Advanced Packaging Technologies and Designs

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Oak Ridge National Laboratory

2016 U.S. DOE Vehicle Technologies Office Review

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Overview

Timeline

- Start – FY15
- End – FY17
- 58% complete

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.

Budget

- Total project funding
  - DOE share – 100%
- Funding received in FY15: $ 600K
- Funding for FY16: $ 600K

Partners

- **Industry:** CREE, ROHM, Remtec, USCAR Electrical and Electronics Tech Team
- **NREL:** D. DeVoto, P. Paret
- **UTK:** Fred Wang, Fei Yang
- **ORNL team members:**

  Madhu Chinthavali, Andy Wereszczak, Steven Campbell, Randy Wiles, Larry Seiber

Project Objective and Relevance

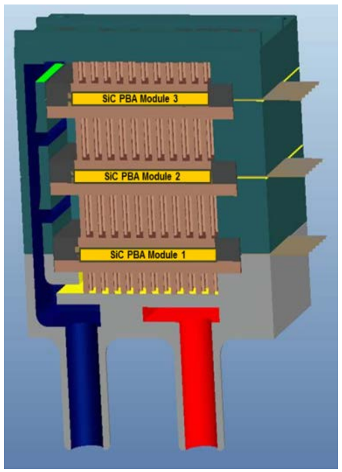
- **Overall Objective**
  - The objective of this project is to address the challenges and barriers in the use of wide bandgap (WBG) technologies for automotive electric drive. This research will develop advanced WBG automotive power modules in inverters/converters through packaging innovation by replacing silicon (Si) devices with their silicon carbide (SiC) counterparts to promote their accelerated adoption in traction drive systems and development of novel power module packaging to achieve the superior attributes of WBG power semiconductors. These comprehensive advances can directly affect the cost, efficiency, reliability and density of the power electronics systems in electric drives of EVs.
- **FY16 Objective**
  - Develop optimized designs and packaging technologies for advancing SiC power modules used in the automotive inverters/converters with higher power conversion efficiency and higher temperature operation reliability enabling 40% cost reduction and 60% power density increase.

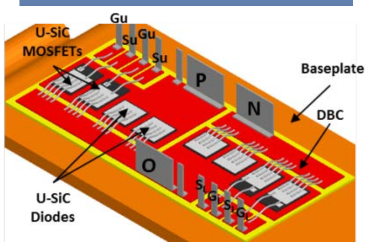
Milestones

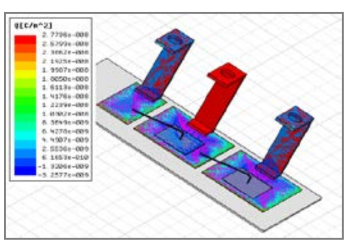
Date	Milestones and Go/No-Go Decisions	Status
Sept 2015	Milestone: Develop advanced all-SiC phase leg power module rated at 100A/1200V prototypes	Completed: Delivered modules and evaluated successfully
Dec 2015	Go/No-Go decision: Confirm design of a 10 kW, 3D printed module that will improve the power density and specific power for inverters and converters	Go: Simulation results met the proposed targets
March 2016	Milestone: Design and build planar modules that will undergo thermal evaluation by NREL	Completed: Delivered module prototypes to NREL
June 2016	Milestone: Develop high temperature die attach process for WBG device-based applications to improve the reliability of the high temperature packages	On Track: Prototypes are fabricated and evaluation is underway
Sept 2016	Milestone: Complete electrical reliability analysis of a commercially power module to identify the issues related to packaging	On Track: Completed the design and the setup is under construction

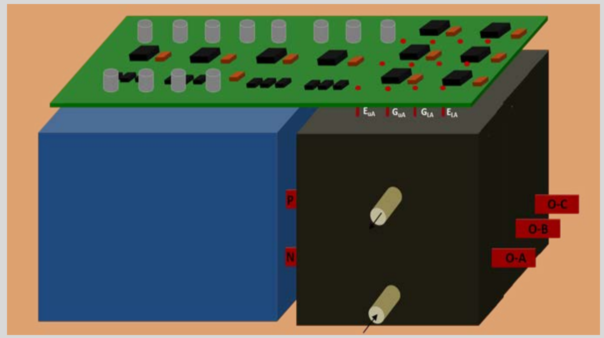
Approach/Strategy Comprehensive Methodology

Modeling







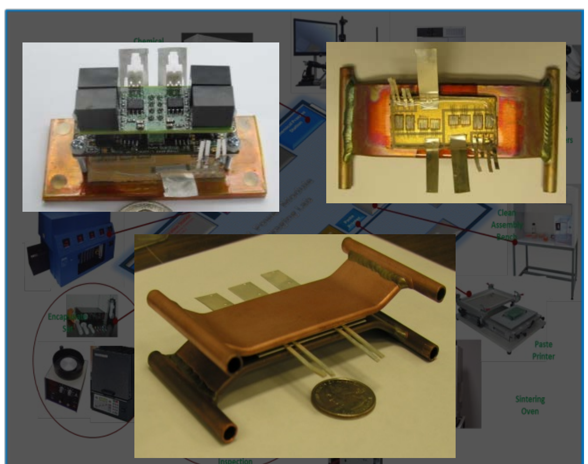


Integrated Power Electronics

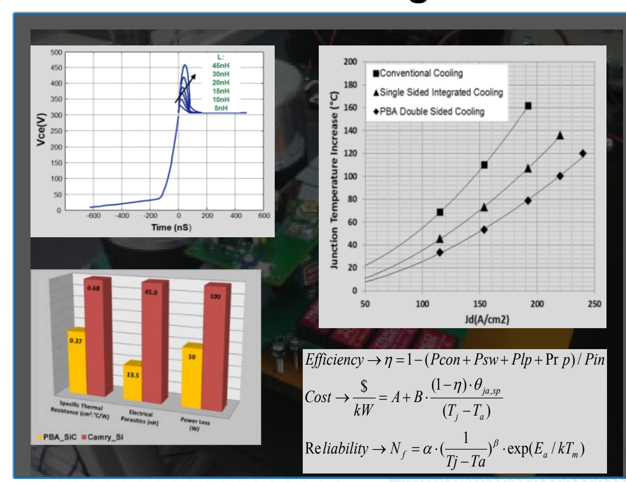
Advanced Packaging Solutions

- ✓ Designs for Optimal Packaging Structure
- ✓ Data for Reliable Materials and Combinations
- ✓ Techniques for Novel Processing

Prototyping



Evaluating



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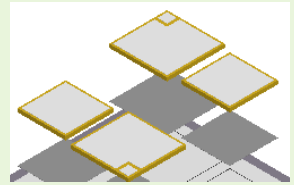
Approach/Strategy Focus on WBG Power Devices

- 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



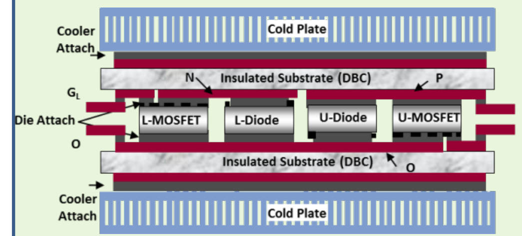
WBG (SiC, GaN) Power Devices

✓ High Current Density and Low Losses

✓ Fast Switching

✓ High Temperature

Integrated WBG Power Module



Cost Reduction
Power Density Increase
Power Efficiency Improvement

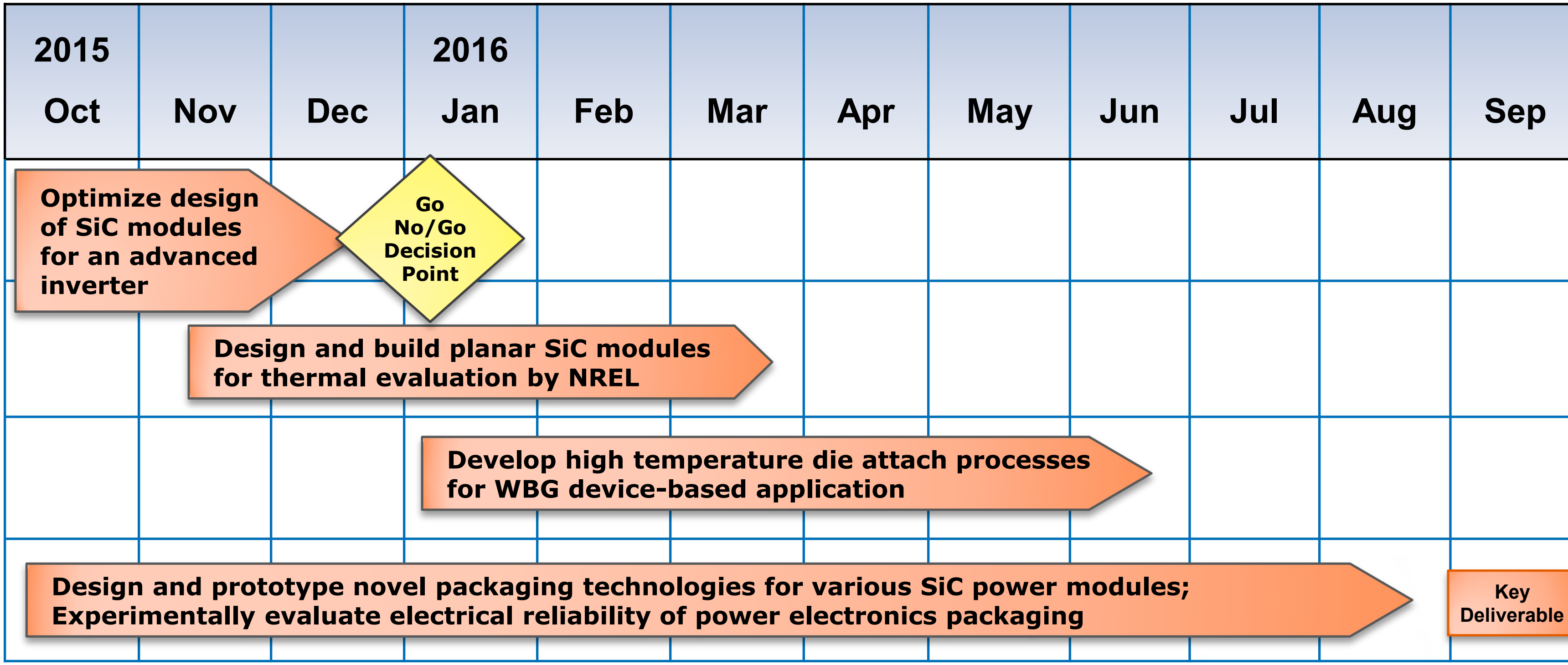
Planar-Bond-All (PBA) Packaging

❑ 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

Approach FY16 Timeline

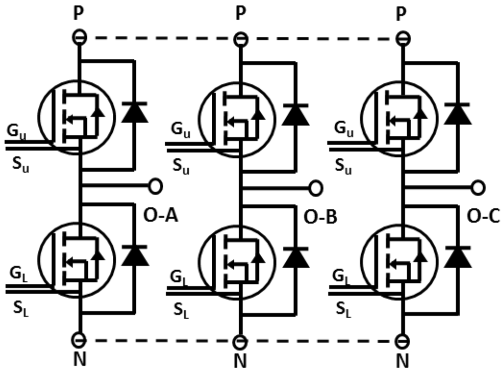


Go No/Go Decision Point: If simulation results show that the developed module-based inverter will meet EDT 2022 power electronics targets, then the power module will be built.

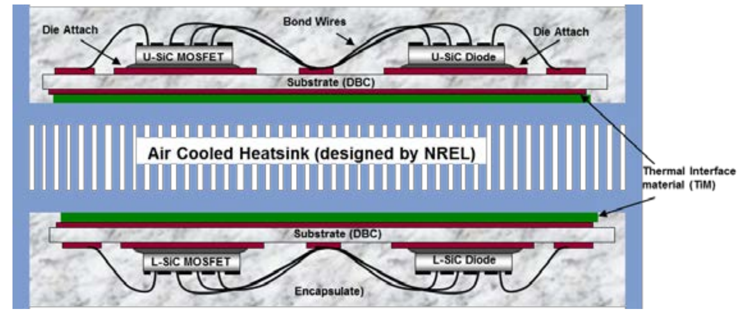
Key Deliverable: Highly reliable integrated SiC module prototypes.

Technical Accomplishments - FY15

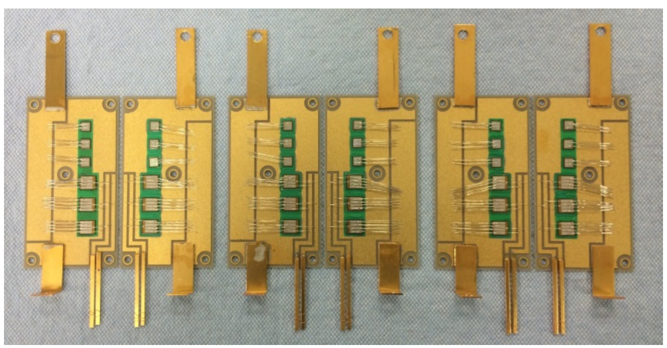
Air-cooled SiC Inverter Module Packaging



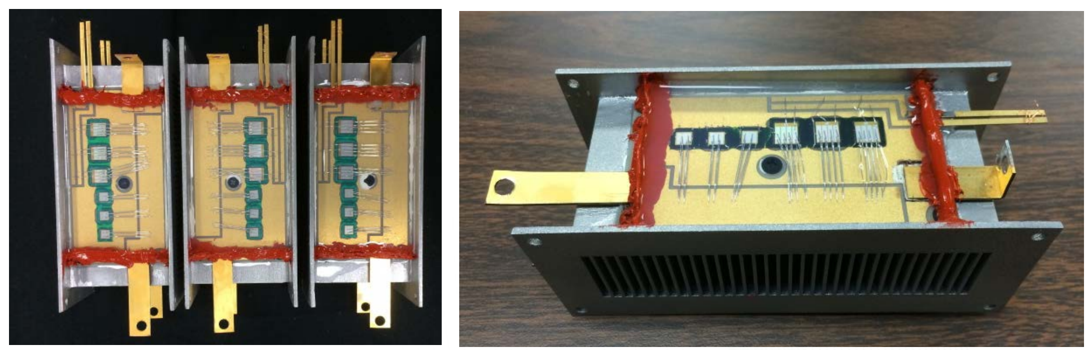
Electrical Diagram of an all-SiC 300A/1200V (each phase) Module



Schematics of Integrated Packaging Design (3-D printed heatsink, designed by NREL)



Packaged SiC Power Device Units



300A/1200V all-SiC Phase-leg Module

Developed specific packaging processes and prototyped 300A/1200V all-SiC Phase-leg modules, which have been successfully used in the air-cooled inverter (EDT053).

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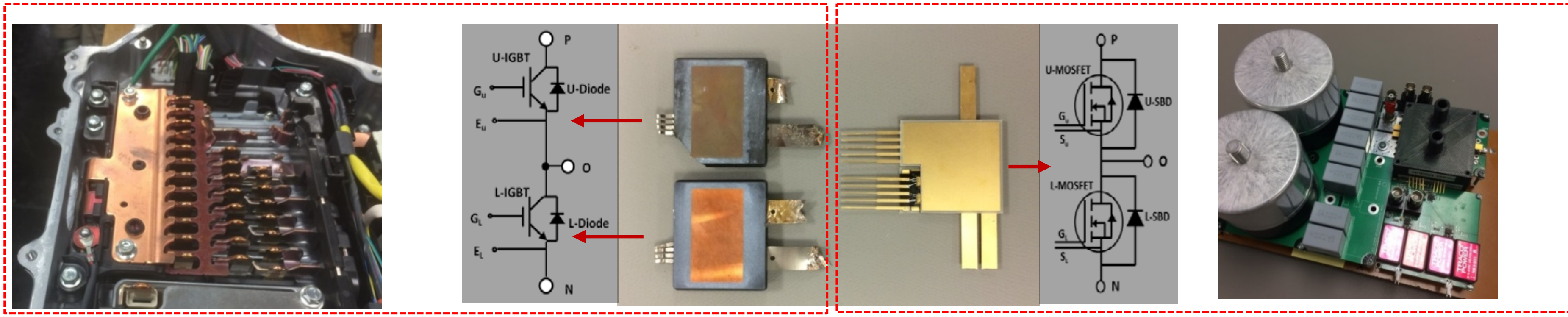
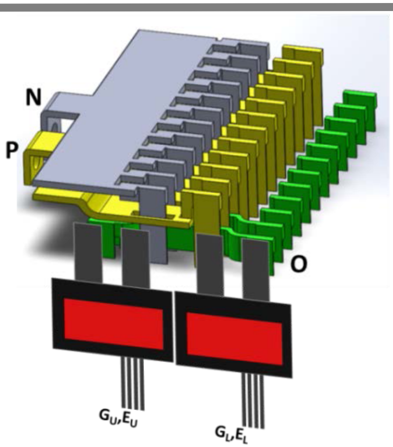
Technical Accomplishments – FY16

Inverter's Parasitic Inductance Analysis

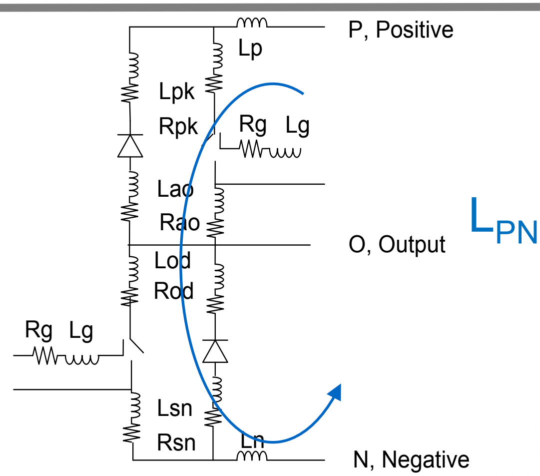


Packaging Comparison: Camry Si Module (left) vs ORNL SiC PBA Module (right) in Inverter

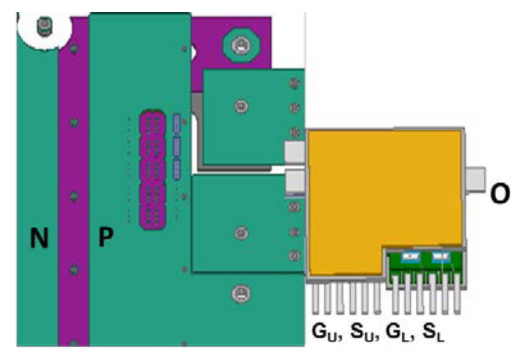


2013 Camry Inverter Module

L_{PN}=63nH (Simulated)



L_{PN}: Inverter's Feature Parasitic Inductance Feature



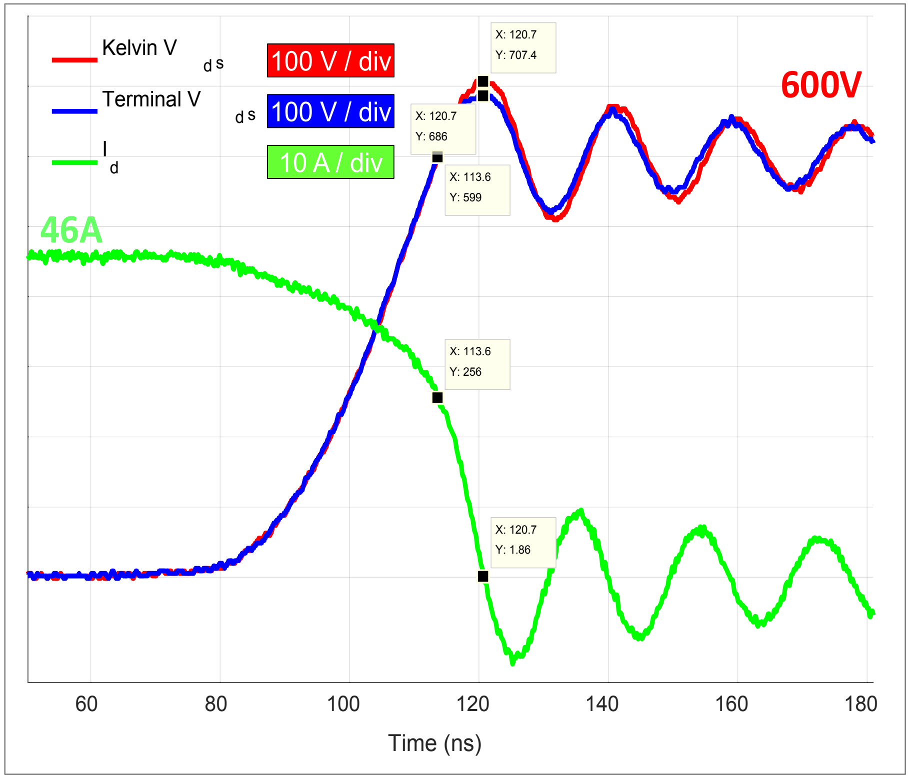
ORNL SiC PBA Module

L_{PN}=23nH (Simulated)

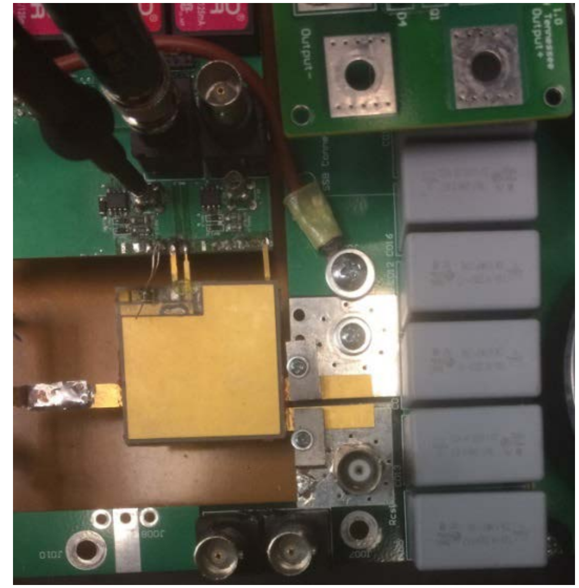
PBA SiC module-based inverter offers 60% reduction of parasitic inductance through shorter connection and integrated cooling loop.

Accomplishments to Date - FY16

Experimentally Analyzing SiC PBA Module Parasitic Inductance



Electrical Waveforms of SiC MOSFET during turn-off Transition



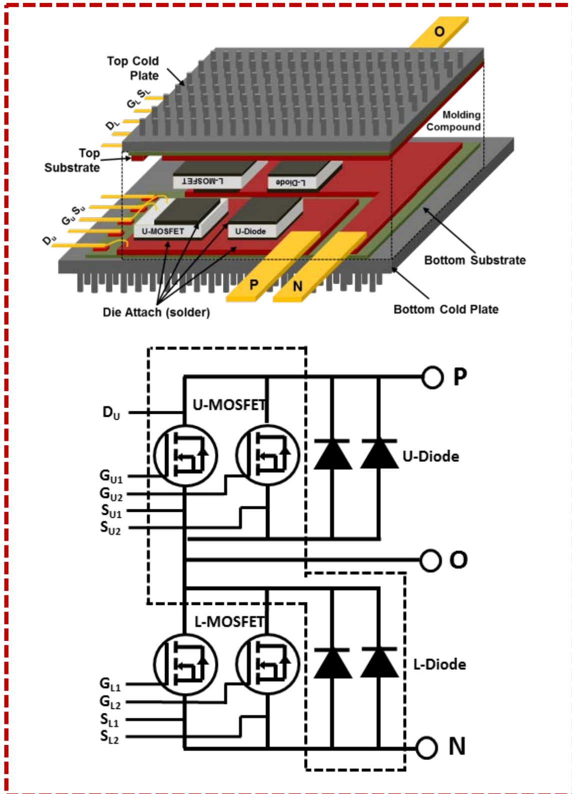
Measured PBA Module-Based Inverter Parasitic Inductance

Inductance (nH)	L_{PN}	Lp+Ln	$L_{internal}$
	30.17	24.03	6.14

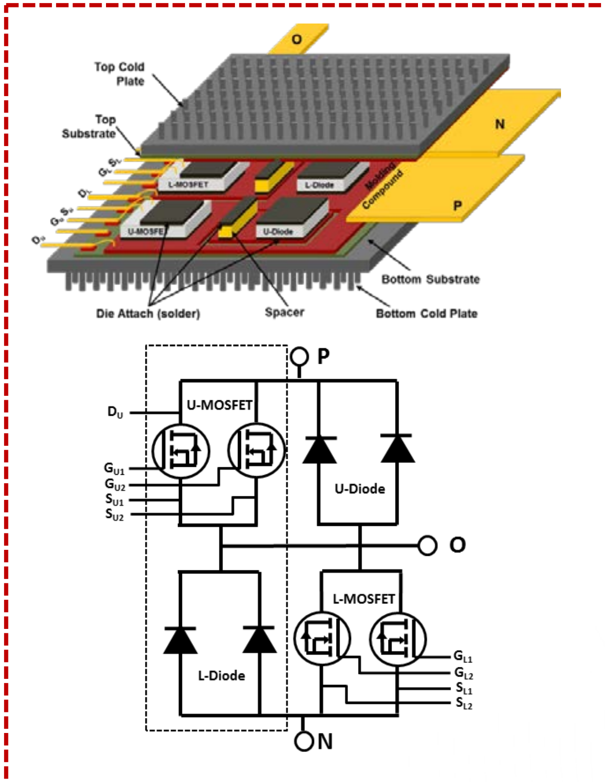
The stray inductance associated with power terminals and connectors to the capacitor bank makes up most of the inverter's parasitic inductance. PBA SiC module's internal parasitic inductance is lower.

Technical Accomplishments - FY16

Optimizing PBA SiC Power Module Package



Baseline PBA Module Package



Laminated PBA Module Package

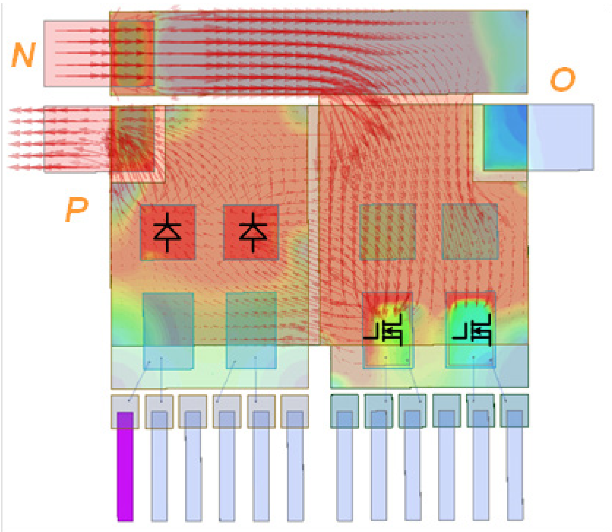
Features

- ✓ Switches and diodes are connected in switching cells
- ✓ Folded current loop results in cancellation of internal parasitic inductance
- ✓ Laminated power terminals (P, N)
- ✓ Integrated decoupling Cap assembly

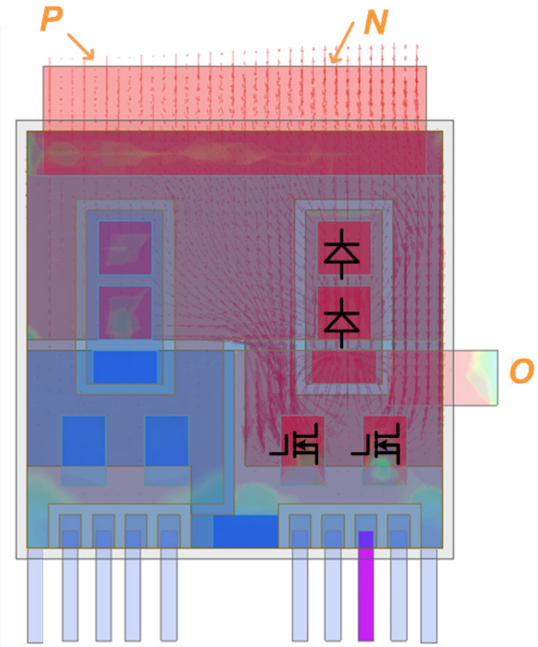
New design reduces significantly the inverter's feature parasitic parameters through completely laminated power paths and integration to the laminated busbar.

Technical Accomplishments - FY16

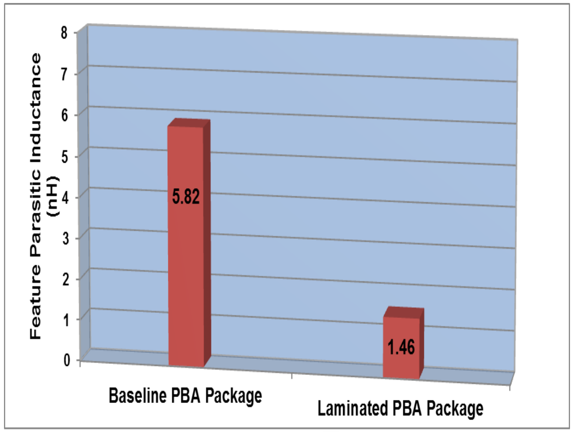
Electromagnetic Analysis of New PBA SiC Power Module Design



Current Distribution in Baseline PBA SiC Module during Lower MOSFET Turn-off



Current Distribution in Laminated PBA SiC Module during Lower MOSFET Turn-off

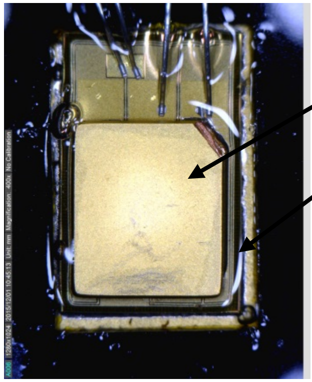


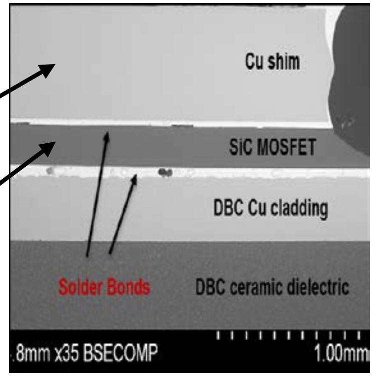
Comparison of Parasitic Inductance in Modules

The internal parasitic inductance of new design is reduced by 75%, through rearrangement of SiC dies and terminals.

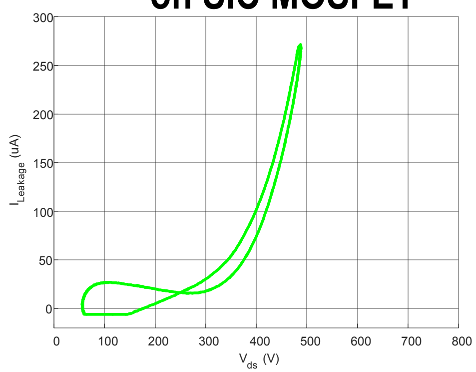
Technical Accomplishments - FY16

High Temperature PBA SiC Power Module Packaging

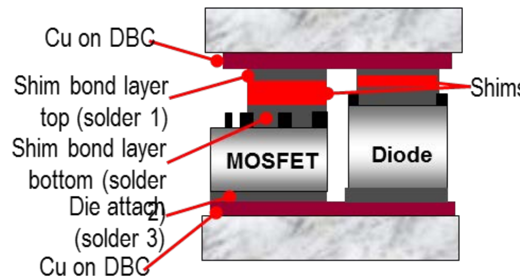


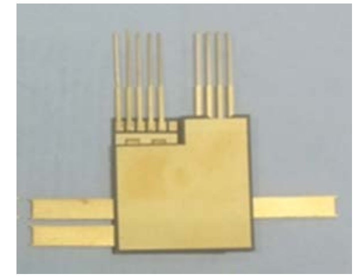


AuSn (280°C) Solder Bonded Copper Shim on SiC MOSFET

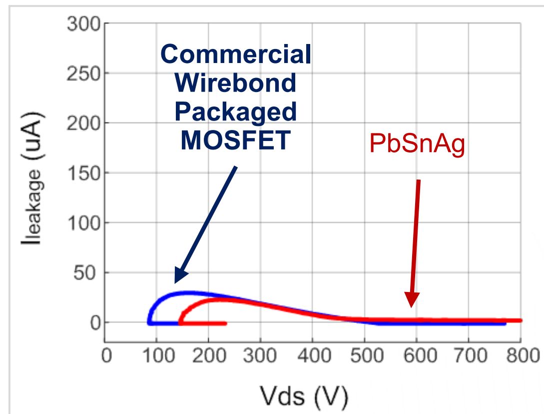


Large Leakage Current Induced in the MOSFET

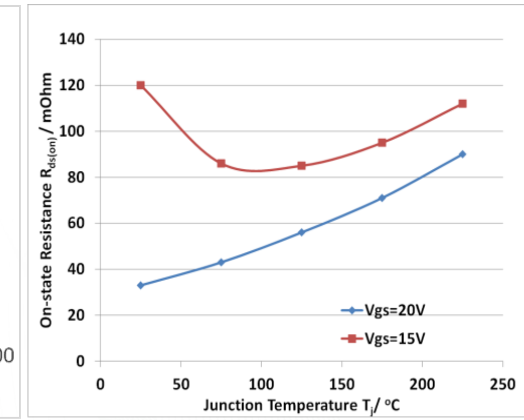




Pb92.5Sn5Ag2.5 (287-296°C) Solder Bonded Module



No Change in Leakage Current of the MOSFET



Operated up to 225°C

The combination of the substrate/shim/solder/SiC is critical in PBA package. The leakage current increase in copper shim/hard solder/SiC needs further investigation.

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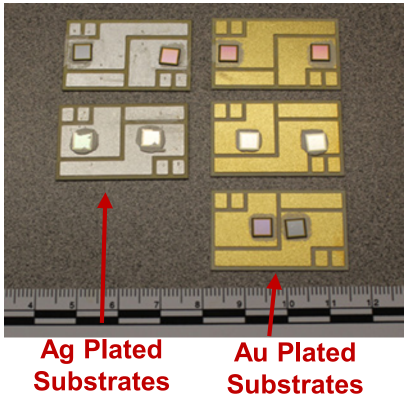
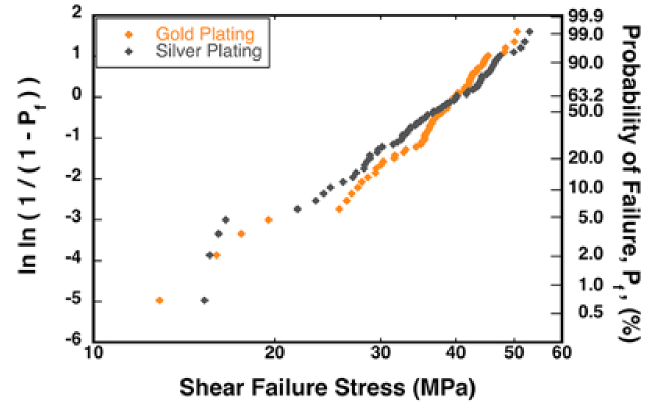
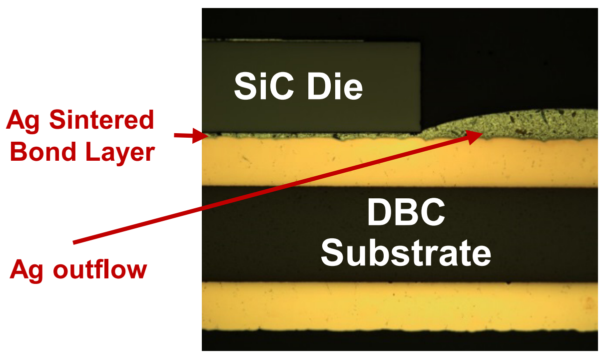
Technical Accomplishments - FY16

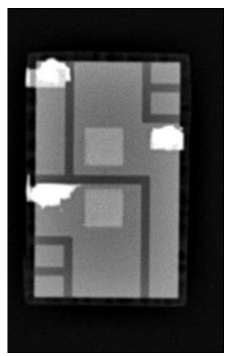
Implementing Ag Sintering Technology in SiC Module Packaging





Shear Strength vs Finishing Metallization on Substrate (A. A. Wereszczak, pm054_wereszczak_2016_o, DOE AMR (VTO) 2016)





SEM image of Cross Sectional View (left)
X-Ray Image of Top View (right)

Ag Sintered SiC Power Modules

Ag metallization on the substrate and/or on the SiC die is slightly better than the Au plating; the outflow of the Ag paste during press needs to be confined.

Responses to Previous Year Reviewers' Comments

Reviewer comment: Unclear how this work contributed to the cost reduction.

Response/Action: Developed technical cost models, with partner to identify how the improvements of the technical metrics affect the system cost of the WBG inverter.

Reviewer comment: Insufficient to perform reliability analysis.

Response/Action: Extensive efforts have been made to improve the reliability by optimizing planar structure, studying Ag sintering technology and working with NREL for thermal reliability and performing comprehensive electrical reliability tests.

Reviewer comment: Adding OEM/Tier 1, or/and 2 suppliers to the team.

Response/Action: Collaborations with OEMs through USCAR EETT on establishment of project objectives, tasks and standards. Shared the benchmarking information of the technologies in state-of-the-art products with industry.

Collaboration and Coordination with Other Institutions

Logo	Company	Role of company
	CREE	Source of the specialized SiC MOSFET and diode dies
	ROHM	Source of the specialized SiC MOSFET and diode dies
	REMTEC	Source of designed packaging components
	USCAR Electrical and Electronics Tech Team	Standard establishment, collaboration in technical development
	NREL	Packaging thermal characterization/ thermo-mechanical characterization
	University of Tennessee	Packaging electrical simulation/characterization

Remaining Challenges and Barriers

In addition to high current (power) density, high frequency, 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 FY16**
  - Analyze reliability of the Ag sintering technology in SiC power packaging.
  - Perform electrical reliability test (majorly power cycling) and analysis of packages and identify the technical strategies for further improvement.
  - Prototype the integrated SiC modules in a converter to identify the system performance: efficiency, density and cost, etc.
- **FY17**
  - Develop high temperature SiC power module packaging technologies: materials selection, processes optimization, and characterization implementation.
  - Prototype highly reliable, high temperature phase-leg SiC power modules.
- **FY18 and Beyond**
  - Develop packaging technologies for integration of high temperature SiC power inverters and electric motors.
  - Prototype integral SiC power inverters for integrated electric drive system

Summary

- **Relevance:** Focused on achieving 40% cost reduction and 60% power density increase to facilitate DOE EDT 2022 power electronics targets: $3.3/kW, 14.1kW/kg, 13.4kW/L.
- **Approach:** The highly integrated WBG packaging technology being developed should leapfrog barriers of existing industrial baseline and bring innovative, systemic development to advance technologies.
- **Collaborations:** The most advanced industrial products and collaborators input have been incorporated into the project.
- **Technical Accomplishments:**
  - Developed high-power SiC power modules for air-cooling system evaluation, which allowed a reduction of 30% in overall volume and weight.
  - Demonstrated that the integrated SiC power electronics modules not only increase the power density by 60% but also enable a threefold increase in current density over their conventional Si counterparts, resulting in a 35% reduction in the die size; 40 and 80% reductions in conduction and switching power losses, respectively; and a 35% reduction in package thermal resistance.
  - Implemented Ag-sintered die-attached technology in advanced SiC power module packaging. Performed microstructure analyses and material tests to generate guidance to develop high-reliability, high-temperature WBG power electronics
- **Future Work:** Continue to optimize the technologies and work with industry to transfer them to manufacturers.