Advanced Low-Cost SiC and GaN Wide Bandgap Inverters for Under-the-Hood Electric Vehicle Traction Drives

APEI

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APEI
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Project ID: APE058

Overview

Timeline

Project Start Date: October 1, 2013
Project End Date: September 30, 2015
Percent Complete: ~25%

Budget

Total Project Funding: $3.8M
DOE Share: $1.8M
Funding Received in FY13: $0
Funding Received in FY14: $0

Barriers and Targets

- Cost ≤ $182 unit cost / 100,000
- Ambient operating temperature ∈ [-40 to +140 °C]
- Volume ≤ 4.1 liters

Partners

- Toyota Motor Engineering & Manufacturing North America, Inc.
- GaN Systems, Inc.
- National Renewable Energy Laboratory
- University of Arkansas National Center for Reliable Electric Power Transmission

Project Objectives

- Develop two independent 55 kW traction drive designs (one SiC based and one GaN based) to showcase the performance capabilities of WBG power devices – namely high efficiency, increased gravimetric and volumetric density through high operating junction temperature capability.
- Demonstrate a substantial cost reduction from the die level to the system level.
- Optimize proven productized high temperature WBG power modules for increased manufacturability and reduced cost.
- Integrate existing APEI high temperature silicon on insulator (HTSOI) application specific integrated circuit (ASIC) designs as a means to low-cost, high-reliability, high-temperature circuitry.

Project Objectives & Relevance

- Application of advanced system-level packaging techniques to completely eliminate a vehicle’s secondary cooling loop system, utilize 85 °C rated capacitors, reduce interconnects, and enable increased system reliability.
- Demonstrate of design robustness and reliability through extended testing of subsystems and systems under realistic application operating conditions.
- Complete cost and manufacturing analysis to aid commercialization effort.

The goal of this research is to **reduce traction inverter size** (≥ 13.4 kW/L), **weight** (≥ 14.1 kW/kg), and **cost** (≤ $182 / 100,000) while maintaining 15 year reliability metrics.

If successful, this project has the potential to change the automotive industry’s perception and adoption of WBG technology.

Relevance

Current HEVs, PHEVs, and BEVs use inverters based on silicon power semiconductor devices.

These devices and present-day packaging technology make it difficult to meet the VTO efficiency, cost, weight, and performance targets.

Requirement	Target
Continuous power output (kW)	30
Peak power output for 18 seconds (kW)	55
Weight (kg)	≤3.9
Volume (l)	≤4.1
Efficiency	> 93%
Unit Cost for quantities of 100,000 ($)	≤182
Operating voltage (Vdc)	200 to 450; nominal: 325
Power factor of load	>0.8
Maximum current per phase (Arms)	400
Precharge time – 0 to 200 Vdc (sec)	2
Output current ripple – peak to peak (% of fundamental peak)	≤3
Maximum switching frequency (kHz)	20
Current loop bandwidth (kHz)	2
Maximum fundamental electrical frequency (Hz)	1000
Minimum isolation impedance-input and phase terminals to ground (Mohm)	1
Minimum motor input inductance (mH)	0.5
Ambient operating temperature (^{0}C)	-40 to +140

Milestones & Go/No-Go

Date	Description
December 2013	Milestone • Traction inverter specification finalized • Electrical/Mechanical design of traction inverter complete • Large area GaN device design complete • Form commercialization team
March 2014	Milestone • Control system design complete • GaN power device fabrication complete
June 2014	Milestone • Characterization of all power devices • HTSOI driver chip set developed • Power devices designed into custom power module
September 2014	Milestone • Traction inverter subcomponent testing completed • Traction inverter three-phase lab testing begins
December 2014	Milestone • Electrical/Mechanical design cycle 2 complete • Control system design cycle 2 complete • External case design complete
January 2015	Go/No-Go • Traction inverter three-phase lab testing complete

Technical Approach

- This program will develop two completely independent WBG traction inverters: one **SiC based and one GaN based.** This work will provide a unique, **direct comparison** between **inverter designs using SiC and GaN.** (APEI)
- This program will advance GaN HEMT power semiconductor device technology to **600 V, 100 A**. (GaN Systems)
- This program will utilize advanced **high performance power modules** to achieve high power density and efficiency. (APEI)
- This program will use **advanced packaging techniques** (APEI) and **active cooling technologies** (Toyota, NREL) to enable the use of low-cost, 85 °C-rated DC bus capacitors.
- **Custom, in-house HTSOI IC designs** will dramatically reduce the cost of high temperature capable support circuitry. (APEI)

Technical Approach

APEI, Inc. HT-2000 WBG Device-Neutral Power Module. 1200 V and up to 1000 A half-bridge in a 3” × 3.2” × 0.5” package. U.S. Quarter for scale.

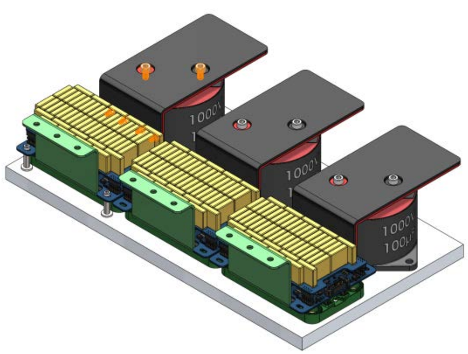
- Work inside out. Optimize from the power devices to the outside world.
- Start with the smallest form factor, lightest weight, and highest performing WBG power module in the world
- Half-bridge power module capable of up to 1200 V and up to 1000 A (device dependent)
- High-temperature packaging materials (250 °C capable)
- WBG device neutral (SiC BJTs, JFETs, MOSFETs, GaN HEMTs, etc.)

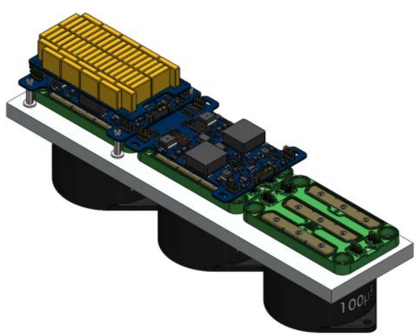
Accomplishments and Progress

Task 1.0 Design, integration & testing of traction inverter system capable of meeting under-the-hood requirements

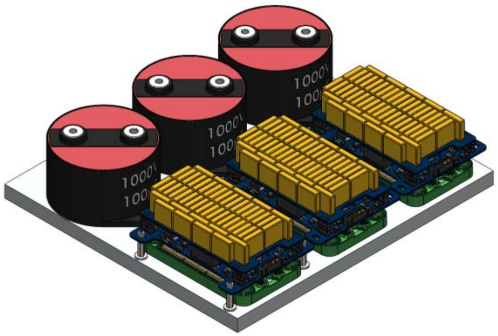
- 1.1 Conceptual design phase:
  - Developed the proposed traction inverters' initial specifications and outline the technical approach to the electrical, mechanical, and thermal designs.

Configuration A

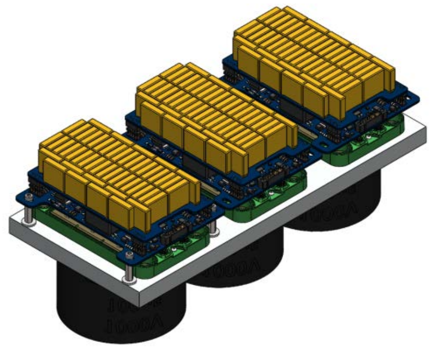




Configuration B



Configuration C



Configuration D

Accomplishments and Progress

– 1.2 Design Cycle 1:

Developed the complete electrical, mechanical, and thermal design to meet or exceed all technical targets with focus on cost reductions for mass commercialization.

- Finalized technical specifications
- Finalized complete electrical and thermo-mechanical design of SiC-based and GaN-based power module optimized for cost and manufacturability
- Performed detailed thermal modeling and simulation of the power stage, single phase
- Finalizing control system design – Space vector PWM + sensored FOC, MATLAB/Simulink simulation, sensor signal conditioning, digital control platform, CAN communication, etc.

Accomplishments and Progress

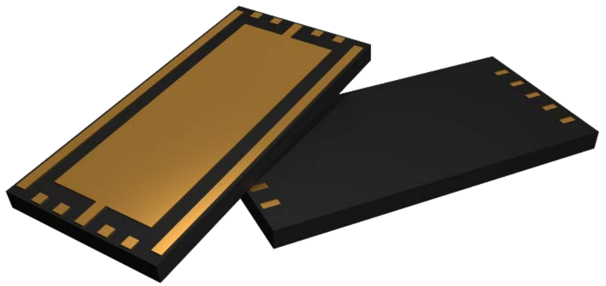
- 1.2 Design Cycle 1:

  Developed the complete electrical, mechanical, and thermal design to meet or exceed all technical targets with focus on cost reductions for mass commercialization.

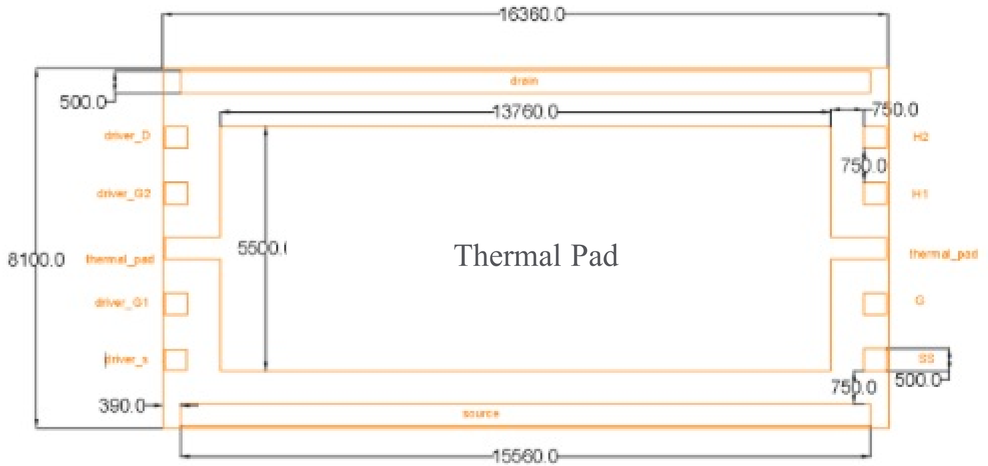
  - PCB schematics in progress
  - Complete first round of GaN power device characterization
  - Completed conceptual packaging design of GaN System's C40 package into APEI's power module
- 1.3 Power module package development Cycle 1: Complete
- 1.6 Design and fabricate test bed, single phase: Complete
- 1.7 Testing Cycle 1, single phase: Ongoing

Technical Accomplishments and Progress

- Development of a high current GaN switching transistor, 600 V, 100 A – C40
- Mounted on a direct bond copper power substrate within the power module
- High current, ultra-compact low inductance package
- Eliminates wire bonds
- Large die (~ 50 mm^2)
- Includes temperature sensor, current sensor, GaN driver



Embedded package – GaNPX - for the C40



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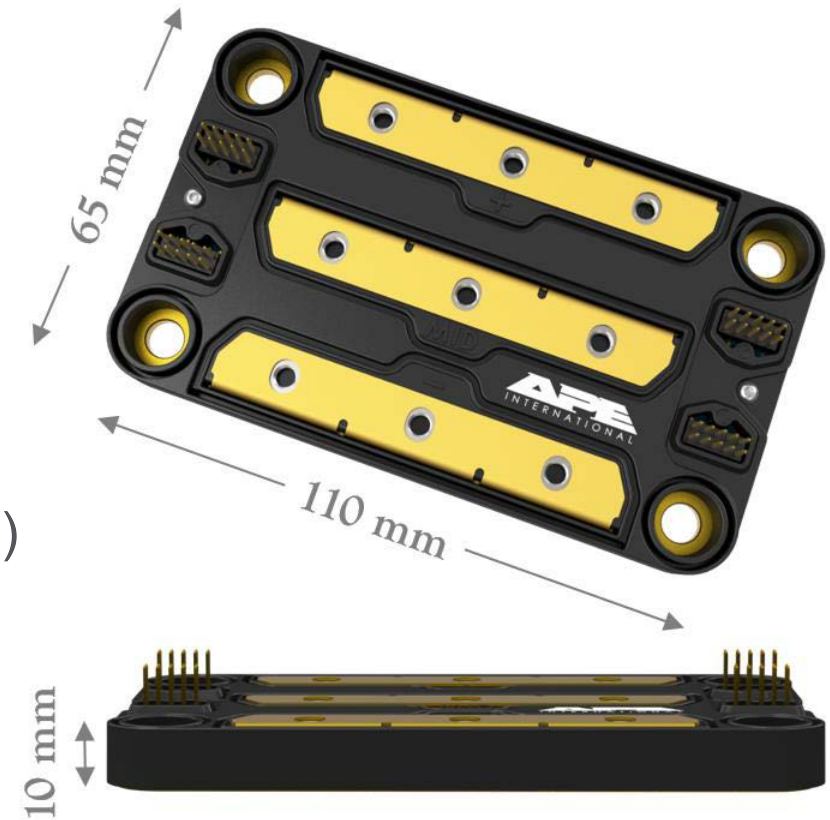
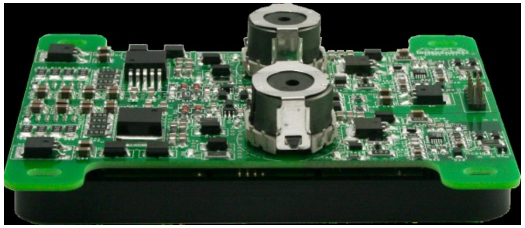
Accomplishments and Progress

- Half-bridge configuration: HT-3201
- 110 x 65 x 10 mm
- Standard footprint
- Device neutral
- 225 °C maximum junction
- Minimized parasitics (< 7 nH)
- Low thermal resistance (< 0.1 °C/W)
- Low volume/weight using advanced packaging materials ($72\ cm^3$ and 140 g)



Accomplishments and Progress

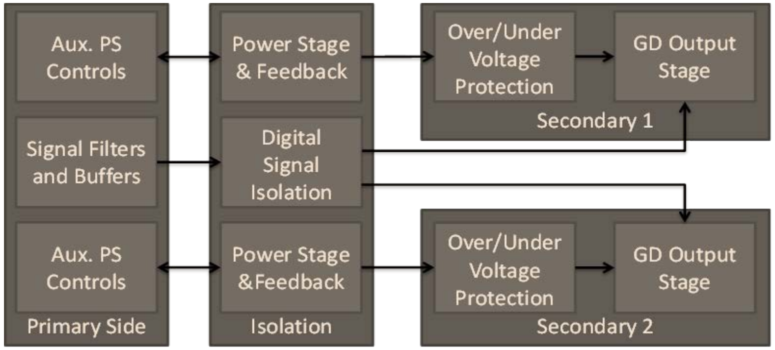
- First prototypes successfully built
- Configuration: 7 MOSFETs / 6 SBDs
- Static characterization performed on initial prototypes up to 450 A
- Dynamic switching characterization performed on initial prototypes up to 600V / 400A
- Present status: **operating and debugging the custom complete full power test setup**
- First version of preliminary datasheet created— will be updated as we gather additional test data



Technical Accomplishments and Progress

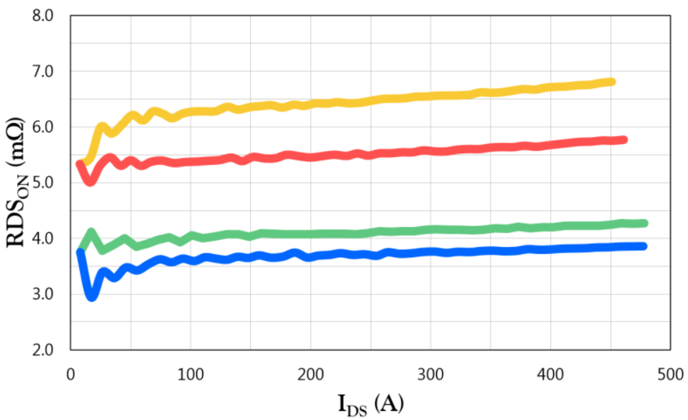
Military Temperature Gate Driver with Isolated Power Supplies

- T_A = 125 °C, T_J = 150 °C
- Bipolar voltage rails, +20 V / -5 V
- Programmable UVLO with hysteresis
- ± 14 A peak, ± 4 A continuous
- 500 kHz switching frequency
- 4 kV galvanic signal isolation
- Capable of short excursions to 150 °C ambient

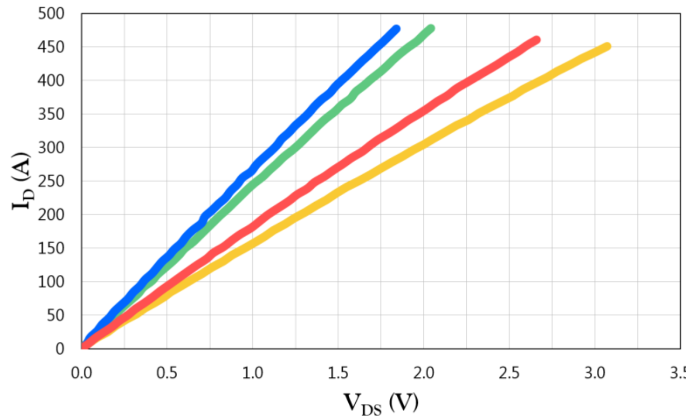


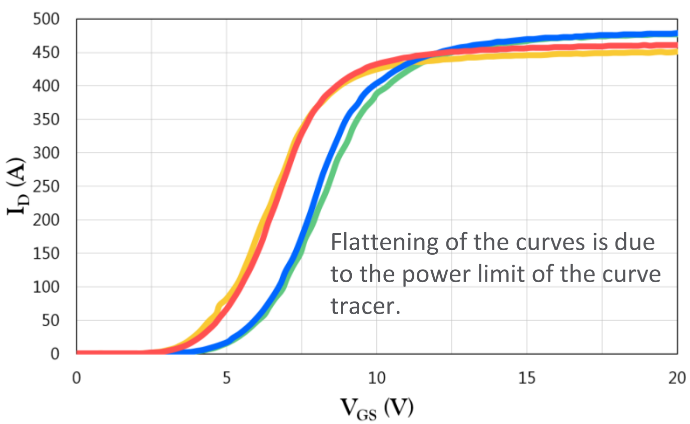
Accomplishments and Progress

On-Resistance per Switch Position
(7 MOSFETs, 6 Diodes)



On-State per Switch Position
(7 MOSFETs, 6 Diodes, V_{GS} = 20 V)





Transconductance per Switch Position
(7 MOSFETs, 6 Diodes)

25°C: Upper Pos. / Lower Pos.

200°C: Upper Pos. / Lower Pos.

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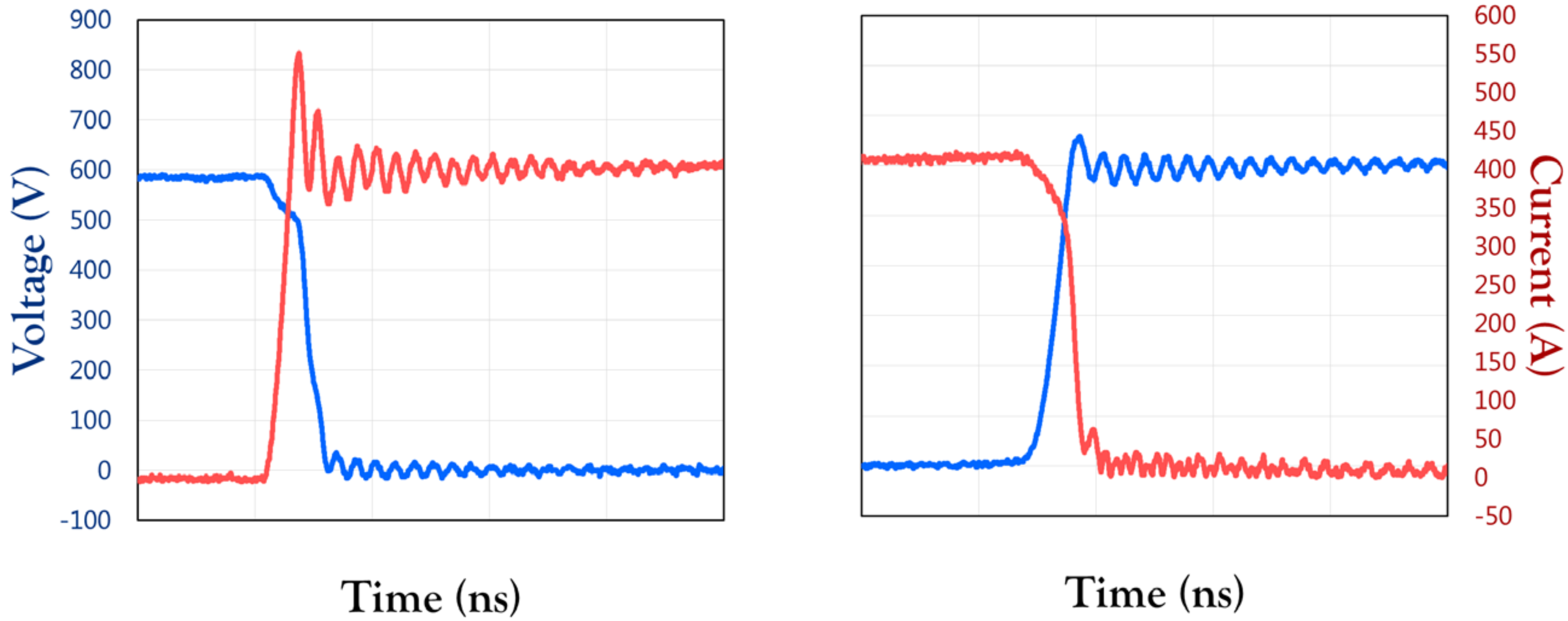
Accomplishments and Progress

Double Pulsed High Speed Switching
7 MOSFETs, 6 Diodes
0 Ω Internal Gate Resistor (per die), 5 Ω External



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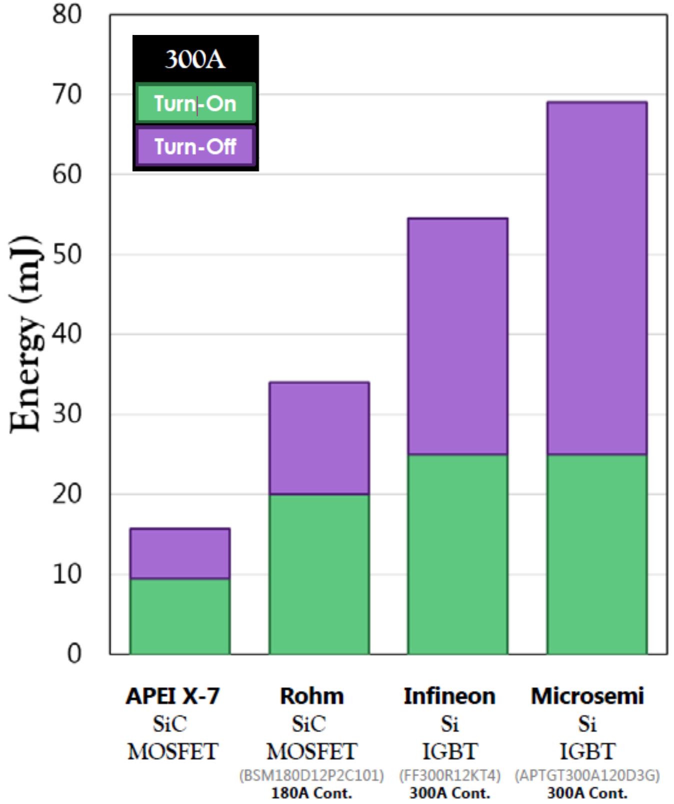
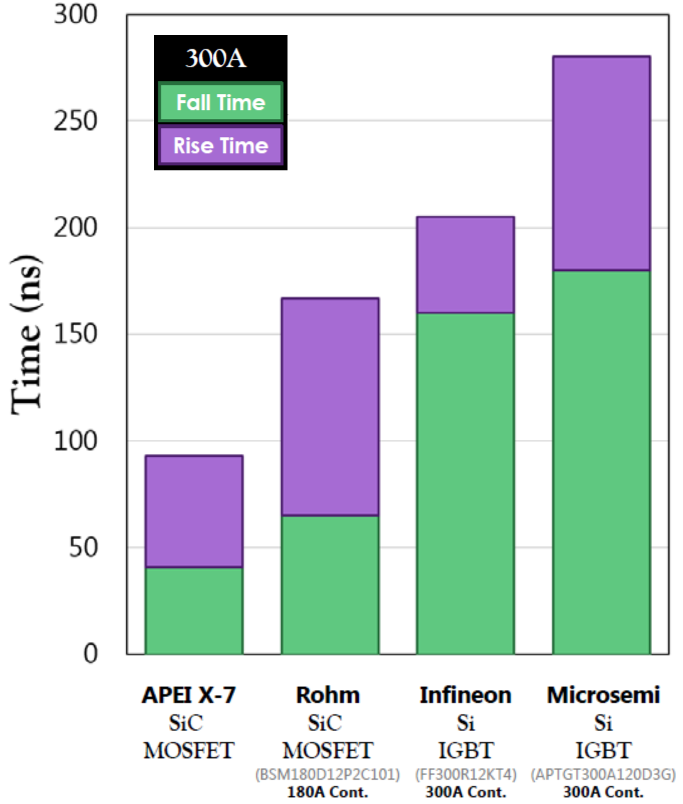
Accomplishments and Progress

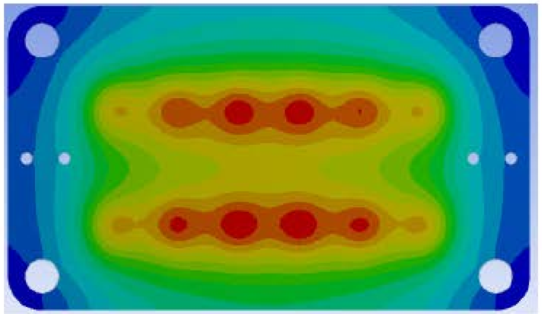
State of the Art Power Module Switching Comparison (*Note*: X-7 ≡ HT-3201)





Accomplishments and Progress

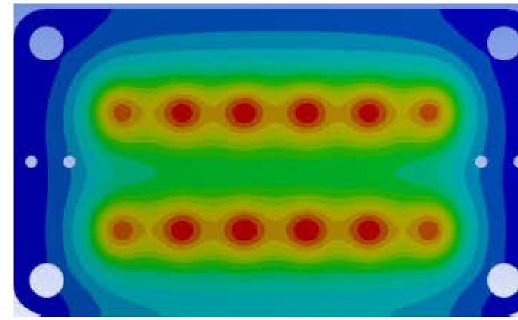
Cold Plate Cooled



Temperature profile of bottom of base plate

$(T_{j,max} - T_{case,max})$ = 95°C*

Base Plate Cooled

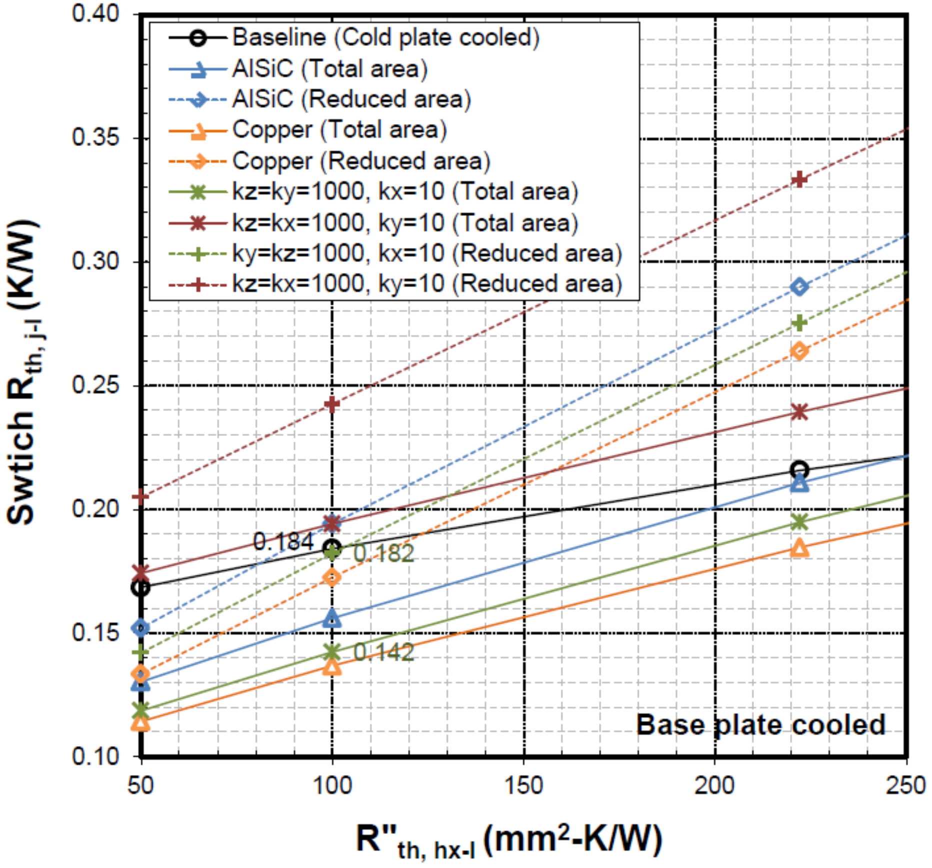


Temperature profile of bottom of base plate

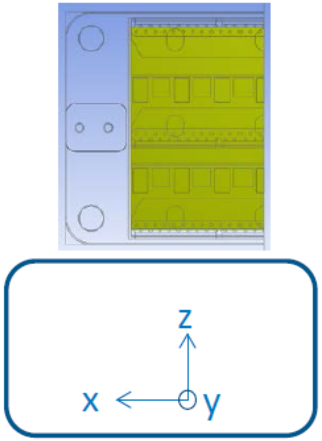
$(T_{j,max} - T_{case,max})$ = 95°C*

#	Cooling Configurations	Thermal Performance	Reliability	Ease of Mfg. Module	Ease of Mfg. Heat Exchanger	Risk	Cost	Average
1	Baseline - Std. module with COTS coldplate and TIM grease	1	3	4	5	5	3	3.5
2	Integrated baseplate with coldplate (Pin-fin baseplate)	3	3	3	4	4	2	3.2
3	Integrated DBC with coldplate (Baseplateless module)	3	4	5	4	2	4	3.7
4	Integrated 3D coldplate with heat exchanger	4	3	4	2	2	3	3.0
5	Integrated baseplate 3D heat exchanger (3D Cooling of Baseplateless Module)	4	4	5	2	2	4	3.5
6	Std. module with custom coldplate design (Toyota led design)	3	3	4	3	5	3	3.5
7	Std. module with high thermal conductivity baseplate inserts	2	3	4	5	4	2	3.3
8	Configuration 2 with high thermal conductivity baseplate inserts	4	3	3	4	4	1	3.2
	1 = Worst case, 3 = Average, 5 = Best case							

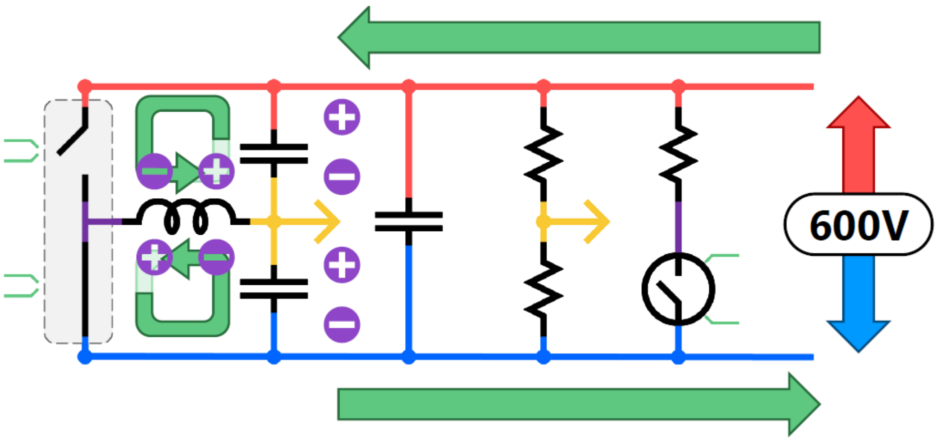
Accomplishments and Progress



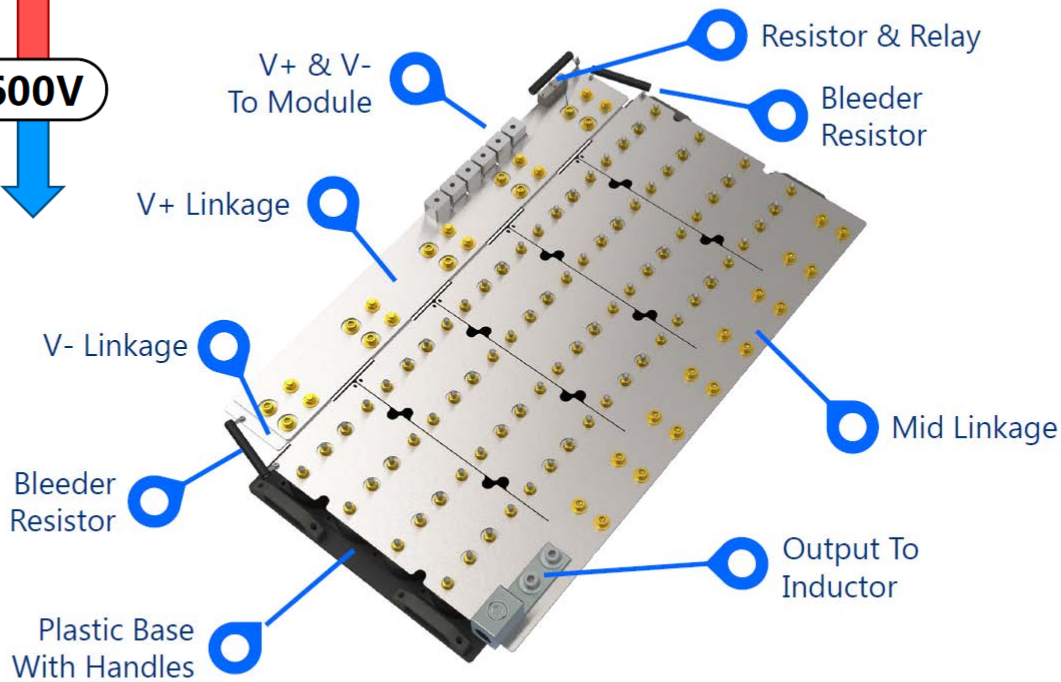
- Performance of *ky*=10 W/m^2-K is worse than the baseline, cold plate cooled configuration
- *kx*=10 W/m^2-K configuration has performance comparable to copper base plate



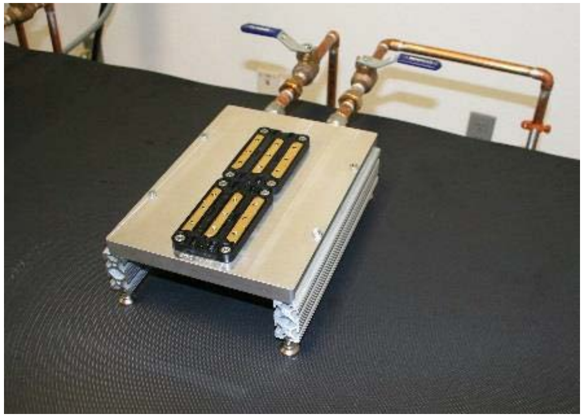
Accomplishments and Progress



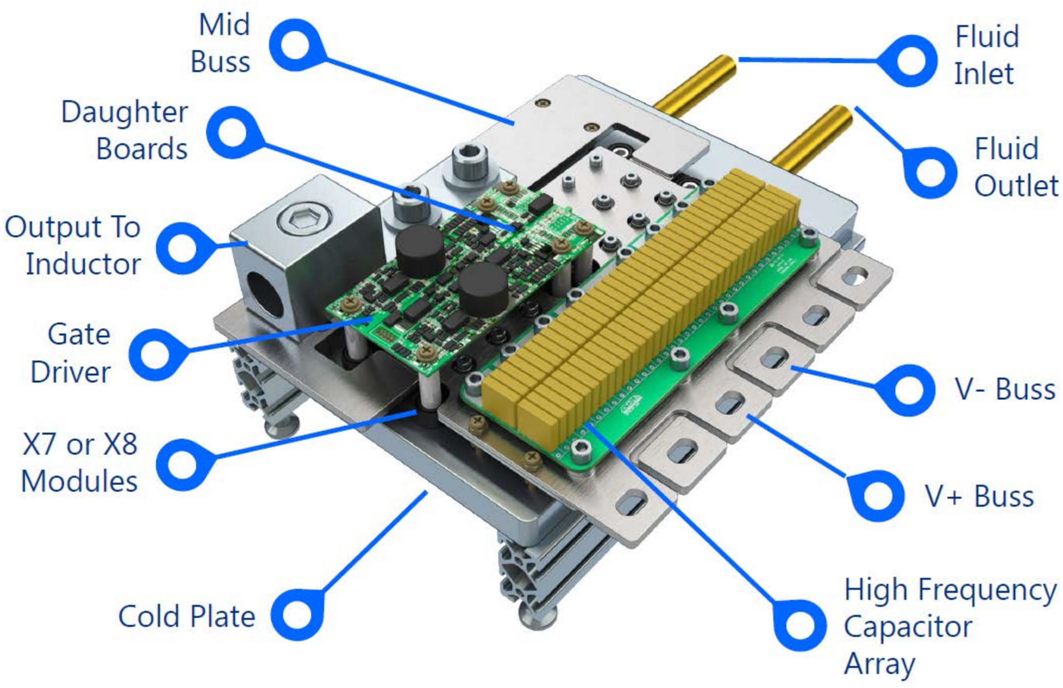
Full Power Test Setup



Accomplishments and Progress



Full Power Test Setup



Responses to Previous Year Reviewers' Comments

- This project was not reviewed last year.

Collaborations and Coordination with Other Institutions

- OEM – Toyota. Toyota will collaborate on system-level **specifications** and on the design of the **thermal management system**.
- Device Manufacturer – GaN Systems, Inc. GaN Systems will fabricate and test ≥ 600 V, ≥ 50 A **GaN HEMTs**.
- Supporting Research Organizations
  1. National Renewable Energy Laboratory – NREL will perform **thermal and reliability analysis** as the module- and system-levels, respectively.
  2. University of Arkansas NCREPT – UA NCREPT will assist in the extensive **characterization and testing** of the traction inverter system using a custom-designed dynamometer test bed.

Proposed Future Work

- Task 1.2 Design Cycle 1:
  - Power module characterization with GaN C40 packages as per the SiC-based results contained herein
  - Control system design: additional simulations, HT current sensor characterization, embedded control implementation and testing
  - PCB layout, fabrication, and testing of controller
  - Characterization of next design cycle GaN HEMT
- Task 1.4 Fabrication Cycle 1: Assemble multiple hardware units of each WBG traction inverter design for internal testing
- Task 1.5 Finalize test plan: Complete test plan for validating both WBG traction inverter designs.
- Task 1.6 Design and fabricate dynamometer test bed: Design is complete; fabrication and commissioning activities begin
- Task 1.7 Testing Cycle 1: Subsystem testing finishes, three-phase functional testing commences

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Project Summary

TOYOTA GaN Systems NREL NATIONAL RENEWABLE ENERGY LABORATORY UNIVERSITY OF ARKANSAS

Questions?