Highly Integrated Wide Bandgap Power Module for Next Generation Plug-In Vehicles

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Overview

Timeline

- Start – 1 January 2016
- Finish – 30 September 2019
- 52% Complete

Funding

- Project Budget $5.67 million
  - $3.79M Federal Share
  - $1.88M GM Cost Share
- 2017 funds received $1.12M
- 2018 funding planned $1.59M

Vehicle Technology Barriers

- Lower Cost Electric Drive Systems
- Higher Efficiency, long range EV
- Higher Performance and Lifetime
- Lower Mass and Volume

Project Team

- Lead:
  - General Motors, LLC
- Subrecipients:
  - Virginia Polytechnic Institute and State University
  - Oak Ridge National Lab
  - Monolith Semiconductor, Inc.
- Key Suppliers:
  - Wolfspeed (Cree Power)
- Collaborations:
  - PowerAmerica

Project Relevance

Research Focus Area: Inverter

- WBG Semiconductor based power stage
- Technical development for key components needed for a WBG Power Stage: gate drive, capacitor, high bandwidth current sense

Objective

- Automotive power module with SiC MOSFET dies
- Reduce Inverter and Motor losses over the drive cycle
- Technology ready for long range BEV's with >600V battery
- Implement selected bonding, joining and thermal management technology to reduce thermal impedance, improve high temperature reliability and reduce volume

Addresses Targets

- Enable inverter to meet or exceed DOE 2020 targets:
- Power Density: 13.4kW/l; Specific power: 14.1kW/kg & $3.3/kW
- Efficiency >94% (10%-100% speed at 20% rated torque)

Uniqueness and Impacts

- Compact, high temperature, low inductance automotive package

Milestones

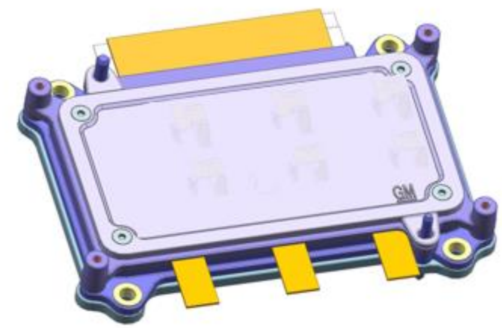
Date	2016-2017 Milestone or Go/No-Go Decisions	Status
Dec - 2016	Initial Power Module Design - Milestone	Completed
June - 2017	Power Module Detailed Design – Phase 2 Go/No-Go	Go
Dec - 2017	Prototype Manufacturing Process - Milestone	Completed
April - 2018	SiC MOSFET Final Builds and Die Tests - Milestone	Completed
June - 2018	Power Module Prototype Perf. – Phase 3 Go/No-Go	On-Track
Oct - 2018	Prototype Performance Test Completed - Milestone	On-Track

WBG POWER MODULE APPLICATIONS

Features

- Low conduction and switching loss
- Ultra-low parasitic inductances
- High switching frequency operation
- Normally-off device operation
- High temperature operation Tjmax=175°C
- High power high voltage power module

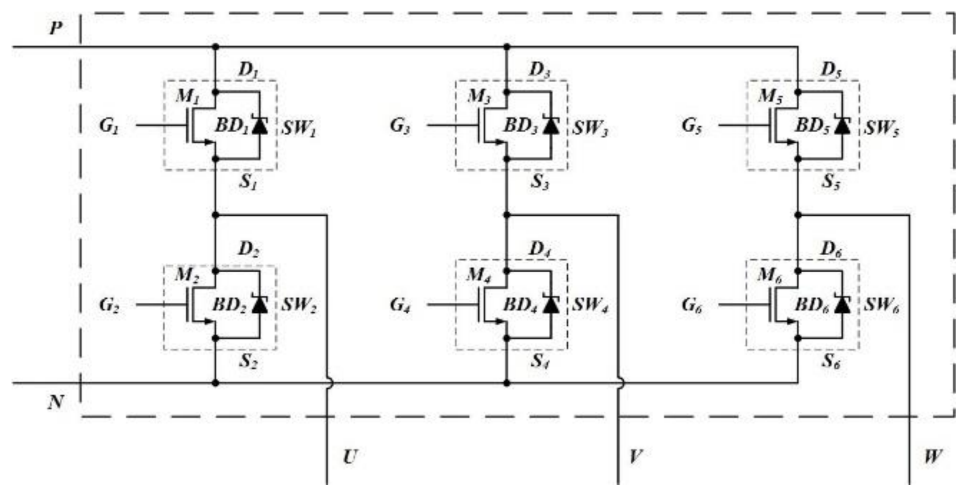
SiC Power Module Package



System benefits

- Reduced size and weight
- Compact design and inverter packaging
- High efficiency inverter
- Increased power density
- Improved thermal performance and packaging

Functional Circuit



Potential applications

- High efficiency converters
  Such as boost converter
- Traction power inverters

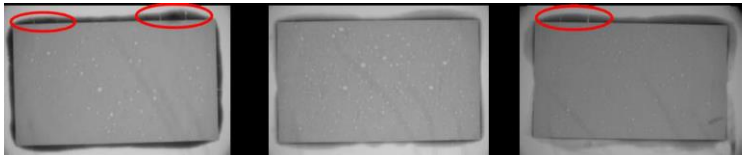
Technical Approach

- This program will develop a highly integrated wide band gap automotive power module with smaller package, lower mass and higher efficiency
- Targets higher DC link bus voltage systems (e.g. 600-800Vdc) and maximum phase currents of 300Arms, 425Apk
- The high power density module utilizes SiC MOSFET dies in an advanced high performance package capable of high temperature operation
- Higher power density will be further enabled through the removal of the external diode by using the third quadrant operational capability of the SiC MOSFET
- Inventing a package with a low DC loop stray inductance path (<5nH) for the module
- Developing advanced current sensing and short circuit protection methods

Accomplishments: Sintering

- Sintering is selected as the attachment method to enable higher temperature operation and long-life reliability
- Both pressure and pressure-less sintering is being evaluated
- Coupons represent small substrates sintered to larger substrates
- Thermal cycling profile:
  - -40°C to 200°C
  - 10-15°C/min
  - 1 h/cycle.
- Die shear testing was used to evaluate mechanical performance
  - Shear strength was still >40 MPa after 1000 cycles
- SAM images show good performance after 500 cycles
  - No cracks in bond-line under device

SAM image of Pressure Sintering (10MPa) of Supplier A Sinter Paste after 500 Thermal Cycles – small cracks identified at edges, not under device



SAM image of Pressure-less Sintering of Supplier B Sinter Paste after 500 Thermal Cycles – similar small cracks identified at edges however, none under device

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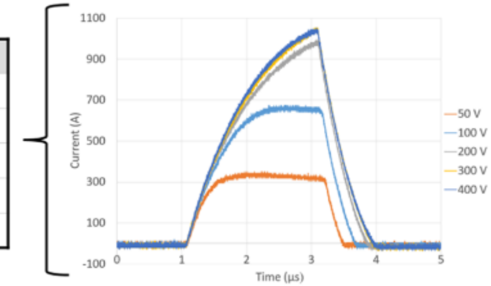
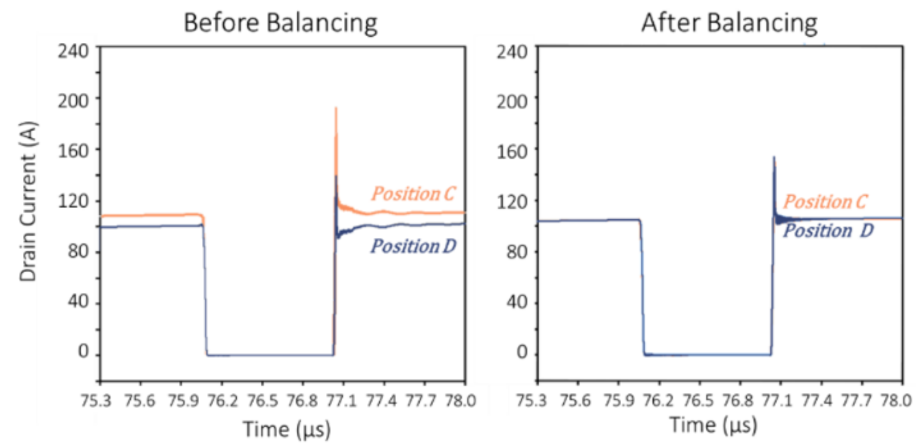
Accomplishments: Electrical Tests

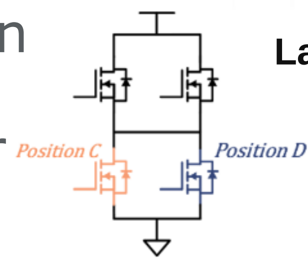
- Evaluation of the short circuit capabilities of the SiC die show good robustness to 2.5us
- Design optimization and fabrication of test coupon in a half-bridge configuration
- Cree 900V-10mOhm die sintered on AlN DBC Substrate
- Half-bridge configuration has <4nH stray inductance in the power loop and <1nH in the control loop

VDS	Max Current
50 V	350.66 A
100 V	673.74 A
200 V	996.82 A
300 V	1051.98 A
400 V	1051.98 A

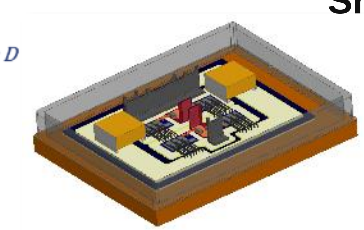


Short Circuit Evaluation of Device

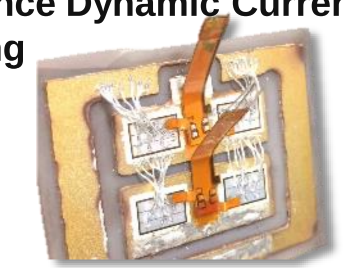




Layout Optimization Balance Dynamic Current Sharing



Electrical Test Coupon Design

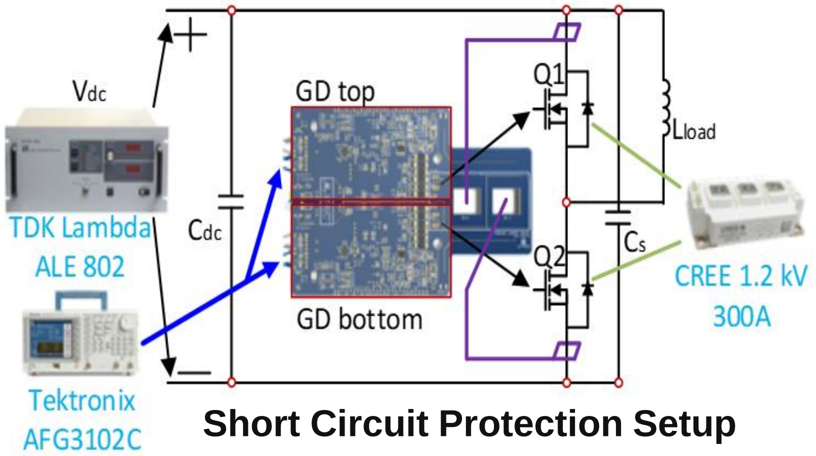


Test Coupon Fabrication

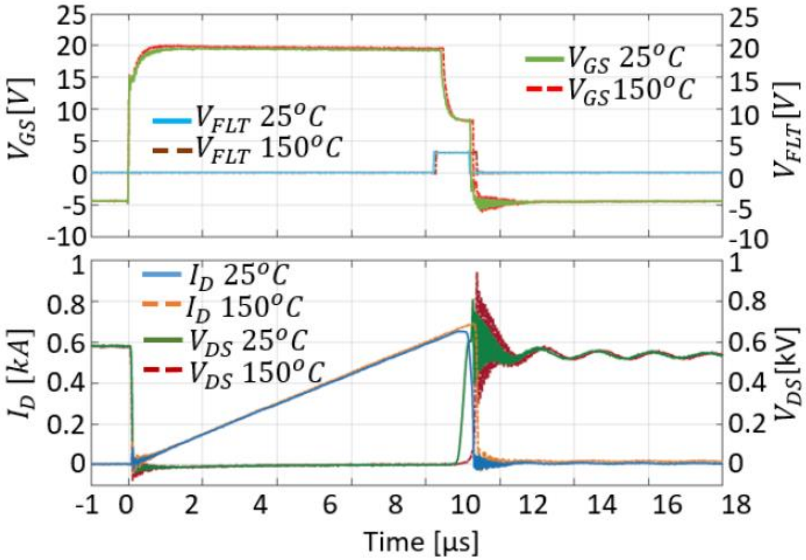
Performed by subrecipient: Virginia Polytechnic Institute and State University

Accomplishments: Gate Drive Short Circuit Protection

- Developed short circuit protection method using Rogowski coil current sensing
- Improved response (200ns) over temperature vs traditional DeSAT protection methods
- Hard fault (i.e. shoot-thru) shows peak energy at device of 1J or less
- Load fault (e.g. motor winding short) shows peak energy of device of 0.1J or less



Short Circuit Protection Setup

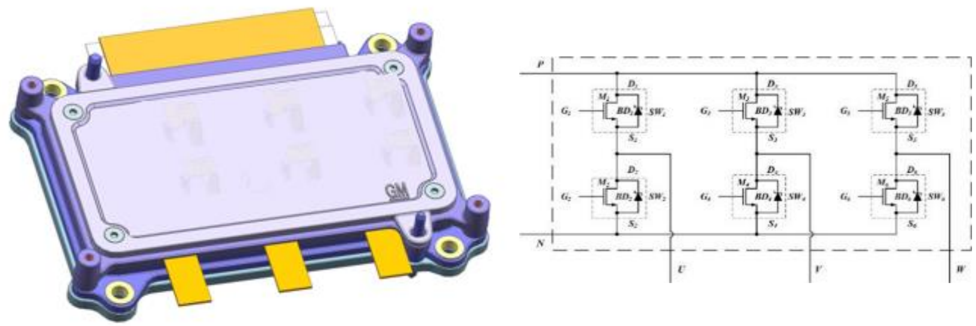


Short Circuit Protection using Rogowski Coil Current Sensing under Load Fault

Performed by subrecipient: Virginia Polytechnic Institute and State University

Accomplishments: Power Module Design

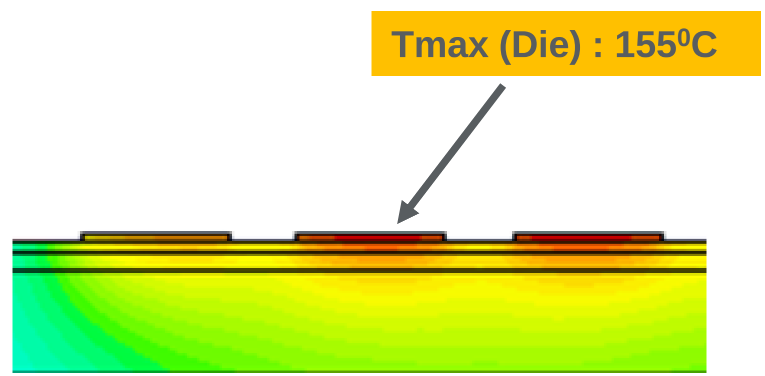
- Module inductance lower than the design targets
- Package Inductance targeted very low to achieve high level of performance
- Analysis predicts adequate thermal margin



Phase 2 Power Module Design

V_{ds}	650 V	Lstray	2.6 nH
I_{rms}	300A	Lcstray	2.0 nH
f_{sw}	30kHz	$L_{totstray}$	10.0 nH

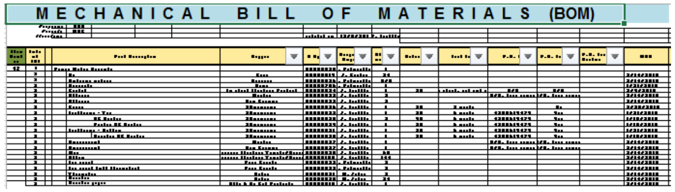
Phase 2 Power Module & Package Inductance



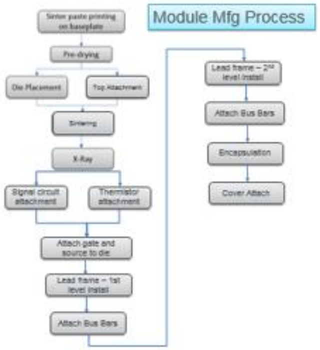
Phase 2 Power Module Thermal FEA Die Temperatures

Accomplishments: Manufacturing Process

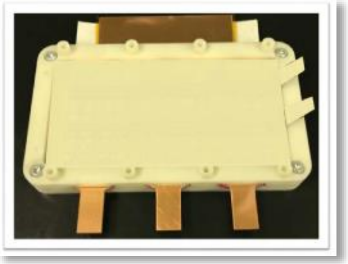
- Completed the Bill-of-Materials (BOM) for the phase 2 prototype
- Completed the milestone for the prototype manufacturing processes and developed a detailed assembly process and instructions
- Concept prototype was built to refine component manufacturing processes and Design for Assembly (DFA)
- Received target die for use in the SiC MOSFET automotive power module
- Demonstrated successful sintering & wire bonding to target die



Bill of Materials



Manufacturing Process Developed



Concept Prototype Build

Assembly Process Detailed

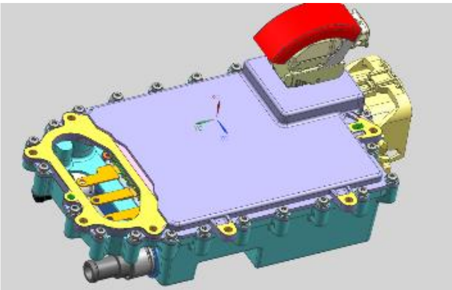
Remaining Challenges Barriers & Future Plans

Challenges & Potential Barriers

- Power Module Yield during prototype phases
- High bandwidth low cost current sensing
- Gate Drive improvements: Three times faster short circuit protection than typical Si IGBT "De-Sat" protection schemes, High common-mode transient immunity (CMTI)
- Cost higher than DOE inverter targets that are Si IGBT based

Future Plans (FY2018)

- Power Module performance testing to targeted performance
- Build half bridge test coupon testing to verify electrical models
- Finish SiC inverter design concept



Proposed future work is subject to change based on funding levels and Go/No-Go gate review

Summary

- Power Module Design Targets finalized
- Gate drive solutions for prototype testing evaluated
- Detailed design reviewed at Go/No-Go - - Go!
- Design package footprint is about half the size of industry leading silicon IGBT power modules
- Package inductance, and thermal performance have been modeled & are below targets
- Prototype manufacturing process defined
- Project is progressing to phase three – Fabrication & confirmation testing