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
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.
## Milestones

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

State of the Art (SOA)

- 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.
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

- Planar-Bond-All (PBA) Packaging
  - Optimized Electrical Interconnection
  - Highly Efficient Heat Transfer
  - Multi-functional Structural Integration
  - Low Cost Manufacturability

- Integrated Power Module
  - Cost Reduction
  - Power Density Increase
  - Power Efficiency Improvement

Reduce Feature Parameters
  - $P_{con}$, $P_{sw}$, $P_{lp}$, $P_{rp}$: Power losses
  - $\theta_{ja}$: Thermal resistance
  - $L_p$, $R_p$, $C_p$: Parasitic electrical impedance
  - $A$: Manufacture cost
  - $\Delta CTE$: Thermal expansion Mismatch
Approach
Strategy to Address Limitations of SOA

Hierarchical Packaging

Integrated Packaging
- Multi-functional Integration
- Building Block
- Advanced Manufacturability
- Superior Performance

- Cost
- Efficiency
- Power Density (Weight, Volume)
## Approach FY15 Timeline

<table>
<thead>
<tr>
<th>2014</th>
<th>2015</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oct</td>
<td>Nov</td>
</tr>
</tbody>
</table>

- **Design multi-functional integrated SiC converter/inverter modules.**
- **Develop packaging processes for fabrication of multi-component integrated SiC power module prototypes.**
- **Perform comprehensive evaluation of the prototypes.**

### 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.
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
Technical Accomplishments – FY14
Built Double-Sided Cooling of SiC Planar-Bond-All (PBA) Module

SiC PBA Module with Dual Pin-fin Baseplates

Double Sided Air Cooling Assembly

Double sided (Liquid) Cooling Design

Integrated Double Sided Liquid Cooling Assembly
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

75% reduction of Lp
90% reduction of Rp

Electrical Parameters Comparison:
- Wire Bond: 50.3, 23.5
- Planar Bond All: 12.8, 2.2
Accomplishments to Date – FY 14/15
Evaluated Integrated Cooling Effects of SiC-PBA Module in System

Current density allowed for different power semiconductor and cooling combinations at ΔTj=100°C for a typical operation (D=0.5, f=5kHz)

<table>
<thead>
<tr>
<th>Item</th>
<th>Wire-bond (1st-gen)</th>
<th>Single Side Integrated Cooling (2nd-Gen)</th>
<th>PBA_double Sided Integrated Cooling (3rd-gen)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current Density Jd (A/cm²)</td>
<td>145</td>
<td>184</td>
<td>220</td>
</tr>
</tbody>
</table>

Comprehensive Test Setup

Comparison of PBA_SiC vs Camry-Si Module

Junction Temperature vs Current Density with Different Packaging

Specific Thermal Resistance (cm²°C/W) | Electrical Parasitics (nH) | Power Loss (W)
--------------------------------------|-----------------------------|-----------------|
0.68                                  | 45.0                        | 100             |
0.37                                  | 13.5                        | 50              |

PBA_SiC                                  Camry_Si
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

Microstructural Analysis of Power Module Packages
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

Proposed Integrated Inverter (3-Phase) Design

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

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)*.

# Partners/Collaborators

<table>
<thead>
<tr>
<th>Logo</th>
<th>Organization</th>
<th>Role</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="CREE Logo" /></td>
<td>CREE</td>
<td>Source of the specialized SiC MOSFET and diode dies</td>
</tr>
<tr>
<td><img src="image" alt="REMTEC Logo" /></td>
<td>REMTEC</td>
<td>Source of manufactured packaging components</td>
</tr>
<tr>
<td><img src="image" alt="Cool Innovations Logo" /></td>
<td>Cool Innovations</td>
<td>Source of manufactured cooling components</td>
</tr>
<tr>
<td><img src="image" alt="Master Bond Logo" /></td>
<td>Master Bond</td>
<td>Source of manufactured encapsulate materials</td>
</tr>
<tr>
<td><img src="image" alt="NREL Logo" /></td>
<td>NREL</td>
<td>Packaging thermal characterization/reliability characterization</td>
</tr>
</tbody>
</table>
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.
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.