Sustainable TRANSPORTATION

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

DOE AMR Review

Cree, Inc., EE0006920 "88 Kilowatt Automotive Inverter with New 900 Volt Silicon Carbide MOSFET Technology"

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Project ID #
EDT073

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CREE | APEI | Ford

Project Overview

Timeline

- Project Start – Dec. 11, 2014
- Project Complete – Dec. 10, 2016
- 5% Complete

Barriers

- Cost (A) – Target < $8/kW by 2020
- Weight (C) – SiC expected to improve power density (>1.4kW/kg by 2020)
- Reliability & Lifetime (D) – SiC ↓ FIT 10x
- Efficiency (E) – SiC expected to improve light-load efficiency and vehicle range

Budget

- Govt. Share: $1,937,752.00
- Cost Share : $2,107,744.00
- Total : $4,045,496.00

Partners and Subcontractors

- Cree, Inc. lead; 900V SiC power MOSFET
- APEI – sub; SiC power modules & inverter
- Ford – sub; SiC evaluation and feedback

Relevance of program targets at macro level

- Depending on topology, x-EV drive system, and motor, the primary target is to make x-EV more affordable through better fuel efficiency, lower system cost, and lower weight
  - 900V, 10mΩ SiC MOSFET developed, sampled and AEC-Q101 qualified at chip level
  - At low-frequency, the SiC MOSFET has better light-load efficiency than Si IGBT
  - Better efficiency leads to reduced cooling costs
  - Record low switching losses expected for 900V semiconductor switch
  - Avalanche energy expected to be 10X that of Si components for better reliability

Metrics	DOE Specified	FUPET (Japan consortium w Nissan)	Delphi	Cree/APEI/FORD targets
Semiconductor	Si or WBG	1200 V SiC FET @ 3.1 mΩ·cm^2	Si IGBT	*900 V SiC FET @ 2.2 mΩ·cm^2*
Year	2010	2011	2013	*2016*
Cost (100k units)	$5/kW	-	$5/kW	*< $5/kW*
Specific Power	12 kW/kg	-	17 kW/kg	*> 22.5 kW/kg*
Power Density	12 kW/L	30 kW/L*	15 kW/L	*>21.5 kW/L*
	- doesn't include controllers, sensors, or gate drivers & power supplies. Ref Materials Science Forum Vols. 740-742, pp 1081-1084, (2013) Trans Tech Publications, Switzerland			

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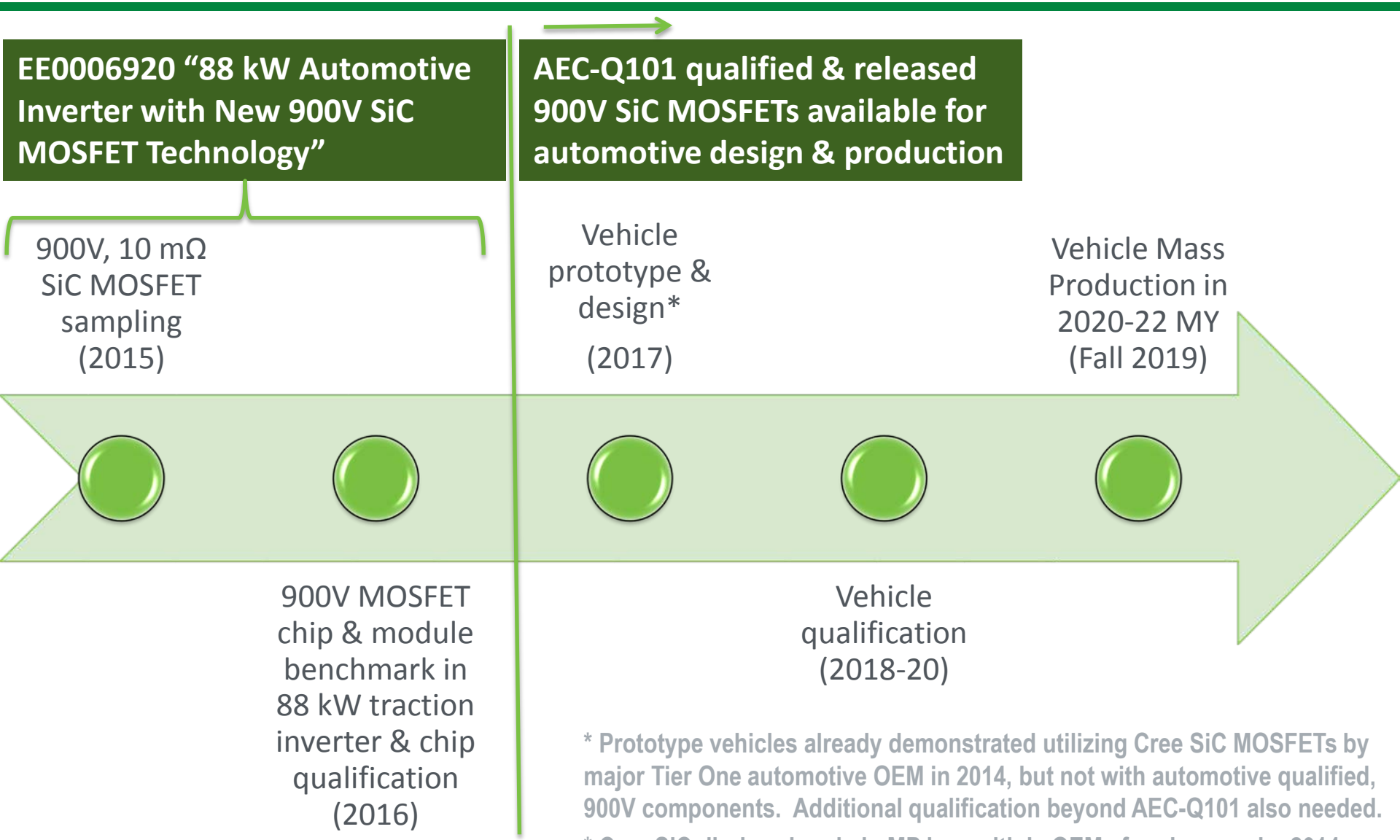
Relevance to Commercialization



* Prototype vehicles already demonstrated utilizing Cree SiC MOSFETs by major Tier One automotive OEM in 2014, but not with automotive qualified, 900V components. Additional qualification beyond AEC-Q101 also needed.

* Cree SiC diodes already in MP by multiple OEMs for chargers by 2014.

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Milestones

Budget Period	Start/End Date	Milestone	Type	Description	Status
1	12/15/2014 – 12/14/2015	Characterization of third optimization of wafer lot of 900 V SiC MOSFET.	Go/No-Go	Test the third power MOSFET lot and measure performance against the target specifications.	On-track. First 900V, 10mΩ SiC MOSFET lot in fab with ECD of
2	12/15/2015 – 12/14/2016	Single-phase traction drive demonstration.	Technical	Perform single-phase traction drive demo using 900V, 200A, ½ bridge power modules and evaluate impact of SiC performance on automotive traction drive system.	Not started. This is for FY16.

- Interim Milestones are defined in the SOPO and PMP

Approach

Task #	900V, 10mΩ SiC MOSFET development & qual	Wafers	Start	ECD
1 .1	Die centering – lot #1	9	Feb 2015	June 2015
1.1	R_{DSON} vs t_{SC} - lot #2	6		Sept 2015
1.1	Re-center lot based on feedback (Go / No-go milestone) – lot #3	6		Nov 2015
1.2	Pre-qual lot – lot #4	6		Jan 2016
1.2	Qualification Lot #1 – lot #5	12		Mar 2016
2.1	Qualification Lot #2 – lot #6	12		Apr 2016
2.1	Qualification Lot #3 – lot #7	12		May 2016
2.1	Qualify 900V, 10mΩ SiC MOSFET chip by AEC-Q101 standards	---		Nov 2016

Task #	900V ½ bridge power module develop & qual	Modules	Start	ECD
1 .3	Assemble, characterize and benchmark power modules (900V, >200A, ½ bridge)	6	June 2015	Sept 2015
2.2	Assemble, characterize and benchmark power modules (900V, >200A, ½ bridge)	70	May 2016	Aug 2016
2.2	Qualification of module using a mix of JEDEC and AEC-Q101 standards	---	Aug 2016	Dec 2016

Task #	88kW peak traction drive demo	Modules	Start	ECD
2.3	Single phase traction drive demo	5	June 2015	Sept 2015
2.3	Three phase traction drive demo	25	May 2016	Aug 2016
2.3	Benchmark 900V SiC based technology with competing technologies	---	Aug 2016	Dec 2016

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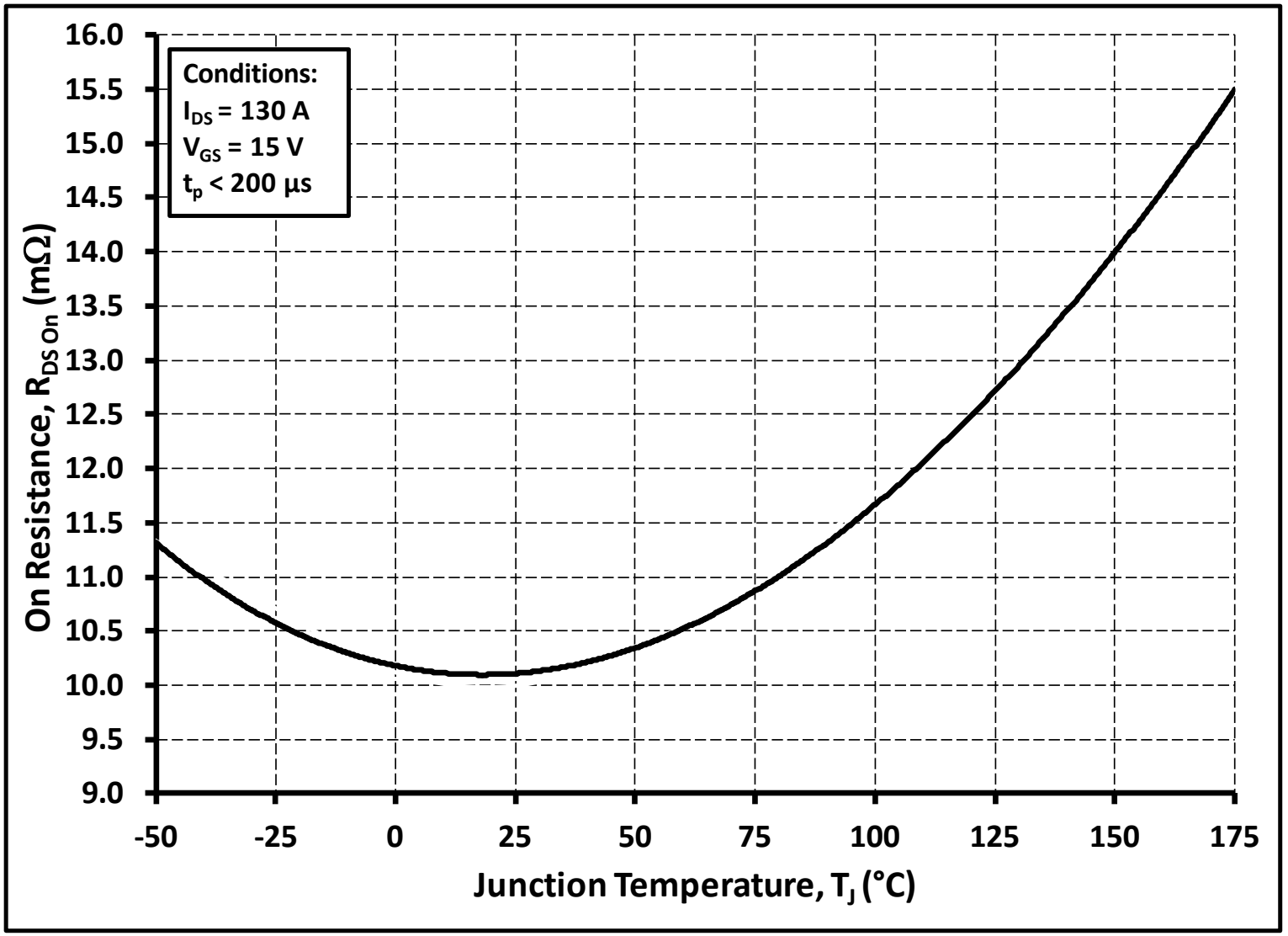
Approach - 900V, 10 mΩ SiC MOSFET Estimated R_{DSON} vs T



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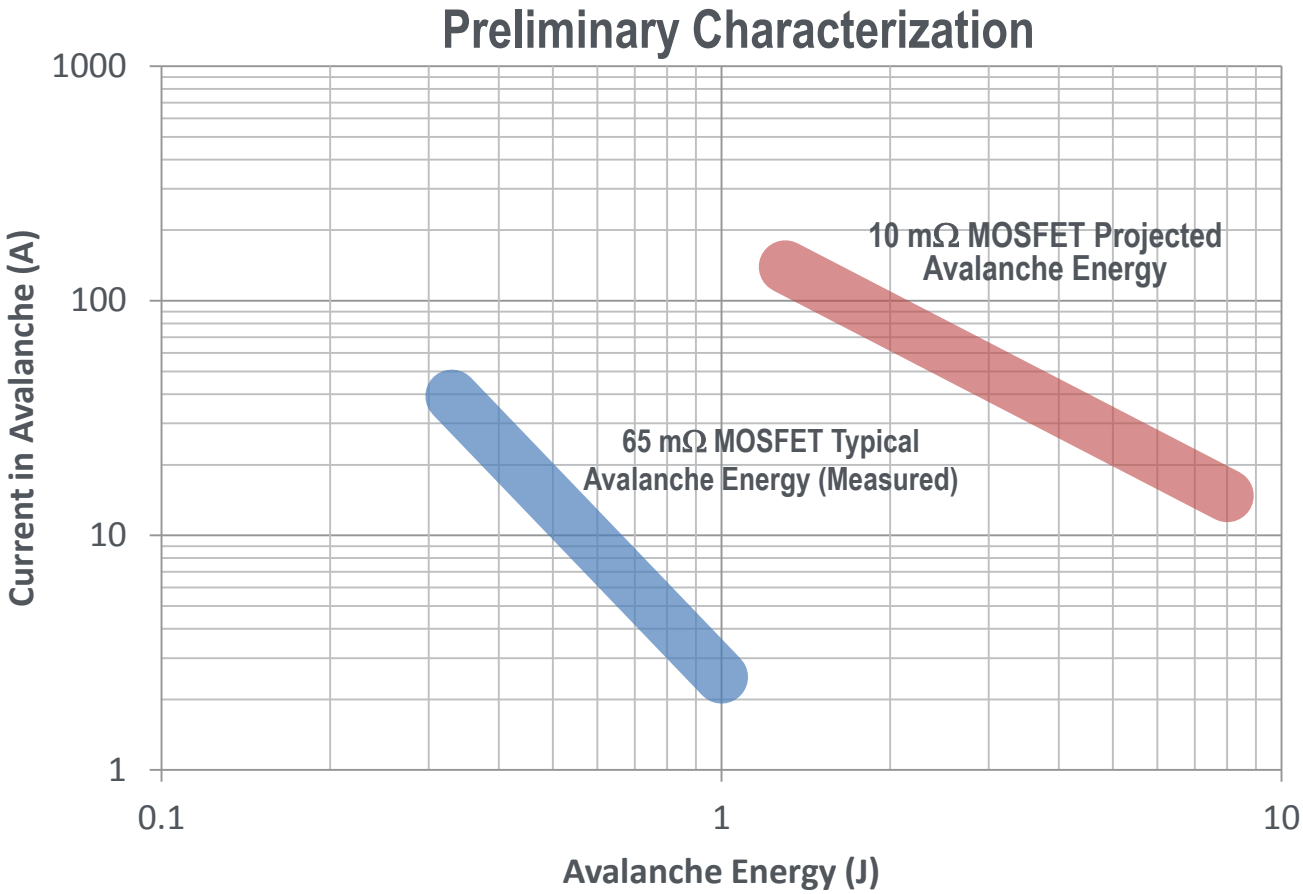
Approach – MOSFET Qualification Plan at 175 °C

- Die to be qualified at a $T_{J,Max}$ of 175 °C under this program
- Reliability at 200 °C will be investigated; qualifying at 200 °C will be a stretch goal
- AECQ101 die level qualification tests in TO-247

Test	Stress Conditions	Duration	Wafer lots sampled	Total devices sampled
HTGB	VGS = 18 V, VDS = 0, Ta=175 °C	1000 hrs	3	231
H3TRB	85 °C, 85% RH, VDS = 100 V, VGS=0	1000 hrs	3	231
HTRB	VDS = 720 V, VGS = 0, Ta = 175 °C	1000 hrs	3	231
TC	-55 °C / +175 °C, JESD22-A104 condition H, soak mode 1	1000 cycles	3	231
IOL	5 min on / 5 mins off, ΔTj ≥ 100 °C, Tmax ≥ 175 °C	6000 cycles	3	231
ESD-HBM	Classification at 25 °C	n/a	1	5
ESD-MM	Classification at 25 °C	n/a	1	5
ESD-CDM	Classification at 25 °C	n/a	1	5

Approach - 900V SiC MOSFETs : Avalanche Ruggedness

- Low defect density material and processing allows SiC MOSFETs to withstand avalanche energy
- Stretch goal will be to avalanche rate 900 V SiC MOSFETs



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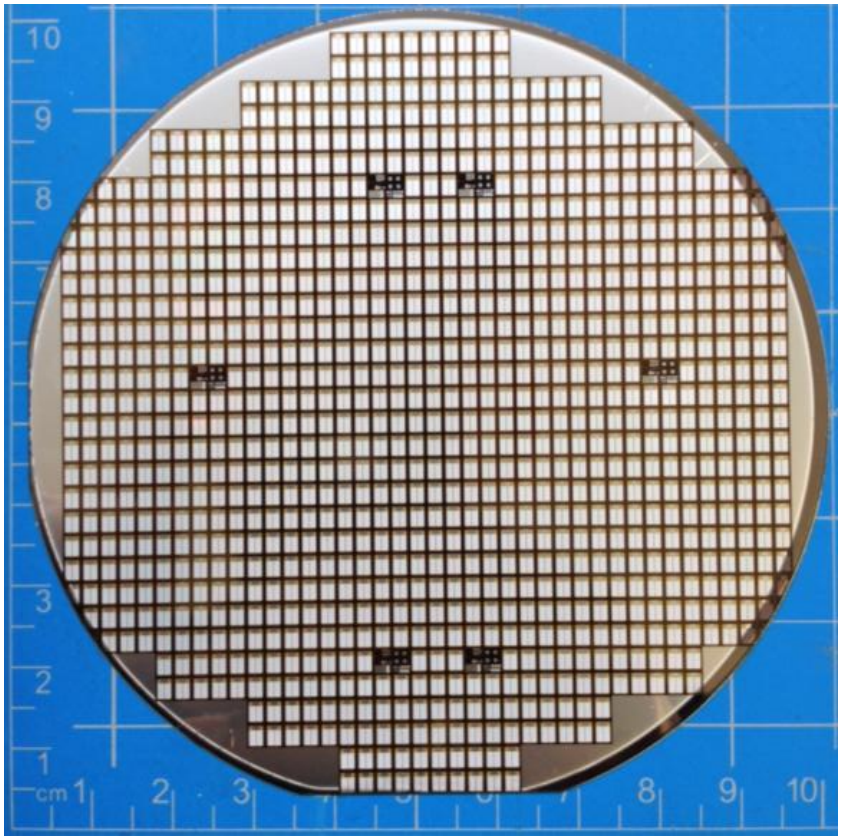
Technical Accomplishment - 900V, 65mΩ SiC MOSFET

- Target applications
  - **ON-board EV chargers**
  - Switch mode power supplies
  - Solar inverters
  - High power DC/DC converters
- AECQ101 qualification effort in progress
  - Expected to be completed in Q2 2015
- Commercial release planned in 2015

100mm 900V, 65 mΩ SiC MOSFET wafer



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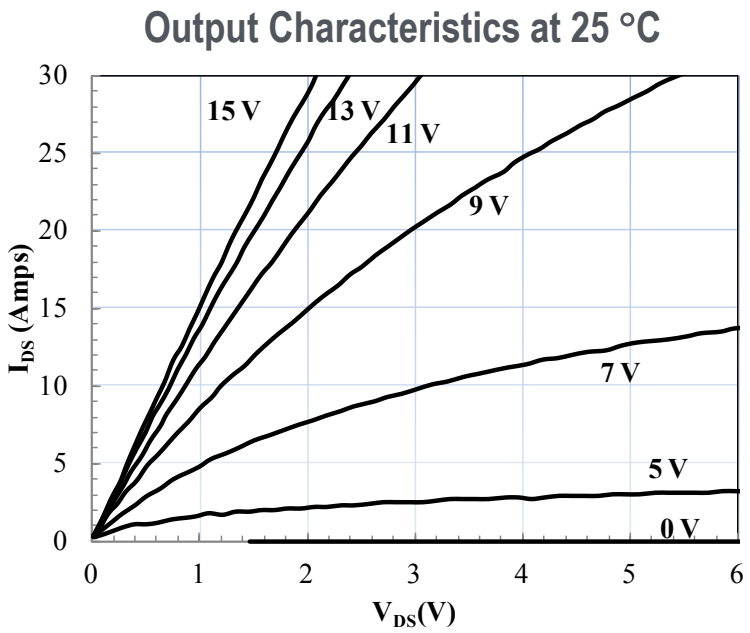
Technical Accomplishment – 150°C JEDEC qualification

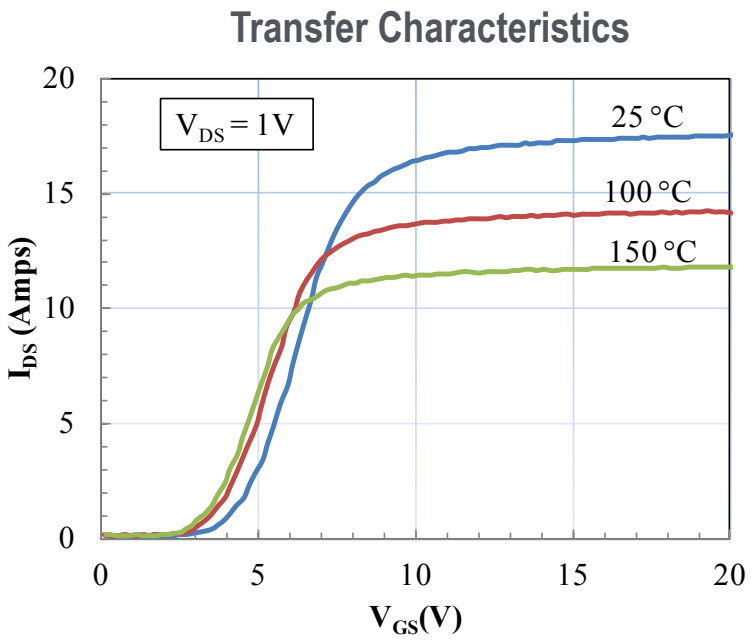
- 900V, 65 mΩ JEDEC Qualification Status (TO-247 Package)
- Qualification complete

Test	Stress Conditions	Duration	Wafer lots sampled	Total devices sampled	Status
HTGB	VGS = +15 V, VDS = 0, Ta=150 °C	1000 hrs	3	75	Complete
HTGB	VGS = -5 V, VDS = 0, Ta=150 °C	1000 hrs	3	75	Complete
H3TRB	85 °C, 85% RH, VDS = 100 V, VGS=0	1000 hrs	3	75	Complete
HTRB	VDS = 720 V, VGS = 0, Ta = 150 °C	1000 hrs	3	75	Complete
TC	-55 °C / +150 °C, JESD22-A104 condition H, soak mode 1	1000 cycles	3	75	Complete
IOL	5 min on / 5 mins off, ΔTj ≥ 100 °C, Tmax ≥ 150 °C	6000 cycles	3	75	Complete
ESD-HBM	Classification at 25 °C	n/a	1	5	Complete
ESD-MM	Classification at 25 °C	n/a	1	5	Complete
ESD-CDM	Classification at 25 °C	n/a	1	5	Complete

Technical Accomplishment – smaller chip demonstrated

- Full turn-ON achieved at +15 V Gate Bias
  - Convenient gate drive using commercial IGBT and MOSFET drivers.





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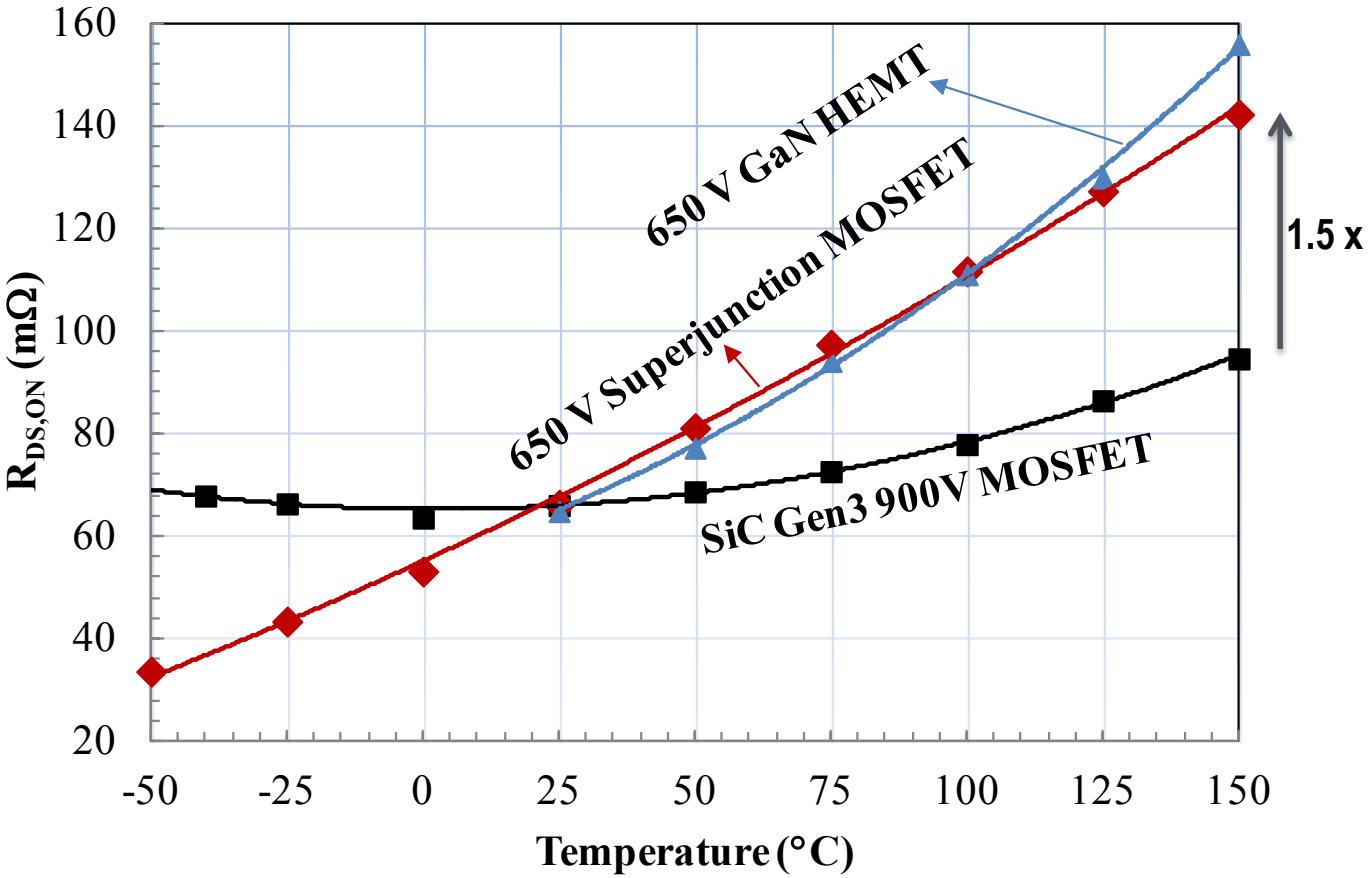
Technical Accomplishment – lower R_{DSON} vs T demo

- 900V SiC MOSFET has a low temperature coefficient of resistance compared to Silicon and GaN
- Enables higher power ratings



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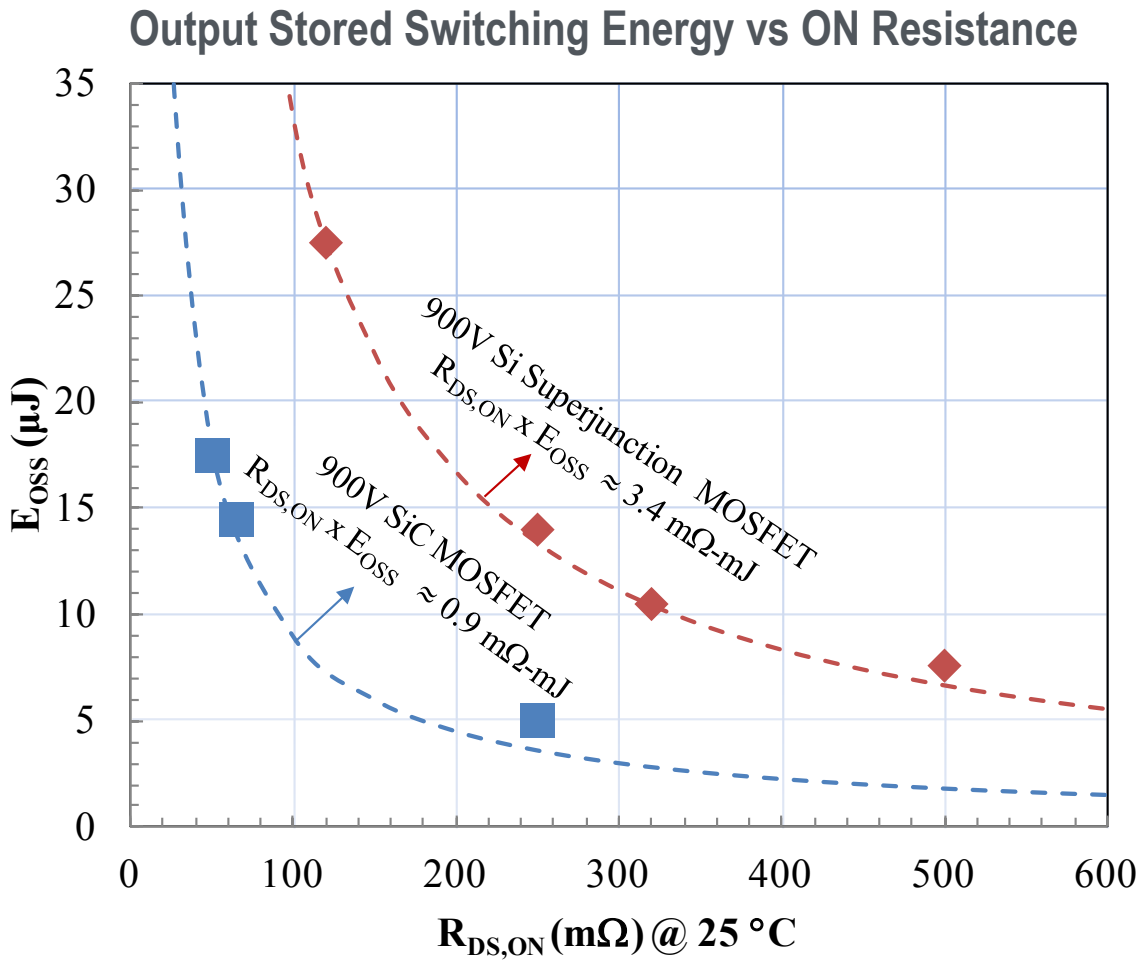
Technical Accomplishment – 6X lower $R_{DSON} \cdot E_{OSS}$



SiC is 4x Better at 25 °C and 6x Better at 150 °C due to lower $R_{DS,ON}$ temperature coefficient

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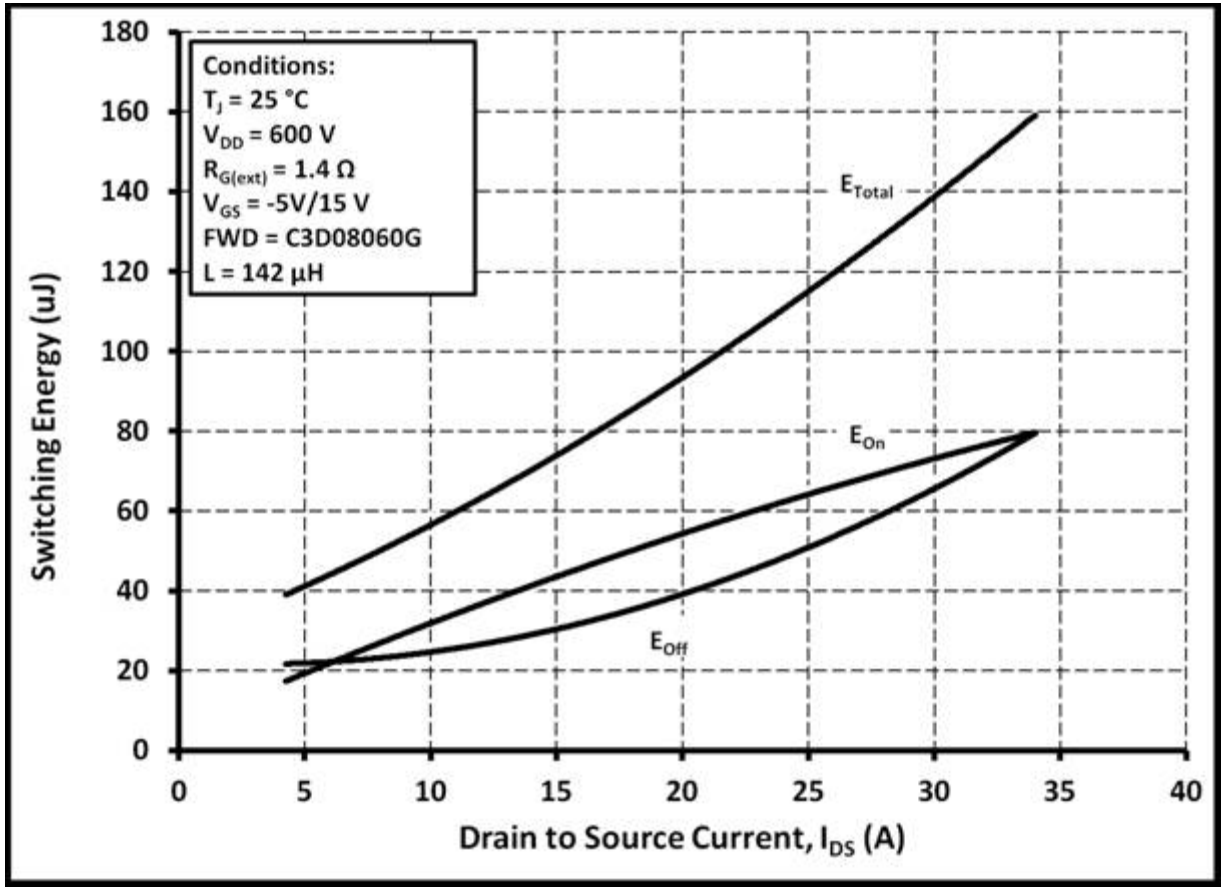
Technical Accomplishment – ultra low measured E_{SW}

Measured Switching Energy compared to Current



Only ~140 uJ at I_{DS} = 30A

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Response to Reviewer Comments

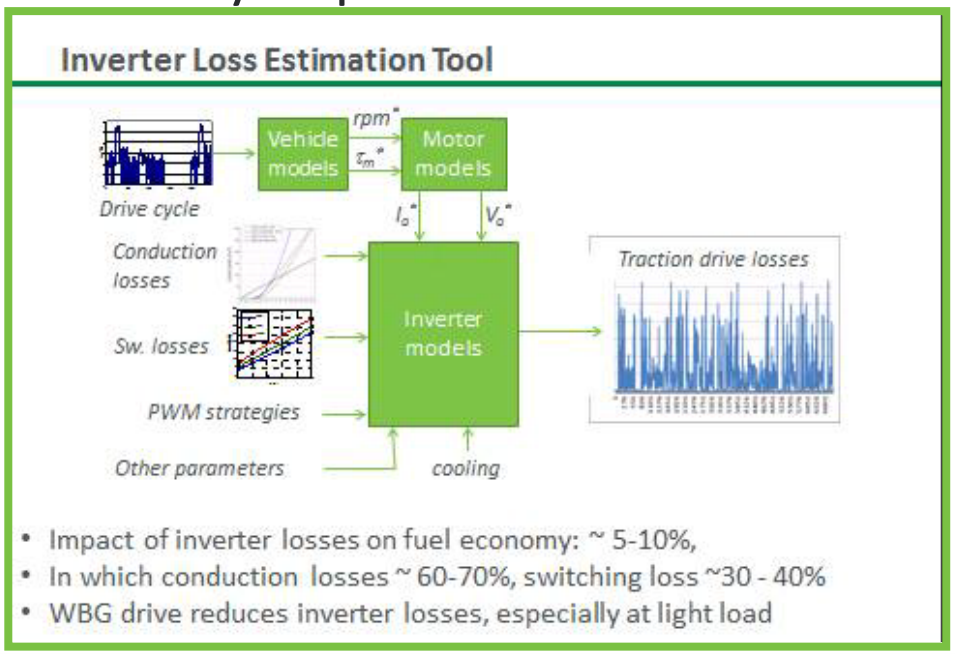
- New project
- No reviewer comments from last year

Partnerships / Collaborations

- None for public disclosure

Remaining Barriers / Challenges

- AEC-Q101 qualification of lowest R_{DSON} SiC power transistor (10mΩ) of any voltage range to date
- Inverter demo – single phase and three phase
- Verifying expected light load efficiency improvement from SiC in drive train



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Future Work

- In 2015:
  - Finish three lots of 900V, 10mΩ SiC MOSFETs and sample to automotive OEM and Tier One suppliers
  - Build 900V, 200A, ½ bridge power module using new SiC MOSFET chips
  - Simulate the light load efficiency in the drive cycle using the new 900V SiC MOSFET
- In 2016:
  - AEC-Q101 qualification of 900V, 10mΩ SiC MOSFETs at chip level
  - Build 70 ½ bridge power modules using new 900V SiC MOSFETs
  - Test MTTF and IOL of SiC MOSFET based power modules
  - Perform single phase and three phase inverter demo's using new 900V SiC MOSFET power modules

Summary

- Cree will develop and optimize a 900V, 10 m-Ohm SiC MOSFET aimed at x-EV applications, based on specifications provided by Ford and other automotive Tier One suppliers.
  - 200-600 MOSFETs for external sampling from optimization lots.
  - 1,100 MOSFETs to APEI for module assembly from qual lots.
  - Cree will qualify the optimized SiC MOSFET chip according to AEC-Q101 (~1,500 MOSFETs)

~3k MOSFETs

- APEI will construct 900V, 200A, ½ bridge power modules using the 900V SiC MOSFET and benchmark against other technologies. Benchmark includes performance & reliability.
  - APEI will valuate the ½ bridge power module in an 88 kW peak power traction drive inverter for x-EV.

~ 70 modules

- Ford will provide technical input on system specifications, and evaluation of new 900V SiC products developed.