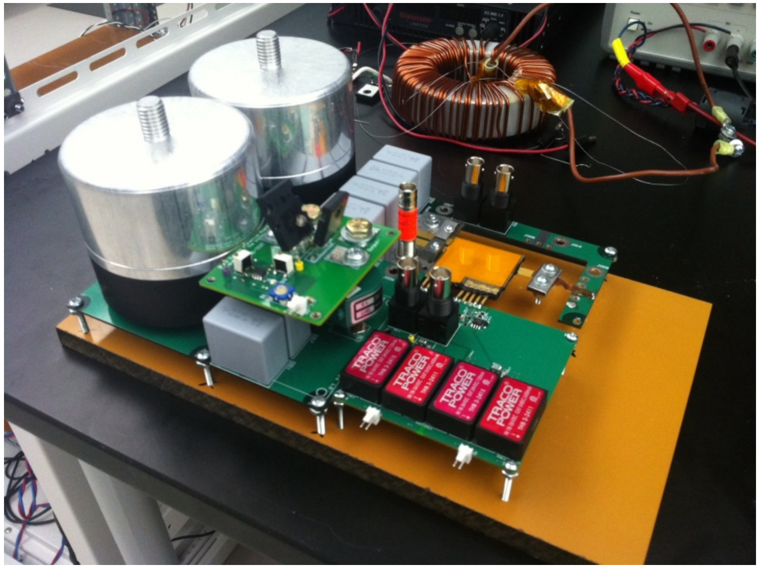
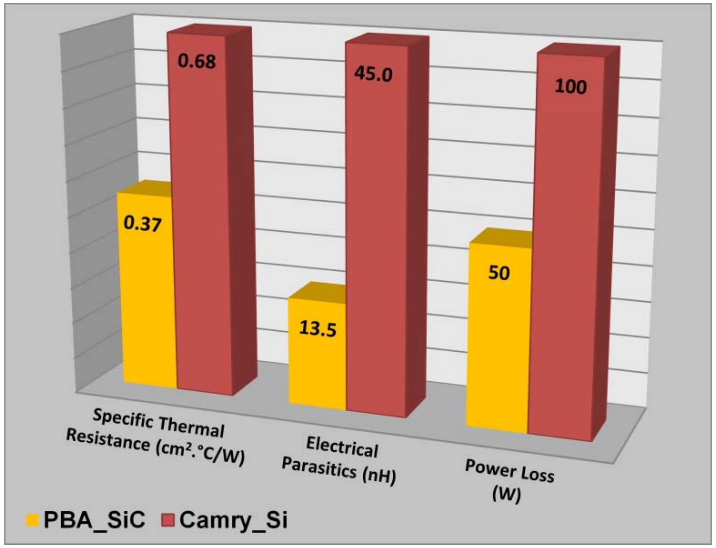
Accomplishments to Date – FY 14/15

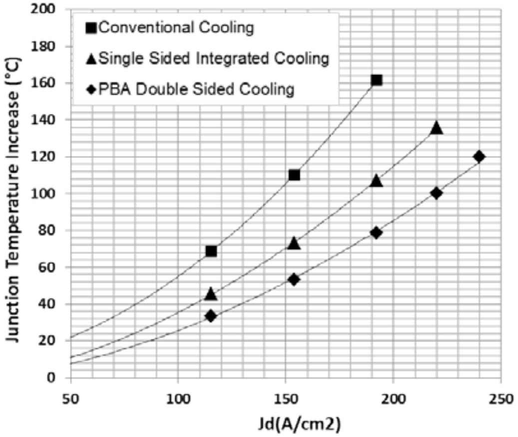
Evaluated Integrated Cooling Effects of SiC-PBA Module in System



Comprehensive Test Setup



Comparison of PBA_SiC vs Camry-Si Module



Junction Temperature vs Current Density with Different Packaging

Current density allowed for different power semiconductor and cooling combinations at ΔT_j=100°C for a typical operation (D=0.5, f=5kHz)			
Item	Wire-bond (1st-gen)	Single Side Integrated Cooling (2nd-Gen)	PBA_double Sided Integrated Cooling (3rd-gen)
Current Density J_d (A/cm^2)	145	184	220

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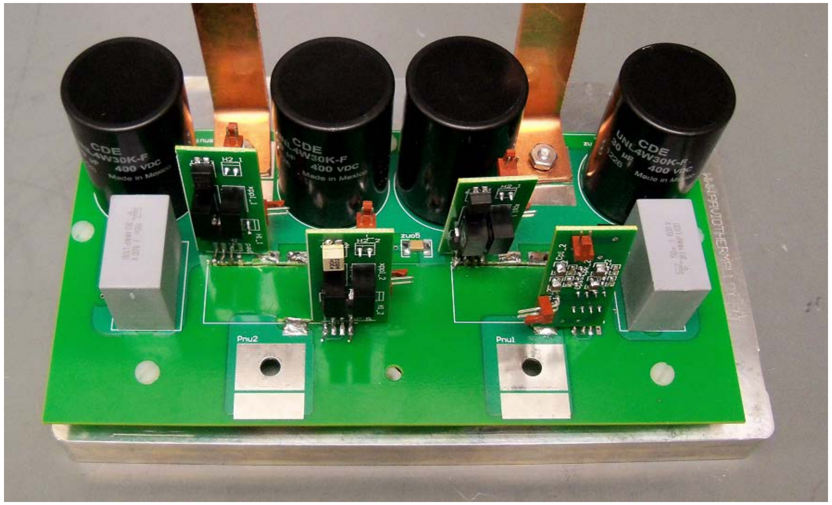
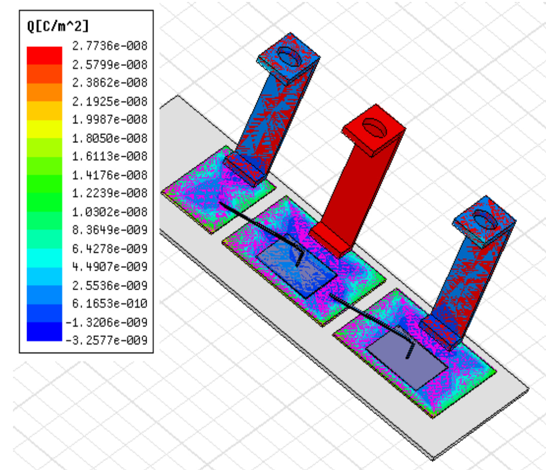
Accomplishments to Date – FY 15

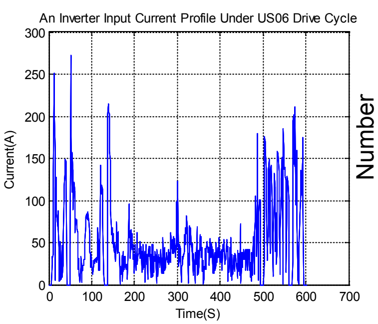
Established Electrical Reliability Test Setup of SiC Power Modules

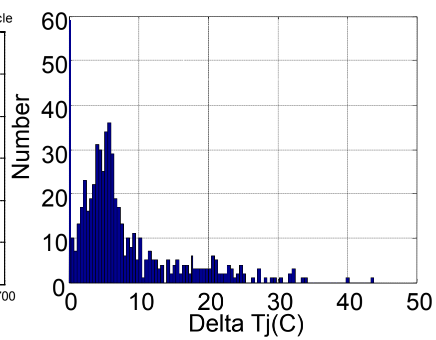


Power Cycling Test Setup

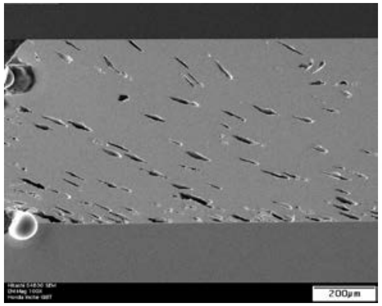


Simulation of Current Density Distribution in Module

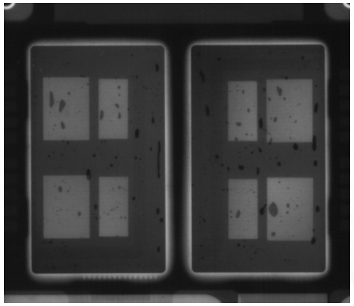




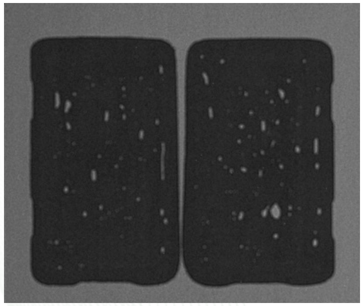
Current Profile and Temperature Variation



SEM



X-Ray



SAM

Microstructural Analysis of Power Module Packages

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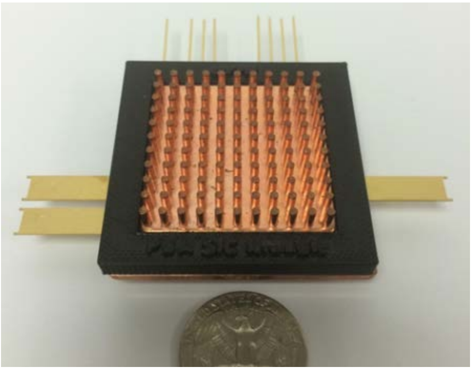
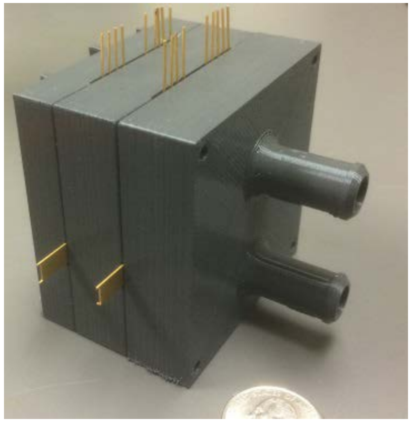
Technical Accomplishments – FY15

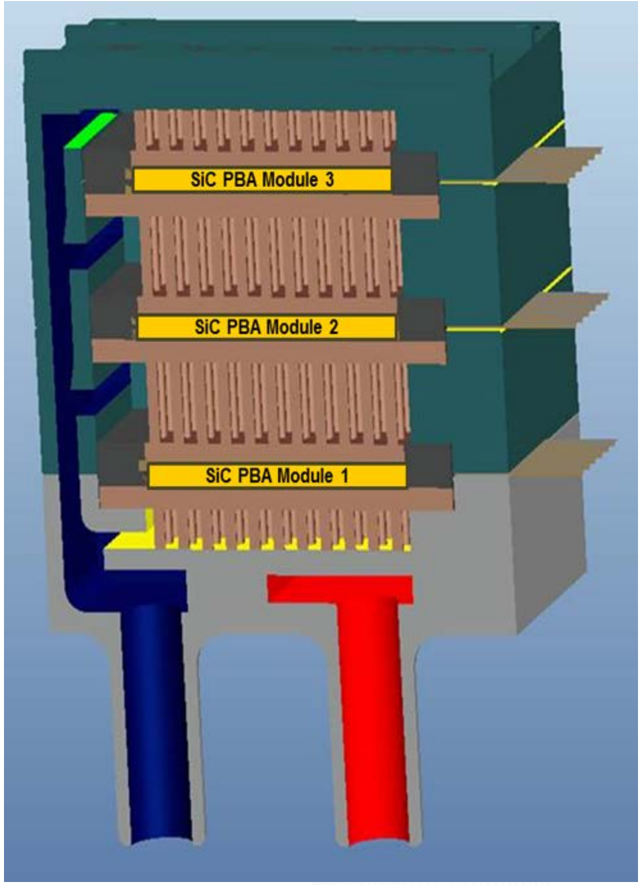
Completed Design and Built Prototypes of Integrated SiC Modules



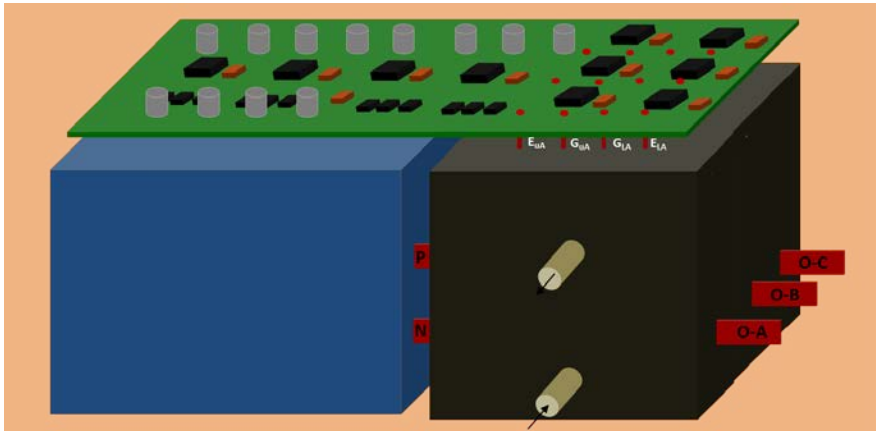
SiC PBA (1-Phase) Module



Integrated Module (2-phase) with 3-D Printed Coolant Manifold



Cross-sectional View of Integrated Module (3-Phase) Design



Proposed Integrated Inverter (3-Phase) Design

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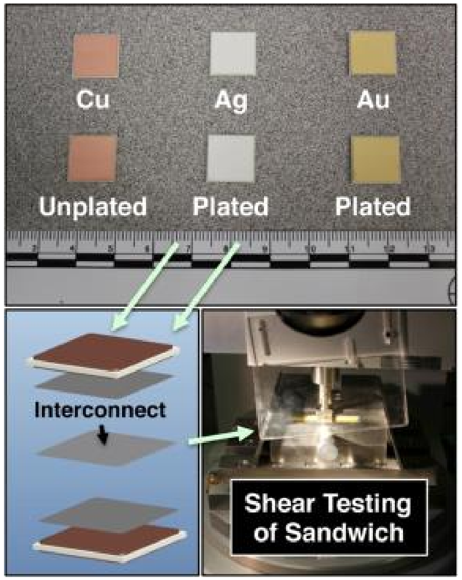
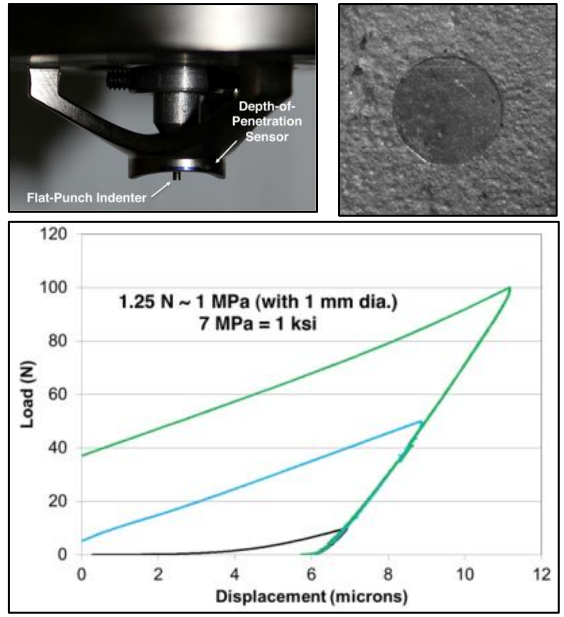
Technical Accomplishments – FY14/15

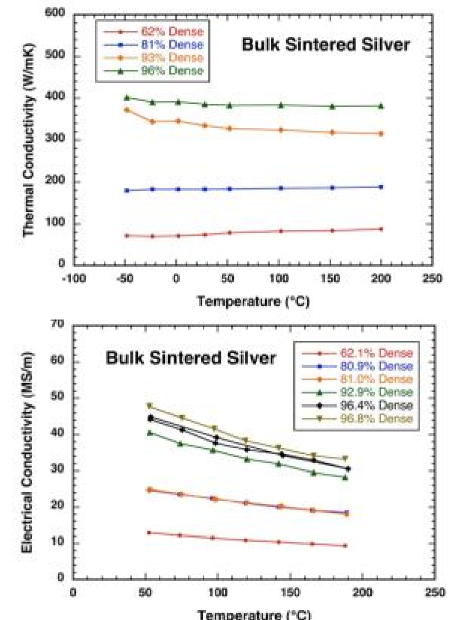
Developed Ag Sintering Technologies



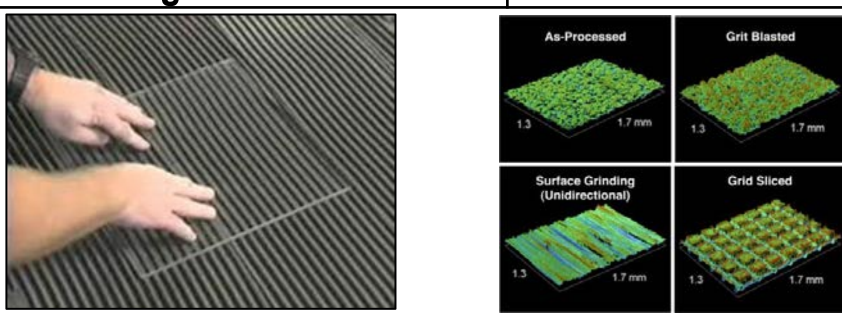
Shear Strength vs Finishing Metallization



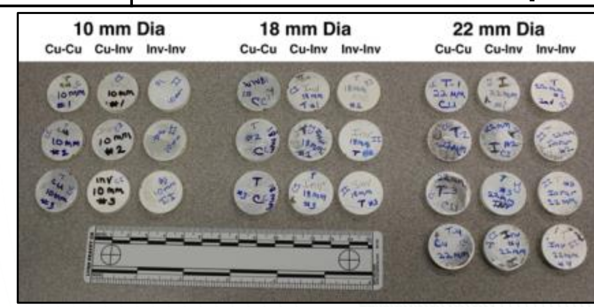
Effects of Process Pressure



Effects of Process Temperature



Effects of Paste Patterning



Effects of Bonding Area and CTE Mismatch

*A. A. Wereszczak et al, "Enabling Materials for High Temperature Power Electronics," pm054_wereszczak_2015_o, DOE AMR (VTO) 2015

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Responses to Previous Year Reviewers' Comments

Reviewer comment: Unclear how this work contributed to the larger system-level goals.

Response/Action: Developed integrated high power density modules will reduce the system size and weight while reducing the cost and increasing efficiency.

Reviewer comment: Insufficient to perform reliability analysis.

Response/Action: Extensive efforts have been made to evaluate and to enhance the electrical reliability of the new power modules, including development of new bonding materials and device/packaging electrical roughness testing through power cycling.

Reviewer comment: Missing active participation with the eventual users of this technology.

Response/Action: Discussions with OEMs and other suppliers resulted in the citation of the this technology in a published report by the Power Sources Manufacturers Association (PSMA)*.

* "Current Development in 3D Packaging With Focus on Embedded Substrate Technologies," *Technology Report*, PSMA, pp.148-150, March 16, 2015. (http://www.psma.com/basiccontentitems/psma-publishes-technology-report-%E2%80%9Ccurrent-development-3d-packaging-focus-embedded).

Partners/Collaborators

Logo	Organization	Role
	CREE	Source of the specialized SiC MOSFET and diode dies
	REMTEC	Source of manufactured packaging components
	Cool Innovations	Source of manufactured cooling components
	Master Bond	Source of manufactured encapsulate materials
	NREL	Packaging thermal characterization/ reliability characterization

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Remaining Challenges and Barriers

In addition to high current (power) density, the high temperature operation attribute of the WBG semiconductors is highly desired for reducing the cost of power electronics in electric drive systems. The challenges are:

- High temperature operation requires much higher reliability for all components/subsystems, especially in harsh environments for a long life.
- High reliability packaging materials and processing are usually costly.
- The interaction (related to reliability) between the WBG semiconductor devices and packaging materials is unknown, specially in high current density and high temperature operation.

Proposed Future Work

- **Remainder of FY15**
  - Perform comprehensive evaluation of the integrated SiC modules in a converter to identify the system performance: efficiency, density and cost, etc.
  - Perform electrical reliability test (majorly power cycling) and analysis of PBA packages and identify the technical strategies for further improvement.

- **FY16**
  - Develop high temperature (HT) SiC power module packaging technologies: materials, processes, and characterization.
  - Prototype high temperature phase leg SiC power modules.

- **FY17**
  - Develop packaging technologies for integration of HT SiC power inverter and electric motor.
  - Prototype integral SiC power inverters for integrated electric drive system.

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Summary

- **Relevance:** Focused on achieving 40% cost reduction and 60% power density increase to facilitate DOE APEEM 2022 power electronics targets: $3.3/kW, 14.1kW/kg, 13.4kW/L.
- **Approach:** The highly integrated WBG packaging technology being developed is to leapfrog barriers of existing industrial baseline and bring innovative, systemic development to advance technologies.
- **Collaborations:** Latest industrial products and advanced research have been incorporated in the project.
- **Technical Accomplishments:**
  - An innovative planar-bond-all (PBA) SiC module has been delivered for system evaluation; SiC power devices compared to Si ones: 55% die size, 60% conduction power loss, 20% switching power loss.
  - New packaging (relative to industrial SOA) achieves 45% thermal resistance reduction, 75% electric inductance decrease, 80% electric resistance reduction.
  - Packaging technologies developed for integration of cooling and electrical subsystems into one block lead to 40% overall volume and weight reduction and 30% cost reduction.
- **Future Work:** Continue to optimize the technologies and work together with industry to transfer them to manufacturers.