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”

June 8, 2016

Project ID #
**EDT073**

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*Chingchi Chen, Ming Su – Ford Motor Company*

Wolfspeed. A CREE COMPANY

Ford

# Project overview

## Timeline*

- Project Start – Dec. 11, 2014
- Project Complete – Dec. 10, 2016
- **67% 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 funds: | $4,045,496.00 |
| • Expended*: | $3,073,690.15 |

- **76% Complete**

* As of 27 Mar 2016

## 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 $m\Omega\cdot cm^2$ | Si IGBT | *900 V SiC FET @ 2.2 $m\Omega\cdot cm^2$* |
| 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***

# Relevance to commercialization

**EE0006920 "88 kW Automotive Inverter with New 900V SiC MOSFET Technology"**

**AEC-Q101 qualified & released 900V SiC MOSFETs available for automotive design & production**

900V, 10 mΩ SiC MOSFET sampling (2015)

900V MOSFET chip & module benchmark in 88 kW traction inverter & chip qualification (2016)

Vehicle prototype & design*

(2017)

Vehicle qualification (2018-20)

Vehicle Mass Production in 2020-22 MY (Fall 2019)

* 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.

# 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. | **Done** |
| 2 | 12/15/2015 – 12/14/2016 | Three-phase traction drive demonstration. | Technical | Perform three-phase traction drive demo using 900V, **400A***, ½ bridge power modules and evaluate impact of SiC performance on automotive traction drive system. | Scheduled to complete in 2016. |

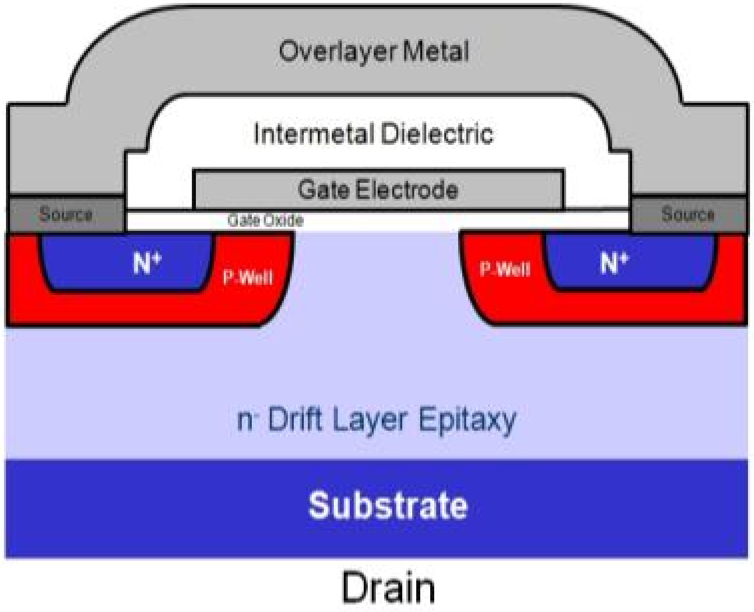
- Interim Milestones are defined in the SOPO and PMP
- * Milestone in BP2 contract call for 900V, 200A module; now targeting 400A stretch goal

# Approach: motivation for 10mΩ, 900V SiC MOSFET

- EV drives, and resonant topologies found in on-board chargers and telecom power supplies desire >600V SiC MOSFETs with the lowest $R_{DSON}$ per TO-247 package
- Emphasis on the lowest $R_{DSON}$ over operating temperature range
- Lateral GaN transistors have improved switching characteristics over Si, but are comparable to Si superjunction MOSFETs with respect to conduction losses per unit semiconductor area, and hence are not expected to bring significant gains in current densities
- Si IGBTs offer very attractive current densities because they have low conduction losses at high power, high temperature operating conditions. However in light load conditions, IGBT losses increase relative to SiC MOSFETs due to their higher switching losses and the knee voltage drop.

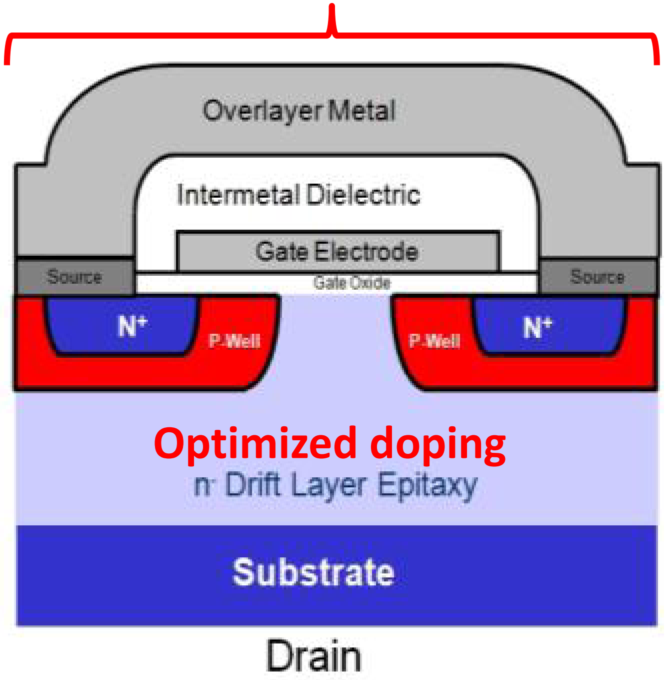
# Approach – scale & automotive qualify 900V “Gen 3” for 10mΩ

## Goal: Automotive qualify lowest $R_{DSON}$ SiC MOSFET



Gen 2 DMOS

**Reduced pitch**



**Optimized doping**

Gen 3 DMOS

Commercially released in **2013** as “C2M” product family at 1.2-1.7kV

Commercially released in **2015** as “C3M” product **65**-280mΩ at 0.9kV

Design and automotive qualify 32mm$^2$ chip with has >2X lower $R_{DSON}$ than any commercial FET

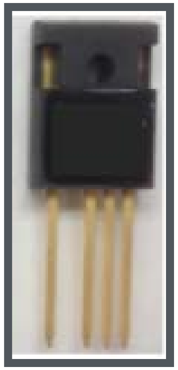
# Approach – detailed work plan; 96 wafers, 76 modules, > 8,000 FETs

| Task # | 900V, 10mΩ SiC MOSFET development & qual | Wafers | Start | ECD | ACD |
|---|---|---|---|---|---|
| 1 .1 | Die centering – lot #1 | 9 | Feb 2015 | Jun 2015 | Jun 2015 |
| 1.1 | Source pad layout options, $R_{DSON}$ vs $t_{SC}$ - lot #2 | 6 | Jun 2015 | Sep 2015 | Sep 2015 |
| 1.1 | 2G bus line source pad risk lot (Go / No-go milestone) – lot #3 (at TEAM) | 6 | Sep 2015 | Nov 2015 | Oct 2015 |
| 1.1 | Doping experimental lots – lot #4; adding four new lots to accelerate | 6 +24 | Oct 2015 | Nov 2015 | Dec 2015 |
| 1.2 | Pre-qual lot – lot #5 **(Delivery of die for 70 module build)** | 9 | Jan 2016 | Feb 2016 | **Apr 2016** |
| 1.2 | Qualification Lot #1 – lot #6 | 12 | Mar 2016 | May 2016 | |
| 2.1 | Qualification Lot #2 – lot #7 | 12 | Mar 2016 | May 2016 | |
| 2.1 | Qualification Lot #3 – lot #8 | 12 | Apr 2016 | Jun 2016 | |
| 2.1 | Qualify 900V, 10mΩ SiC MOSFET chip by AEC-Q101 standards | --- | Jun 2016 | Nov 2016 | |

| Task | 900V ½ bridge power module develop & qual | Modules | Start | ECD | ACD |
|---|---|---|---|---|---|
| 1 .3 | Assemble, characterize and benchmark power modules (900V, >200A, ½ bridge) | 6 | June 2015 | Sept 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 | Three phase traction drive demo | 25 | Jun 2016 | Sep 2016 |
| 2.3 | Benchmark 900V SiC based technology with competing technologies | --- | Aug 2016 | Dec 2016 |

# Approach – MOSFET qualification plan at 175°C

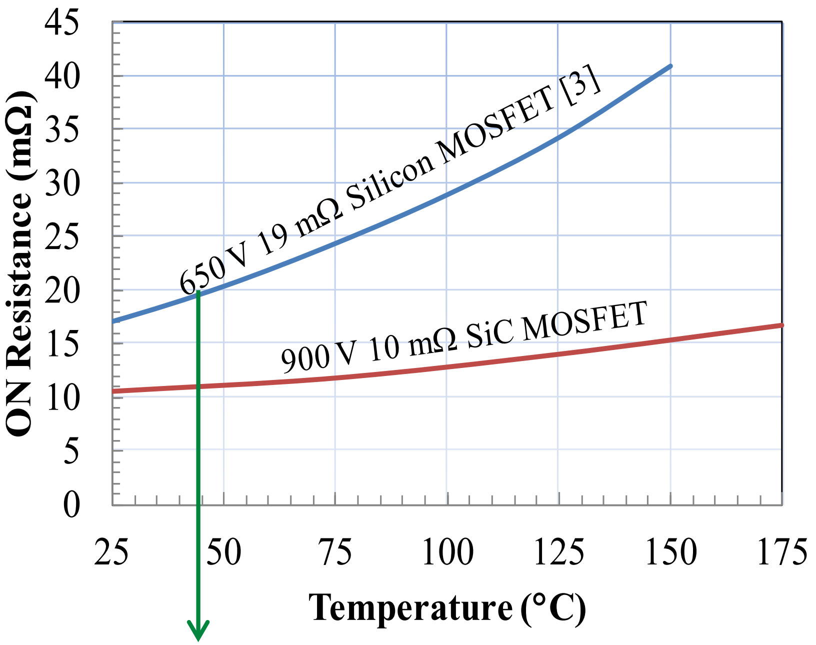


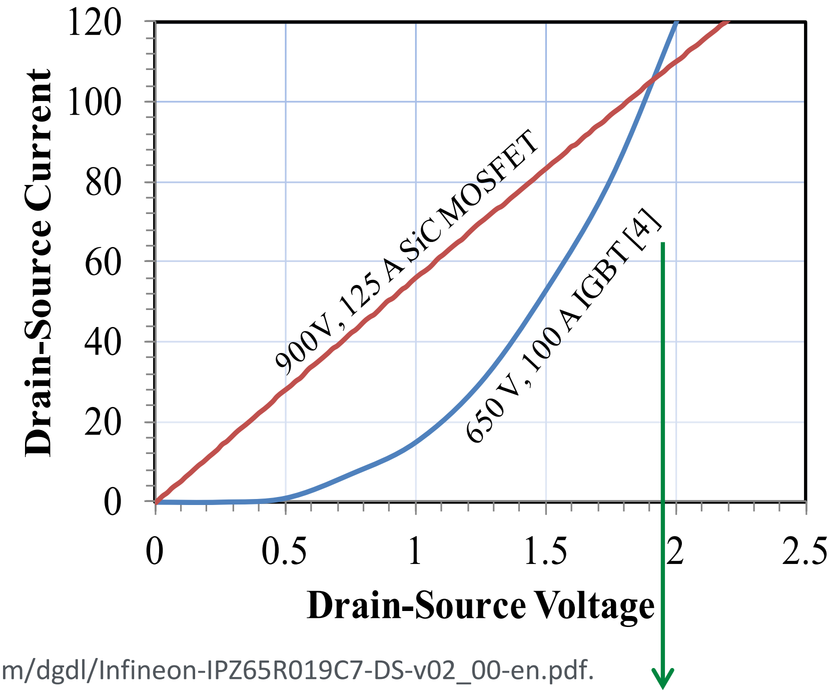
- 32mm$^2$ die to be qualified at a $T_{J,Max}$ of 175°C
- AEC-Q101 die level qualification tests in TO-247
- Lowest $R_{DSON}$ automotive chip qualification attempted to date

| **Test** | **Stress Conditions** | **Duration** | **Wafer lots sampled** | **Total devices sampled** |
|---|---|---|---|---|
| HTGB | $V_{GS}$ = 15 V, $V_{DS}$ = 0,<br>Ta=175 °C | 1000 hrs | 3 | 231 |
| H3TRB | 85 °C, 85% RH,<br>VDS = 100 V, VGS=0 | 1000 hrs | 3 | 231 |
| HTRB | VDS = 720 V, VGS = 0,<br>Ta = 175 °C | 1000 hrs | 3 | 231 |
| TC | -55 °C / +175 °C,<br>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 |

# Technical Accomplishment: 900V 10mΩ SiC MOSFET DC characterization

- Comparing **900V** SiC MOSFET to **650V** Si
- Lower positive temperature coefficient than Si superjunction MOSFET
  - 10mΩ at 25°C increases to ~ 14mΩ at 150°C for **900V SiC** MOSFET
  - 17mΩ at 25°C increases to ~ 41mΩ at 150°C for **650V Si** MOSFET
- No knee voltage as found in IGBT





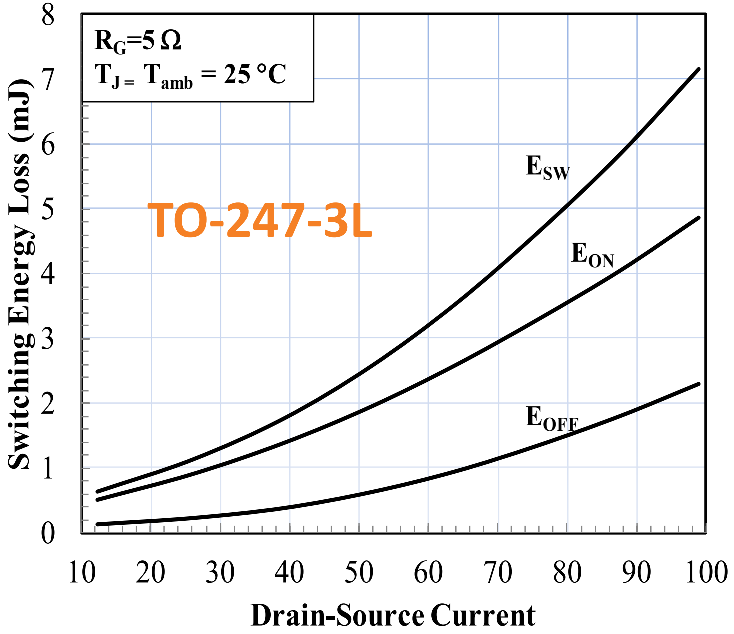
Infineon 650V, 19mΩ MOSFET, part number IPZ65R019C7, http://www.infineon.com/dgdl/Infineon-IPZ65R019C7-DS-v02_00-en.pdf.

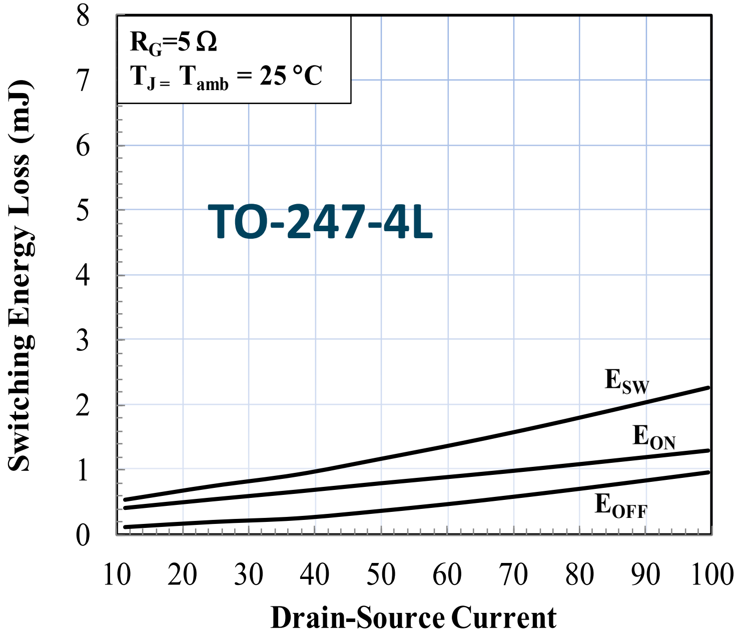
Infineon 650V 100 A IGBT, Part No. IGZ100N65H5, http://www.infineon.com/dgdl/Infineon-IGZ100N65H5-DS-v02_01-EN.pdf.

# Technical Accomplishment: 900V 10mΩ SiC MOSFET switching energies

## ~3.5 lower switching energy with Kelvin Source contact

- LEFT: Switching Energy losses at 25 °C for 900V, 10 mΩ SiC MOSFET in TO-247-3 package ($R_G$=5Ω, $V_{GS}$=-4V/+15V, $V_{DD}$=600V)
- RIGHT: Switching Energy losses at 25 °C for 900V, 10 mΩ SiC MOSFET in TO-247-4 package ($R_G$=5Ω, $V_{GS}$=-4V/+15V, $V_{DD}$=600V)



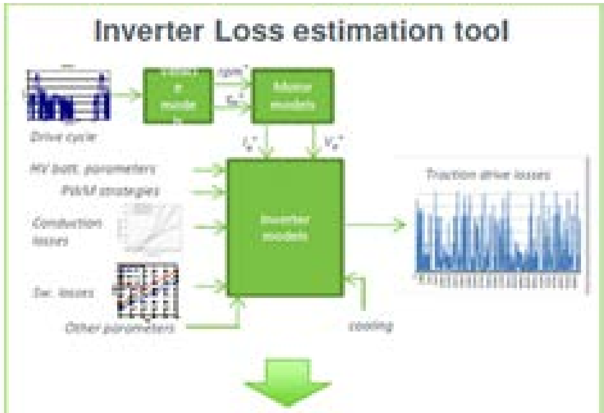


# Technical Accomplishment: BEV loss reduction modeled based on 900V SiC

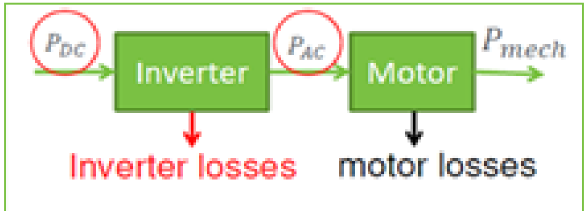
## Compared with Si inverter, SiC reduces inverter losses ~67% in combined EPA drive cycle

pcim EUROPE

Nuremberg, 10 – 12 May 2016

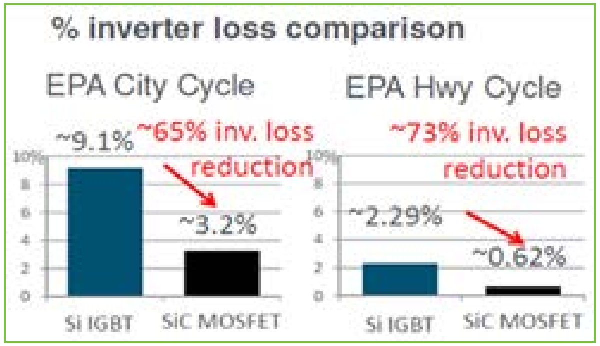


- **Assume Ford Focus EV equipped with 90kW IPM motor**
- **C-Max 90kW Si IGBT inverter or Wolfspeed 88kW SiC inverter as the traction drive**
- **Synchronous rectification of SiC devices; no diodes in parallel w/MOSFETs**

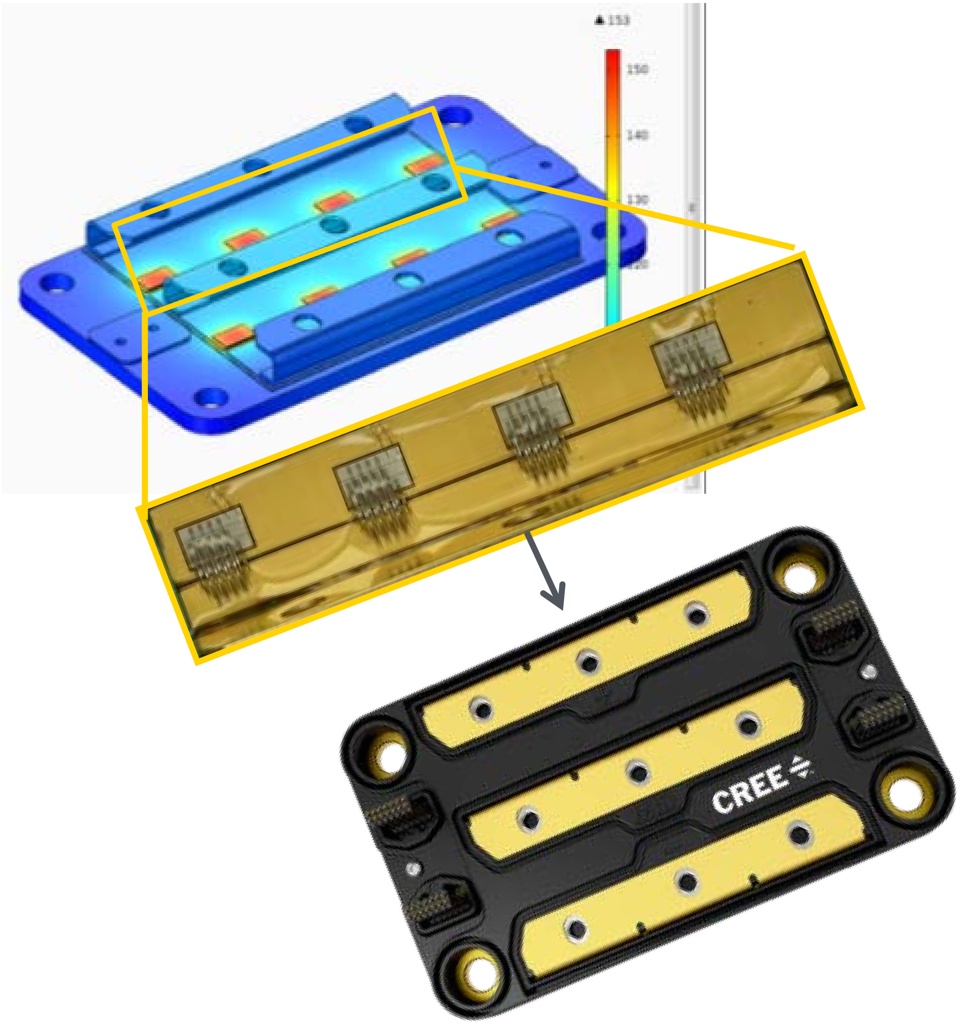


% Inverter losses =

$(1 - P_{ac}/P_{DC})$ * 100%



# Technical Accomplishment: constructed 900V, 400-800A, power modules



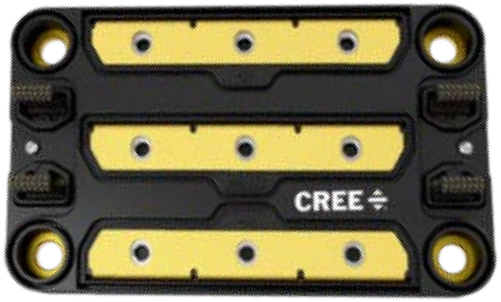
- Assembled 900V, 10mΩ SiC MOSFET chips in custom ½ -bridge module
  - 4 chips – 2.5mΩ module
  - 8 chips – 1.25mΩ module

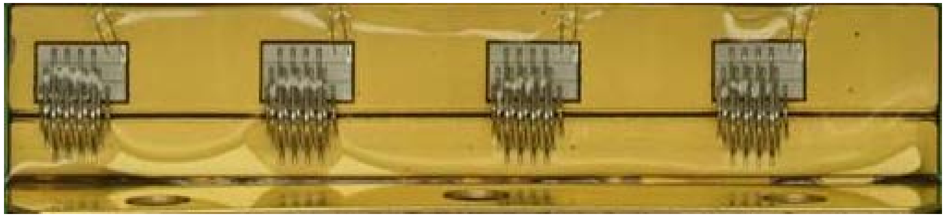
- **HTRB (150°C) completed**
  - 6 modules (48 MOSFETs)
  - 1000 hrs; Zero failures
- **HTRB (175°C) completed**
  - 5 modules (same modules as 150˚C test)
  - 850 hrs; Zero failures

# Technical accomplishment: benchmark 900V SiC & 650V Si power modules

900V SiC XAB350M09HM3 versus the 650 V EconoDUAL3 Si IGBT power module

- 250 V higher blocking voltage
- 10-20x lower body diode recovery, gate charge, and reverse transfer capacitance.
- Symmetrical 3rd quadrant conduction
- Ultra-low on-state losses





| Parameter | Wolfspeed XAB350M09HM3 | Infineon FF450R07ME4_B11 |
|---|---|---|
| Package | HT-3000 (custom) | EconoDUAL3™ |
| Blocking voltage (V) | **900** | **650** |
| $T_{J,MAX}$ (°C) | 175 | 175 |
| $R_{DS,\ ON}$ (mΩ) (25°C/150°C) | 2.5 / 3.6 | N/A |
| $I_{DS}$ @ 150°C (A) | 405 | 430 |
| $Q_G$ (nC) | **648** (162 x 4) | **4800** |
| $Q_R$ @ 150°C (μC) | **2.02** (0.504 x 4) | **35.5** |
| Input capacitance, $C_{iss}$ / $C_{ies}$ (nF) | **15.7** (3.93 x 4) | **27.5** |
| Rev. transfer cap, $C_{rss}$ / $C_{res}$ (pF) | **72** (.018 x 4) | **820** |

# Technical Accomplishment: 8 die / switch position half-bridge module

## Lowest $R_{DSON}$ ½ Bridge Module rated >600V (XAB700M09HM3)

*(of <u>any</u> technology… Si, SiC, GaN, …)*

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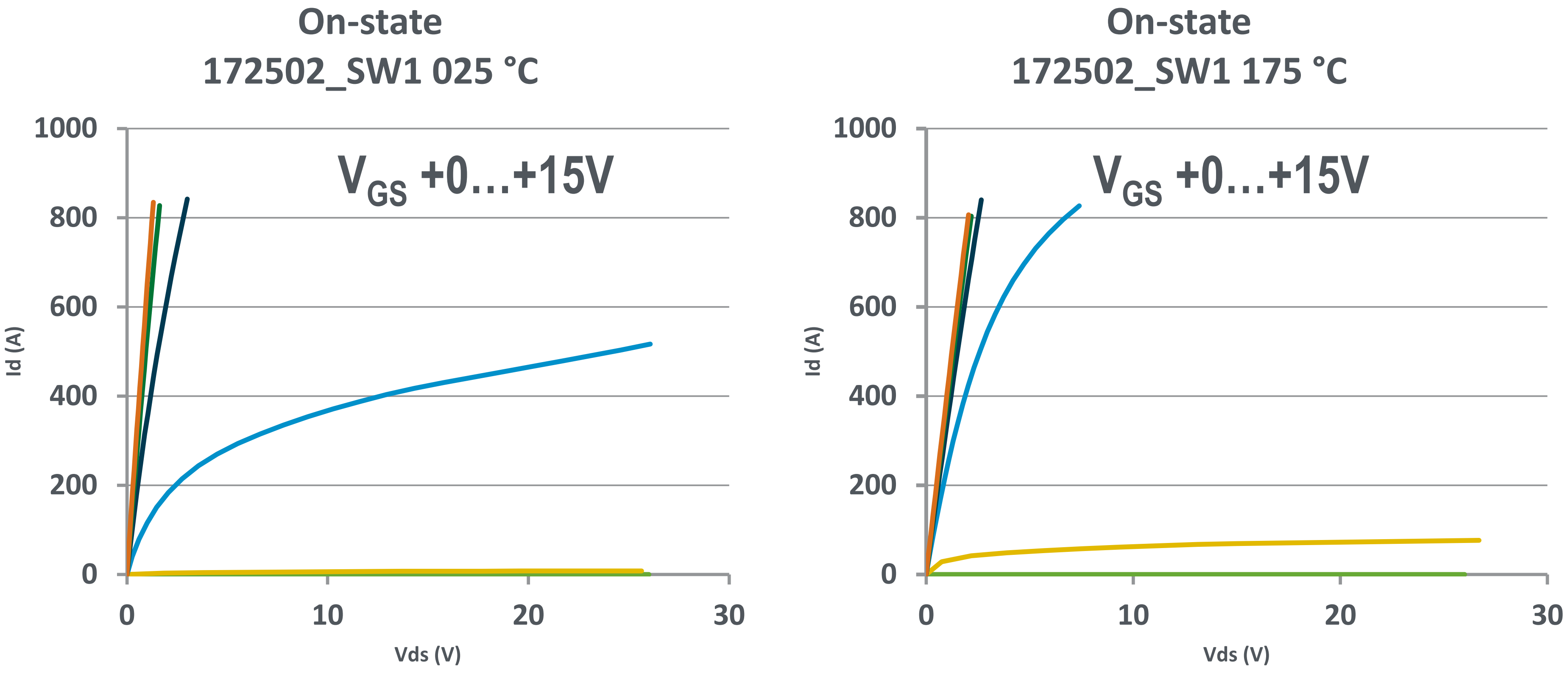

# Technical Accomplishment: 900V, HB – 8 die/switch; 8 modules

## Low $R_{DSON}$ increase up to 175˚C (XAB700M09HM3)

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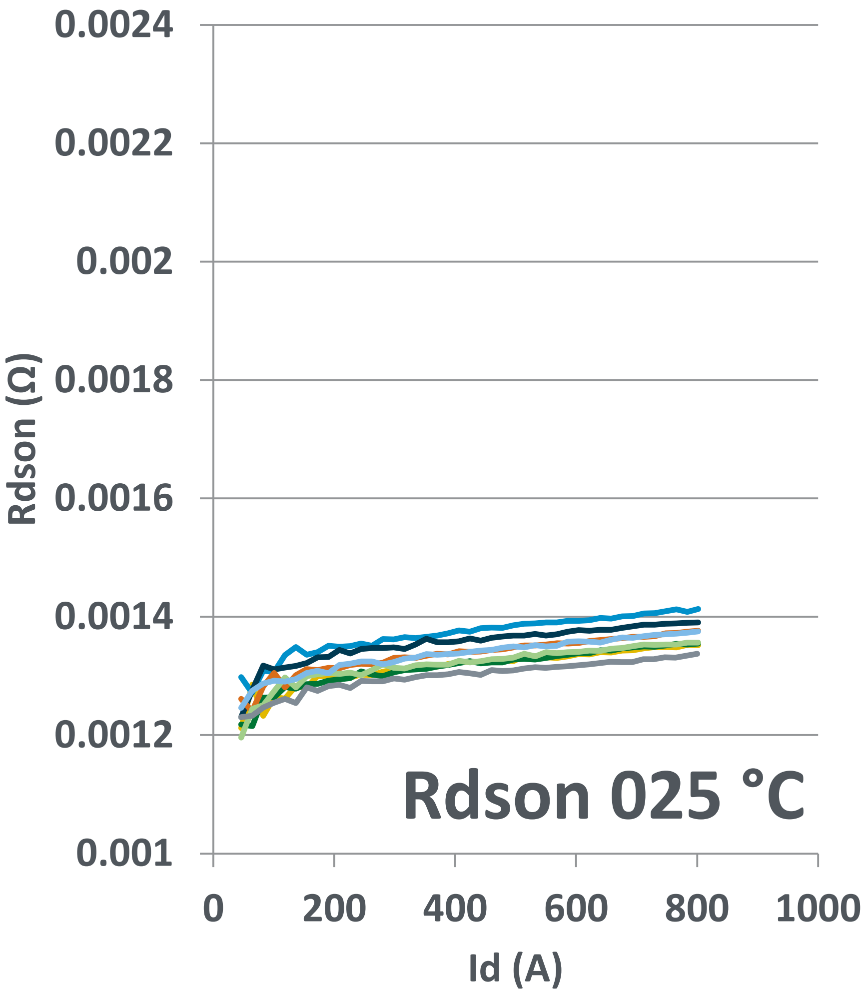
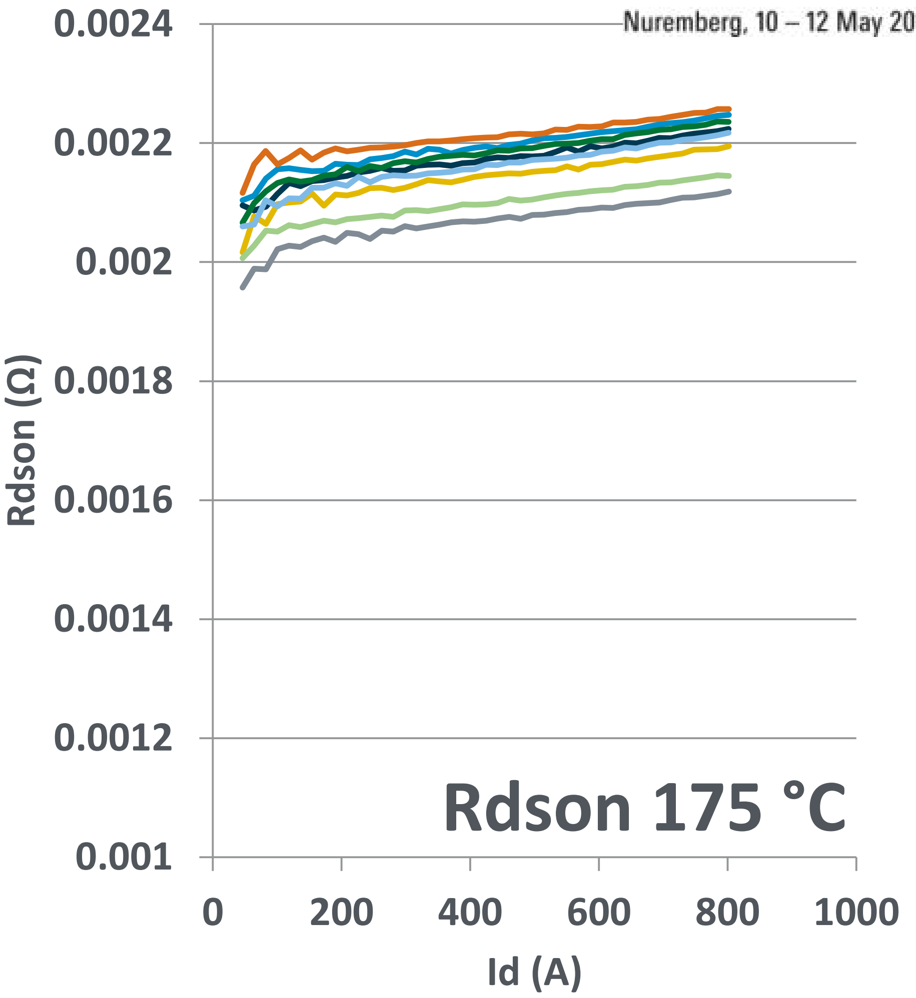
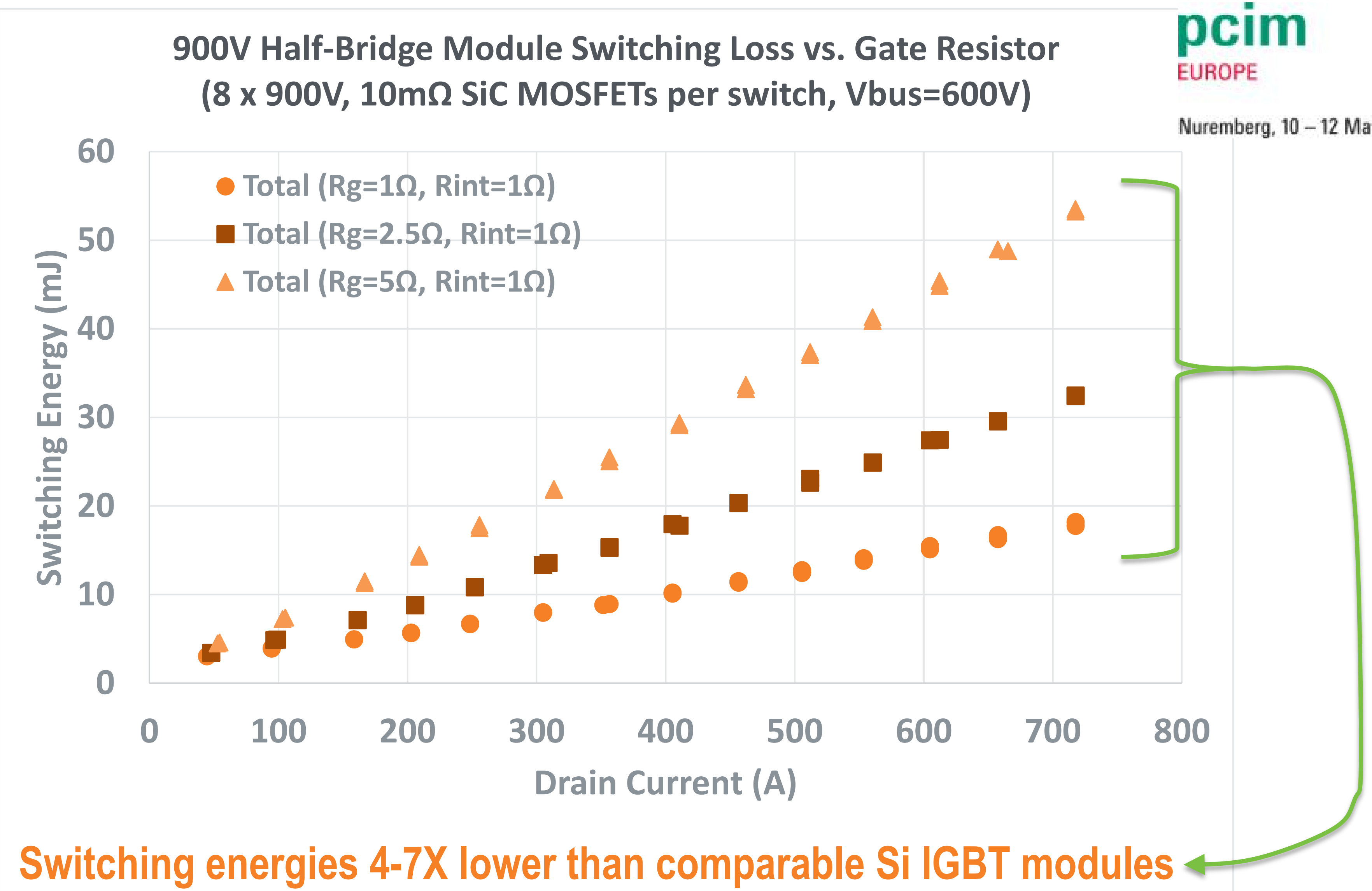




# Technical Accomplishment: 900V, HB – 8 die/switch; switching energy



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**Switching energies 4-7X lower than comparable Si IGBT modules**

Wolfspeed. A CREE COMPANY

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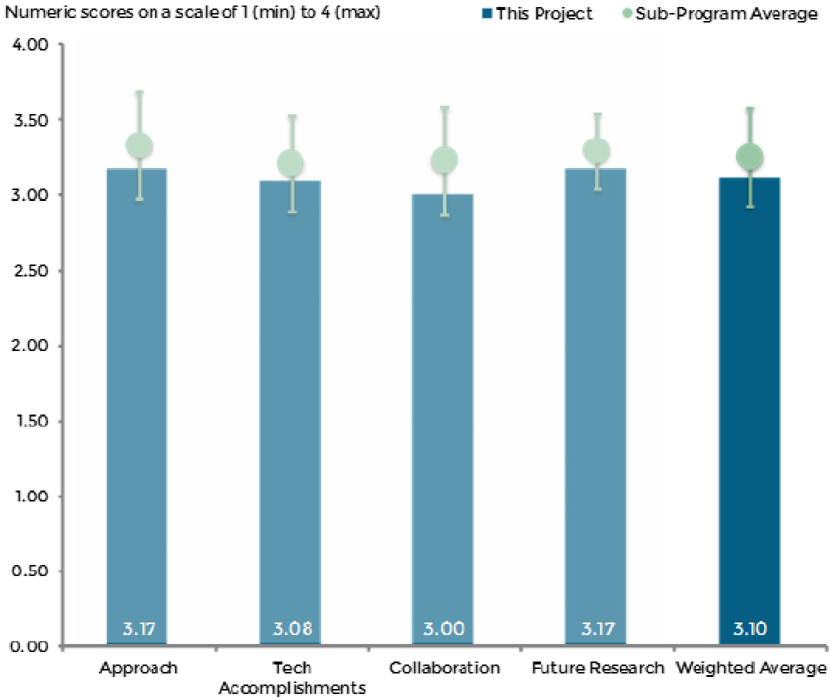
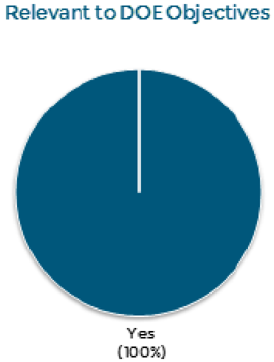
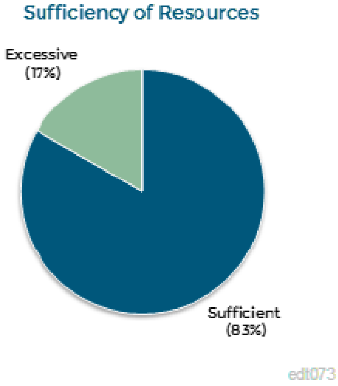
# Response to reviewer comments

- Question 1: Requested details of module level qualification could be disclosed.
  - This qualification will follow the same guidelines as the chip level qualification TO-247, but utilize fewer modules. Each module contains a minimum of eight MOSFETs per module, or 256mm$^2$ of SiC.
- Question 2: Is this appropriate work for DOE, because it just seems to be qualifying and demonstrating a part?
  - The part being developed here is 20% larger than the largest SiC MOSFET in the market today, and significant design work was undertaken to optimize yield, performance, and reliability. It has also an on-resistance which is significantly less than any (Si, SiC, or GaN) power FET in the market with >600V blocking capability. Additionally, to our knowledge, no SiC MOSFETs are AEC-Q101 qualified, so this is a very aggressive goal. To develop and qualify this MOSFET for the automotive market would be a historic milestone for the SiC and WBG industry. It would allow automotive customers to begin designing systems around this MOSFET.





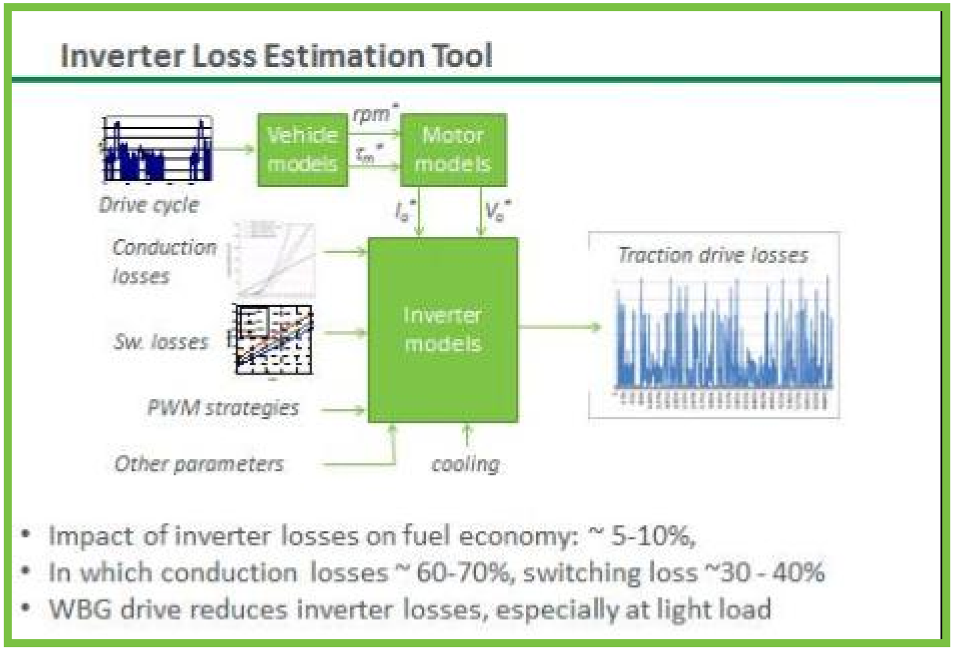


# Partnerships / Collaborations

- 9 automotive OEMs,
- 3 Tier One automotive suppliers
- 1 Tier Two automotive supplier
  - *(parties cannot be named as protected by NDA)*

# Remaining barriers / challenges

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

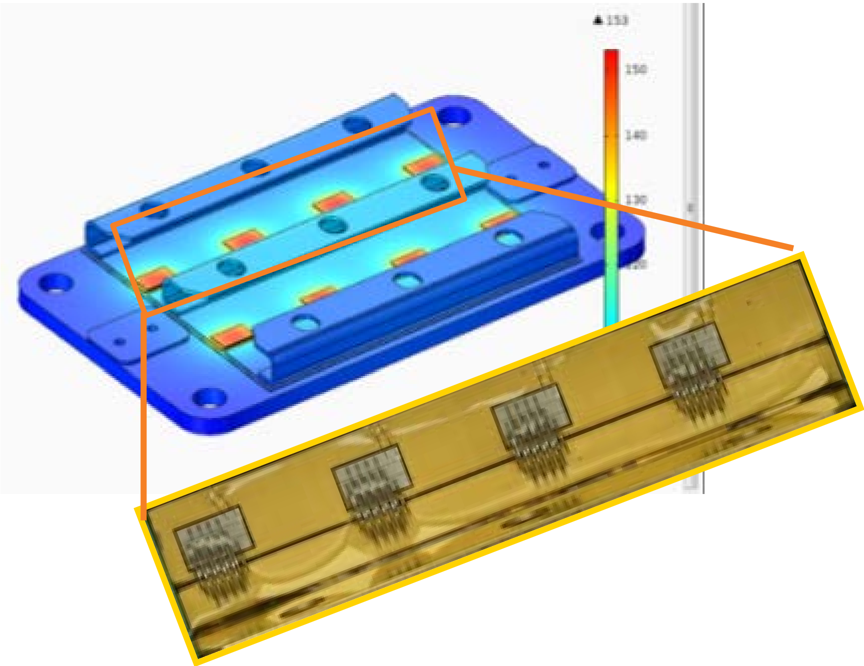


**Inverter Loss Estimation Tool**

- Impact of inverter losses on fuel economy: ~ 5-10%,
- In which conduction losses ~ 60-70%, switching loss ~30 - 40%
- WBG drive reduces inverter losses, especially at light load

# Future work

- 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

~6.3k MOSFETs

- Cree/Wolfspeed **has** developed and optimized a 900V, 10 m-Ohm SiC MOSFET aimed at x-EV applications, based on specifications provided by Ford and other automotive Tier One suppliers.
  - ~600 MOSFETs for external sampled from optimization lots.
  - ~3,000 MOSFETs sampled via external commercial follow-on orders.
  - ~1,200 MOSFETs for module assembly from two lots.
  - Cree **will** qualify the optimized SiC MOSFET chip according to AEC-Q101 (~1,500 MOSFETs)

~ 70 modules

- Cree **will** construct 900V, 400A, ½ bridge power modules using the 900V SiC MOSFET and benchmark against other technologies. Benchmark includes performance & reliability.
  - Cree will evaluate the ½ bridge power module in an 88 kW peak power traction drive inverter for x-EV.
- Ford will provide technical input on system specifications, and evaluation of new 900V SiC products developed.

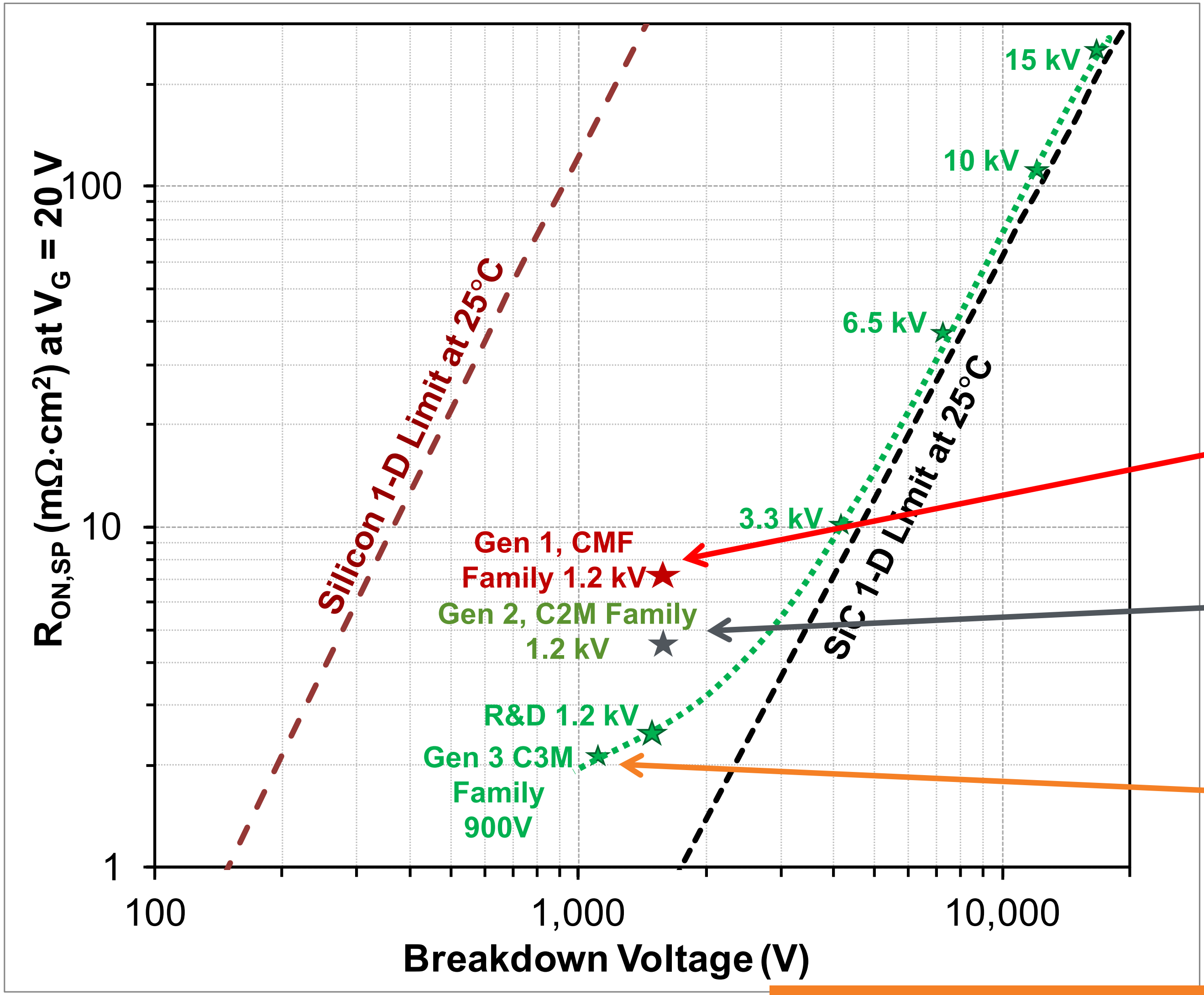
# Summary - continued

- Key measured characteristics of 10 m$\Omega$ 900V SiC MOSFETs were:
  - Record low $R_{DSON}$ in a TO-247 package with a chip size of only 32 mm$^2$.
  - Significantly lower $R_{DSON}$ increase over temperature relative to Si and GaN FETs.
  - Robust, low 510nC $Q_{RR}$ body diode well suited to hard switched topologies with bi-directional conduction

- SiC MOSFETs have much reduced switching losses and knee-less conduction in first ***and*** third quadrant compared to IGBTs, thus simultaneously enabling:
  - high frequency,
  - high power density,
  - lower component count (no external diode required)
  - higher efficiencies (switching and conduction)

# Technical back-up slides

# Approach: next-gen SiC DMOS lowers specific $R_{DSON}$ dramatically



**2011 release (1200V)**

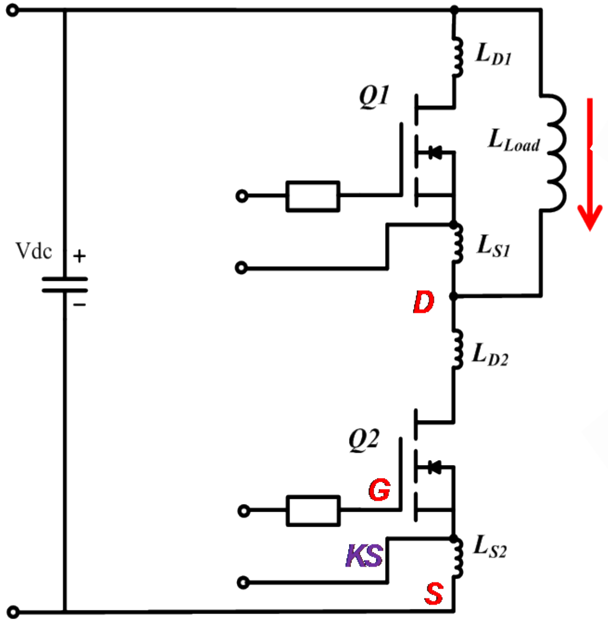
**2013 release (1200V & 1700V)**

**2015 release (900V) 2.3mΩ·cm$^2$**

New 900V SiC MOSFET released is 2.3mΩ·cm$^2$

# Technical Accomplishment:  900V 10mΩ SiC MOSFET AC characterization

- The 900V 10 mΩ SiC MOSFET chip is capable of extremely fast transitions.
- In TO-247-3, $L_S$ in the gate driver loop will limit the switching speed.  TO-247-3 package and TO-247-4 package evaluated.
- TO-247-4 has a separate source return pin for the gate driver equivalent circuit.  $V_{G,KS}$ is not affected by the voltage drop in the source inductance $L_{S2}$ introduced by the *di/dt* of the drain-source current.



**TO-247-4**

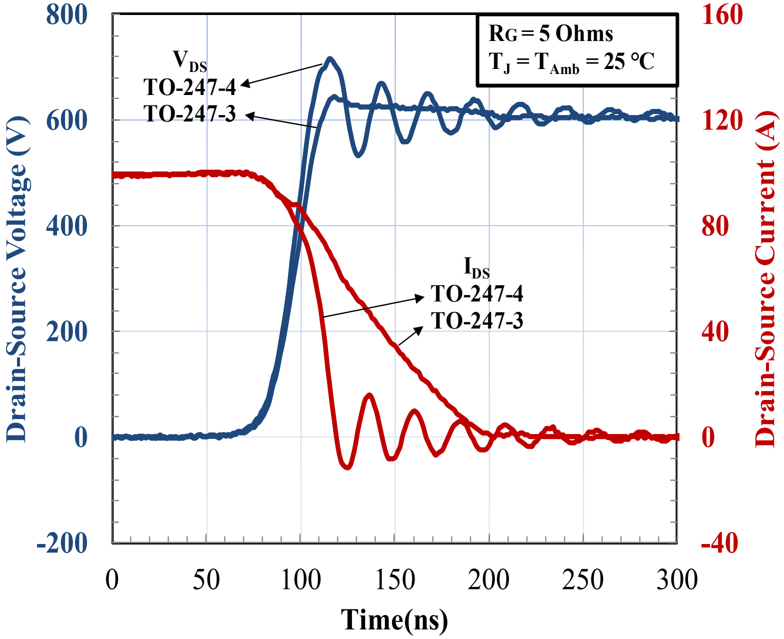
**TO-247-3**

# Technical Accomplishment: 900V 10mΩ SiC MOSFET waveforms (600V, 100A)

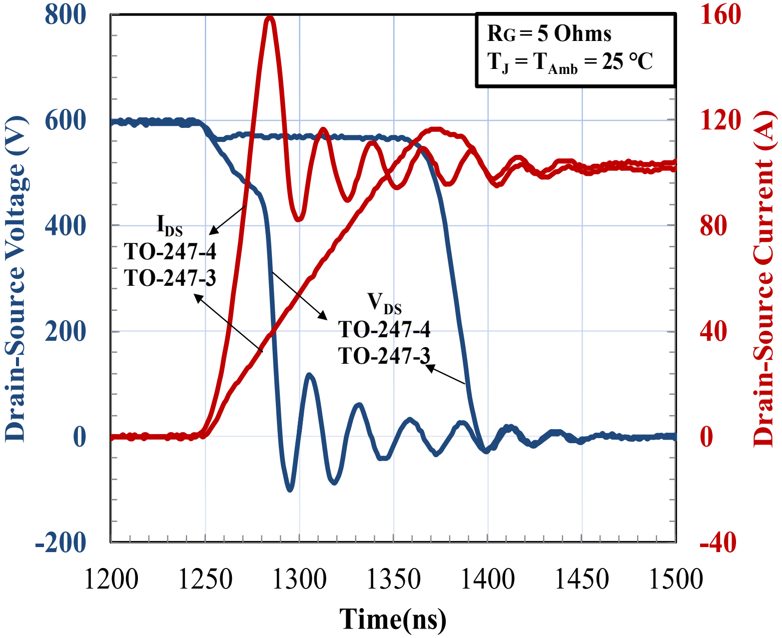
## Up to 9X faster transitions with Kelvin Source contact

- LEFT: Comparison of Turn-OFF for 900V, 10 mΩ SiC MOSFET in TO-247-3 and TO-247-4 packages ($R_G$=5Ω, $V_{GS}$=-4V/+15V)
- RIGHT: Comparison of Turn-ON for 900V, 10 mΩ SiC MOSFET in TO-247-3 and TO-247-4 packages ($R_G$=5 Ω, $V_{GS}$=-4V/+15V)

### Turn-OFF



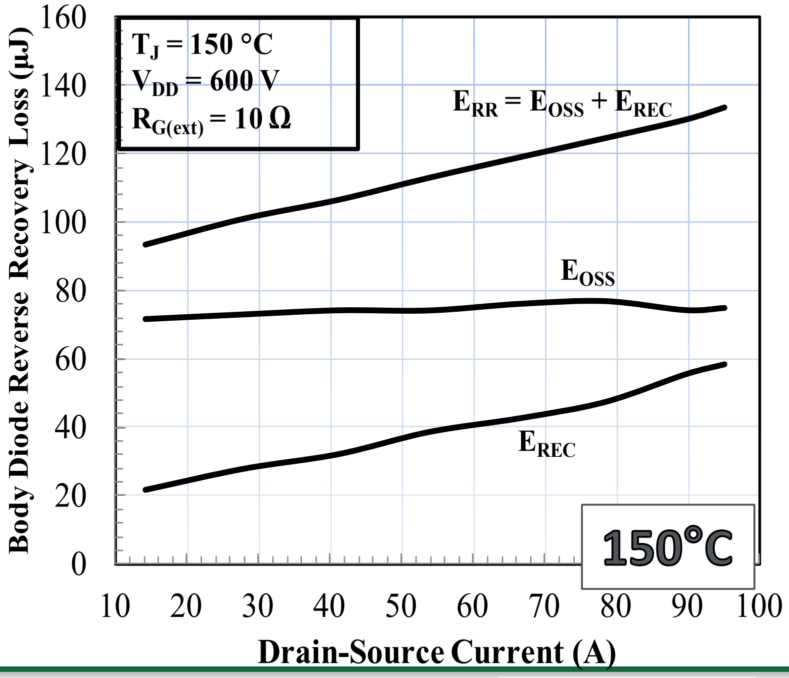
### Turn-ON



# Technical Accomplishment:  900V 10mΩ SiC MOSFET body diode result

## Body diode switching losses are a very low percentage of total switching energy

- Body diode exhibits only a moderate increase in reverse recovery at 150°C., indicating most losses are due to $E_{OSS}$ and not bipolar recombination ($E_{REC}$).
- The stored energy component can be recovered in resonant topologies, further reducing the overall diode loss.
- The 900V 10 mΩ SiC MOSFET body diode tested up to a *di/dt* of 5900A/us with no failures.



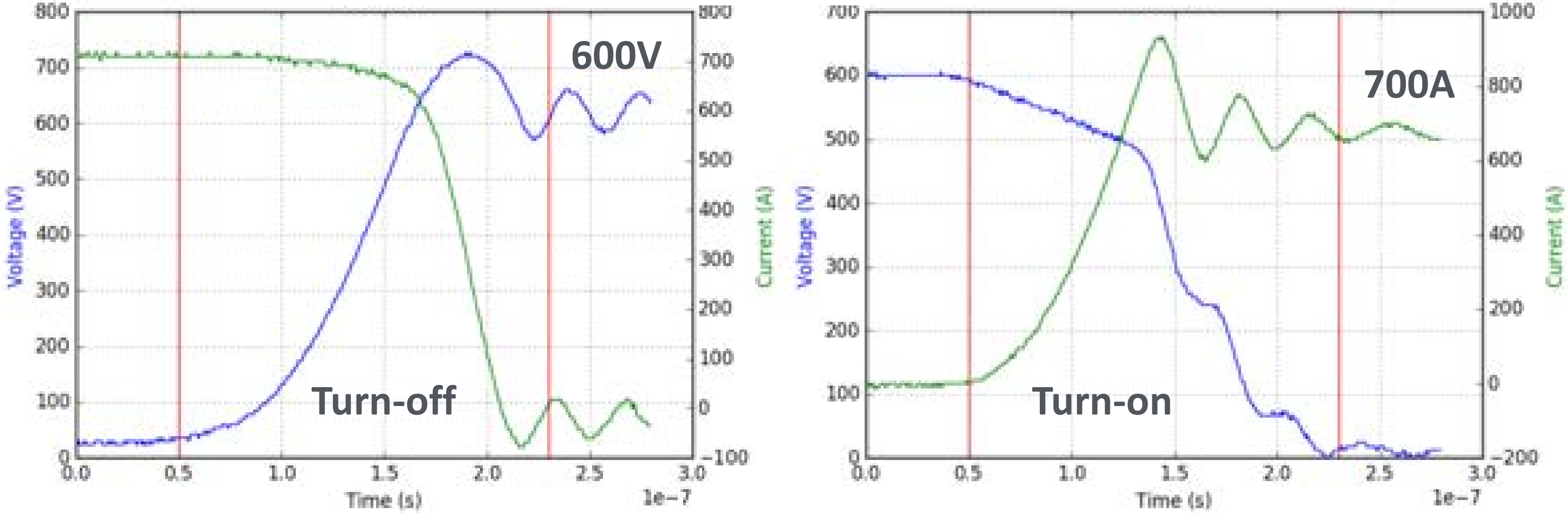
# Technical Accomplishment: 900V, HB – 8 die/switch; switching waveforms

## 35% current overshoot in turn-on can be reduced with filtering

pcim
EUROPE

Nuremberg, 10 – 12 May 2016

XAB700M09HM3 switching waveforms with $R_G$ = 5 Ohm; $R_{Gint}$ = 1



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