Medium Voltage SiC R&D update

Jeffrey B. Casady, Ty McNutt, Dave Girder & John Palmour

Jeff.Casady@wolfspeed.com or 919.308.2280 (US)

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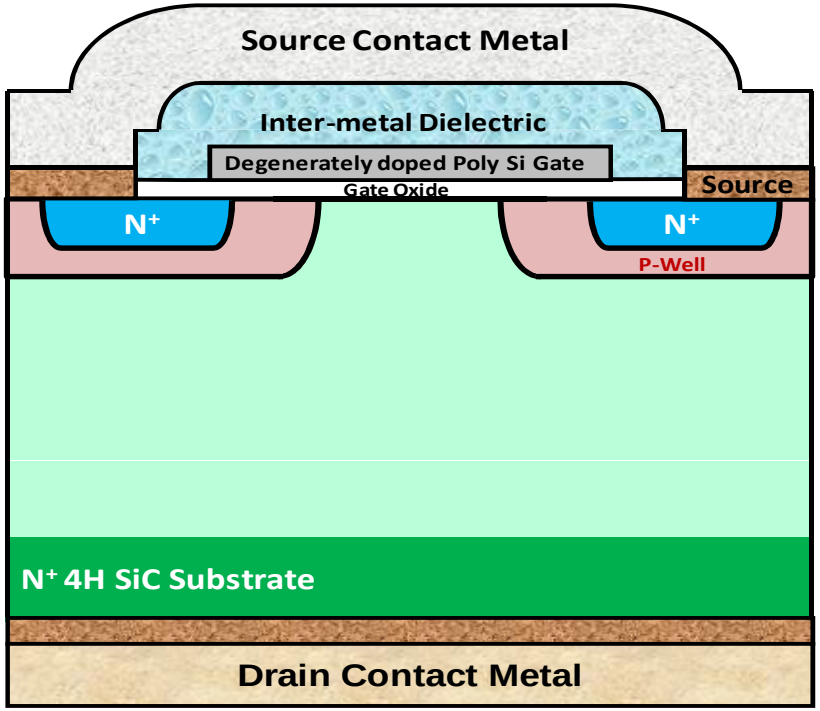
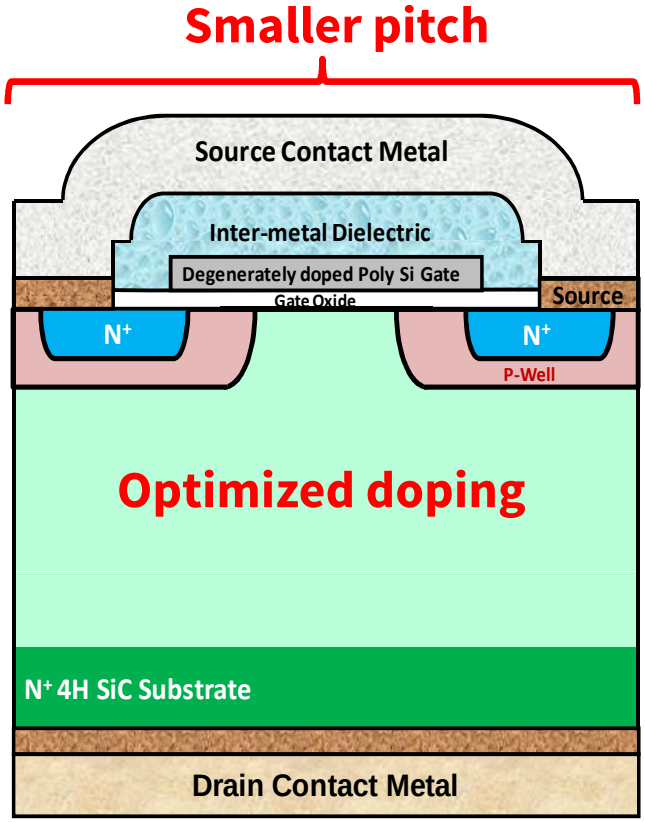
NEXT GENERATION SiC MOSFETS – OVER 5 YEARS IN THE MARKET



Gen 2 DMOS



Gen 3 DMOS

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

Commercially released in **2015** as "C3M" product family at 900V

Same high reliability DMOS Structure, but optimized to dramatically reduce die size

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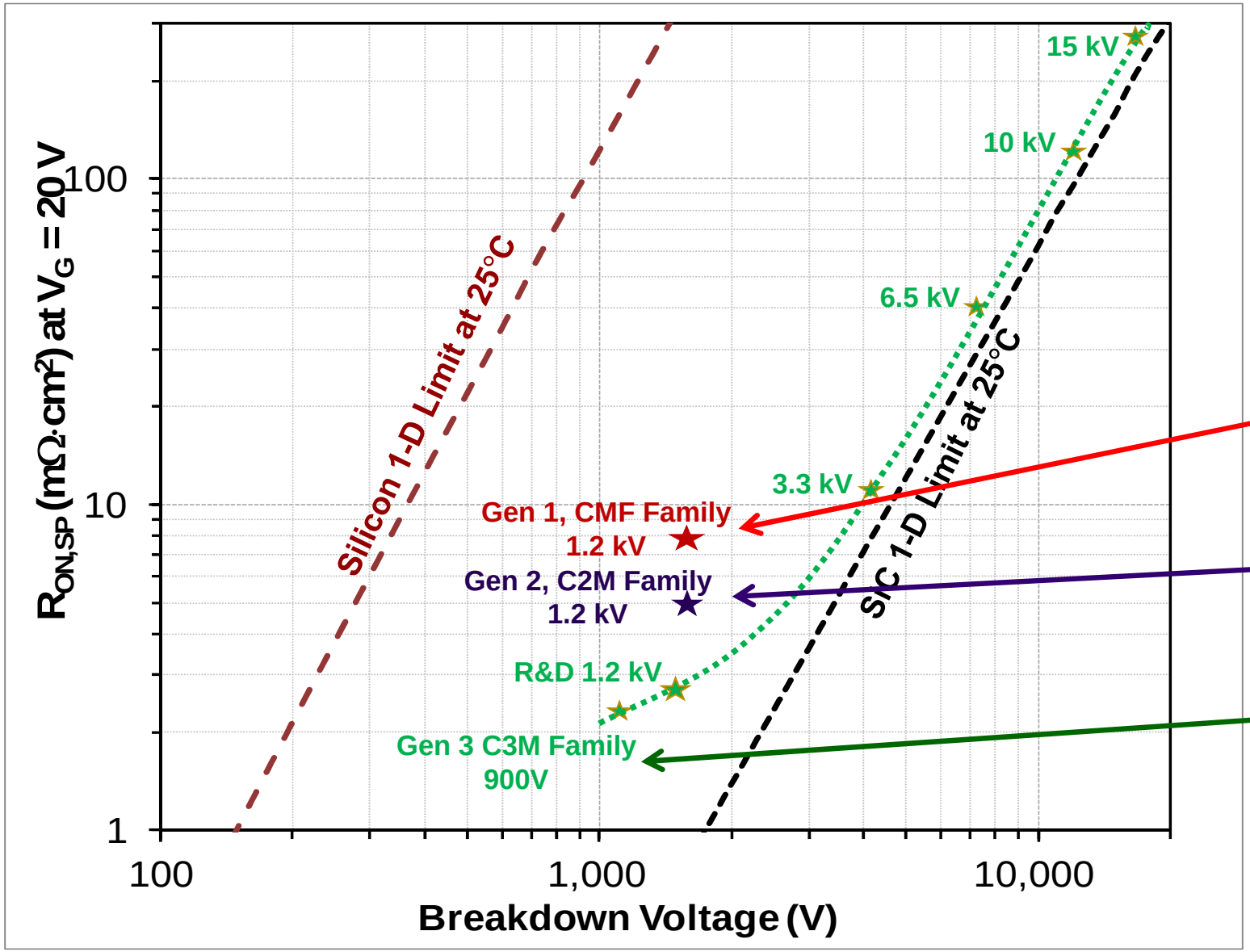
WOLFSPEED NEXT-GEN SiC DMOS LOWERS SPECIFIC R_{DSON} DRAMATICALLY



Reference: J. Palmour, et al (ISPSD 2014)

New 900V SiC MOSFET released is 2.3mΩ·cm²

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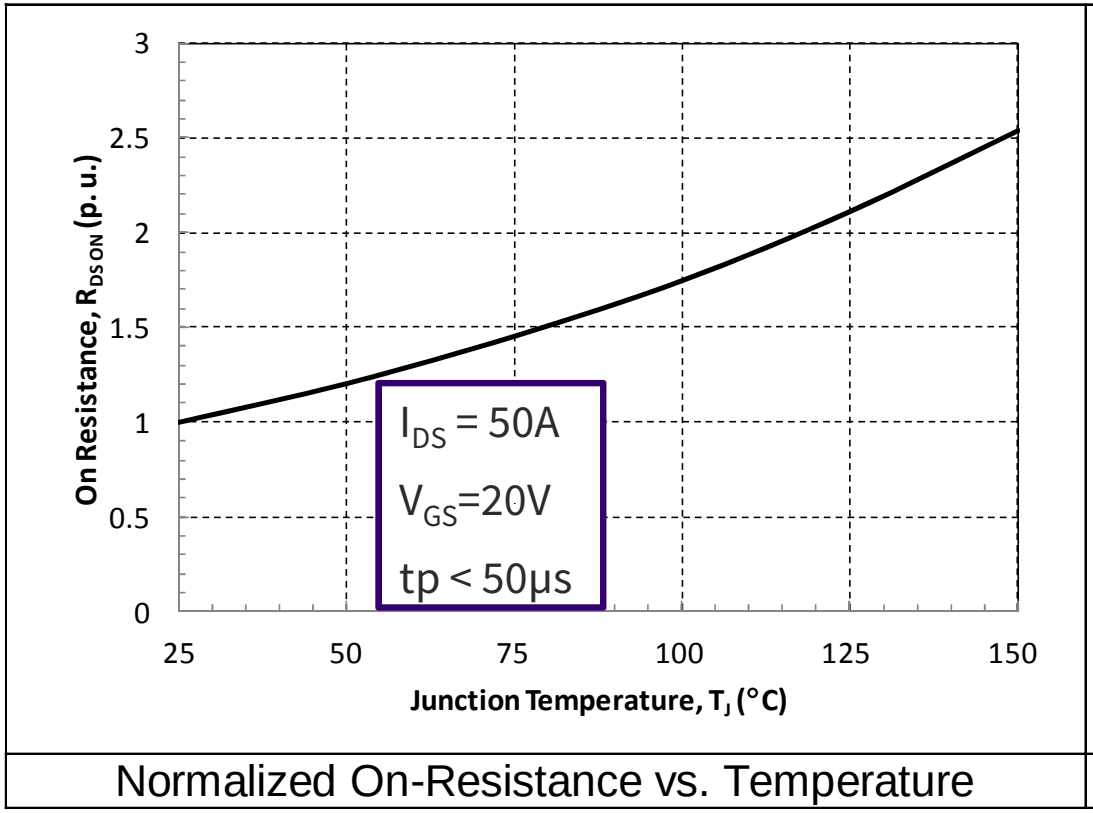
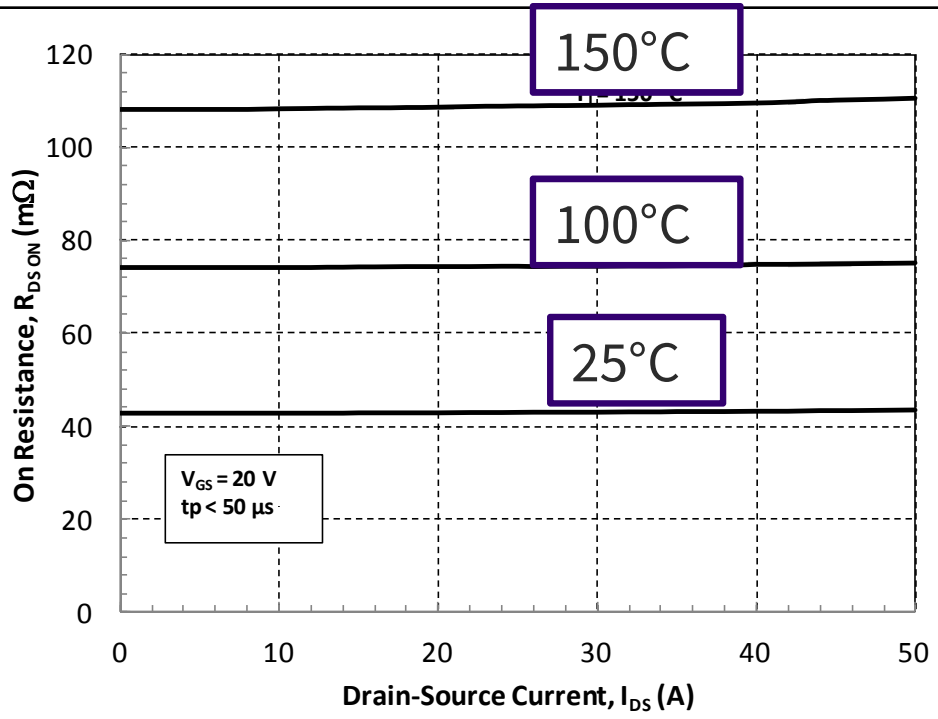
3.3kV, 45mΩ SiC MOSFET CHIP R_{DSON} vs T and I_{DS}



Normalized On-Resistance vs. Temperature



On-Resistance vs. Drain Current

- 2.5X increase in R_{DSON} from 25°C to 150°C
- Positive temperature coefficient
- Devices can be readily paralleled

Reference: J. Casady, et al (ECCE 2015)

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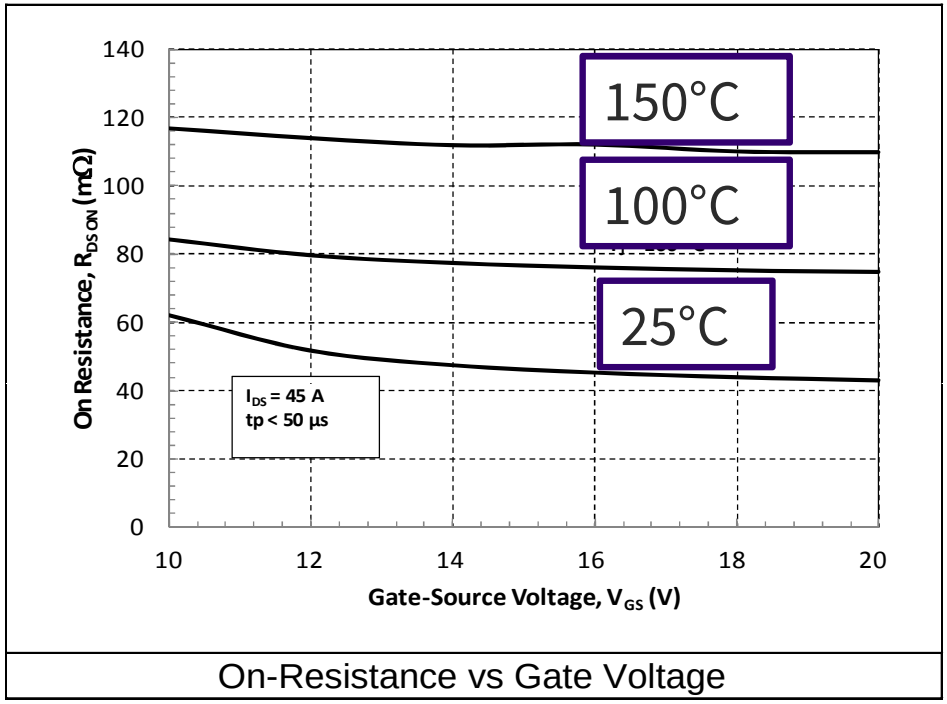
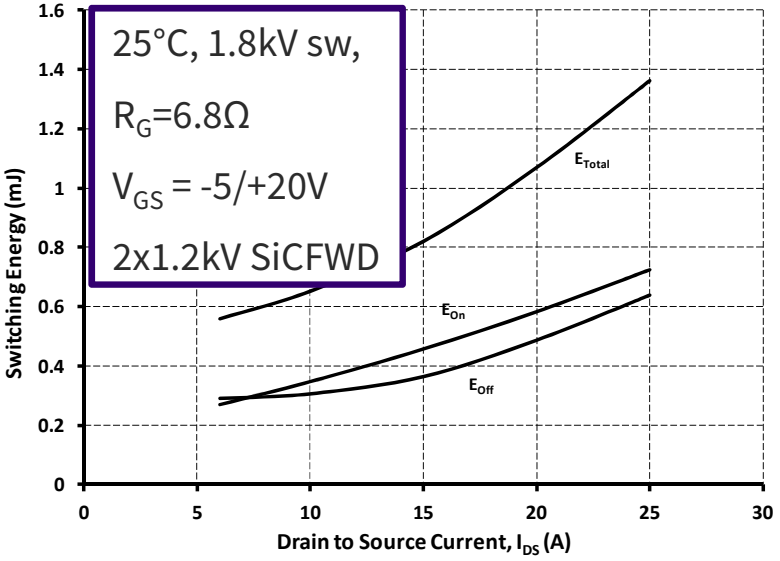
3.3kV, 45mΩ SiC MOSFET CHIP R_{DSON} vs V_{GS}



On-Resistance vs Gate Voltage



Inductive Switching Energy vs Drain Current

- At temperature, little change in R_{DSON} above V_{GS}=+14V
- At 1.8kV, 20A (1/2 rated current), E_T = **1.1mJ** (858 uH load)

Reference: J. Casady, et al (ECCE 2015)

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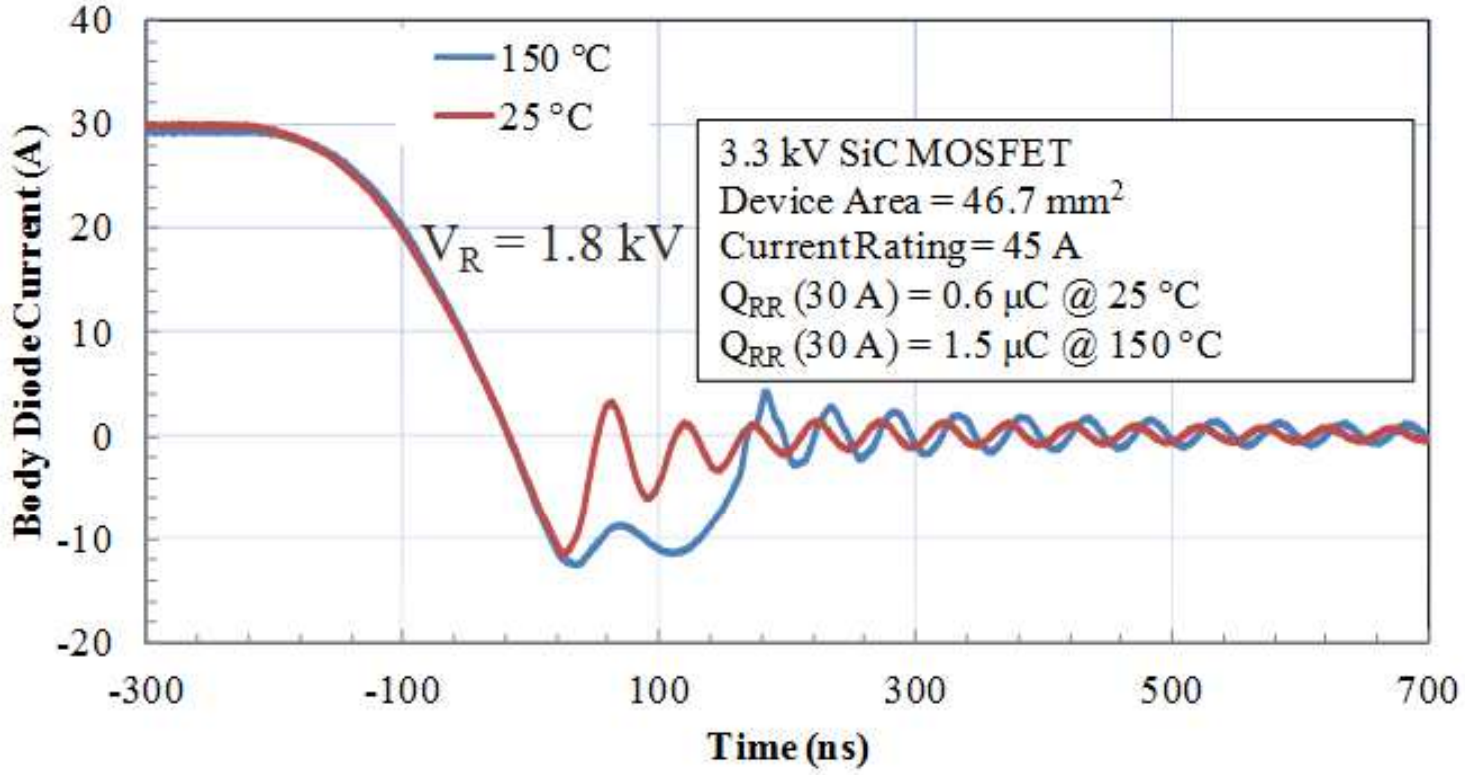
3.3kV, 45mΩ SiC MOSFET CHIP BODY DIODE



- SiC body diode can eliminate external anti-parallel SiC diode
- Elimination of external anti-parallel diode saves cost and space
- Third quadrant operation of MOSFET possible for additional savings

Reference: J. Casady, et al (ECCE 2015)

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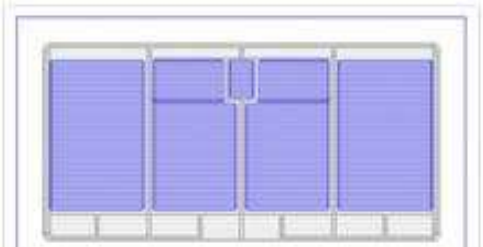
3.3kV/180A SiC HALF-BRIDGE EVALUATION MODULE

For Quick Evaluation

- Each switch position contains:
  - Four (4) 3.3kV SiC MOSFETs (~45A each) and
  - Four (4) 3.3kV anti-parallel SiC diodes (~45A each)
- 62mm module / No snubber used

3.3kV SiC MOSFET chip	
V_{DS}	3300 V
I_D (T_C=90°C)	45 A
R_{DS}(25°C)	45 mΩ



Reference: J. Casady, et al (ECCE 2015)

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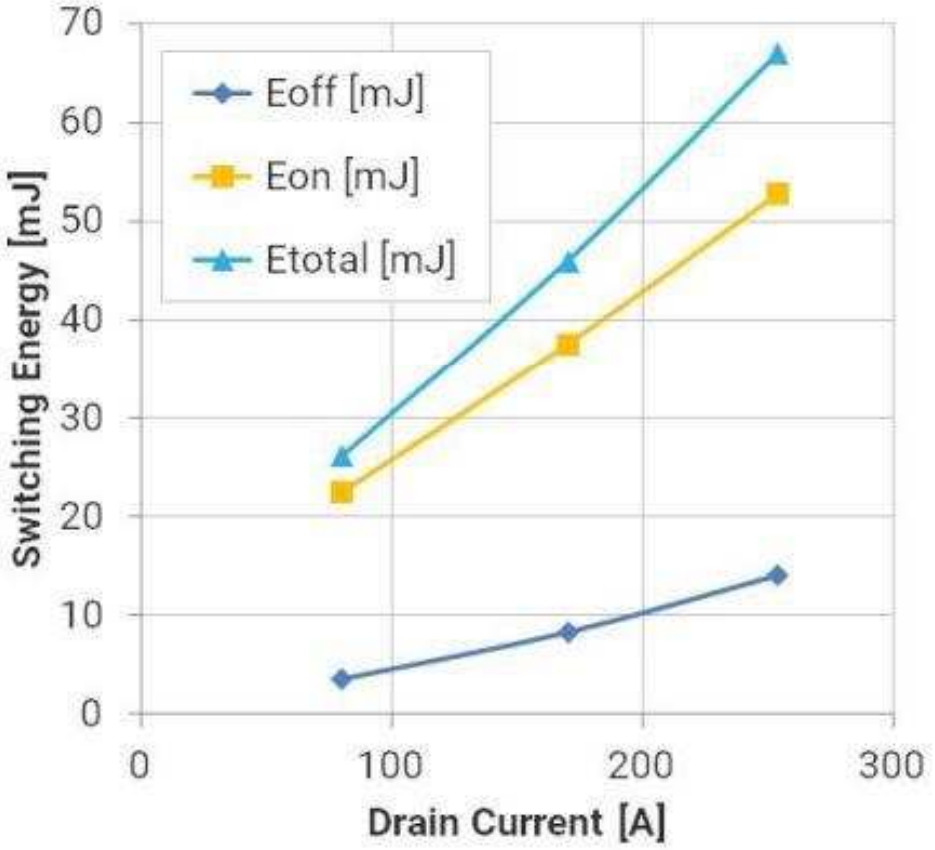
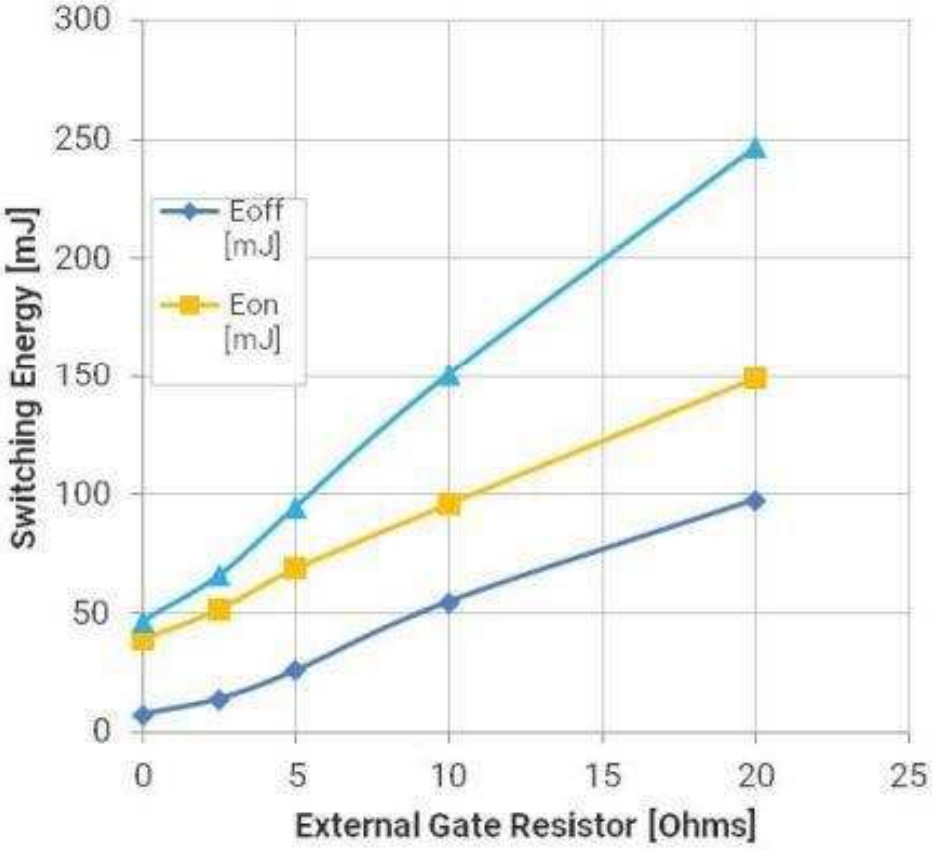
3.3kV SWITCHING LOSS PERFORMANCE @ 25°C

Double Pulse Test

Vlink = 2.2 kV, Rg_ext = 2.5 Ω



Vlink = 2.2 kV, Ids = 250 A



- At 2.2kV, 180A switching event, **45mJ** total switching energy
- **3.3kV SiC MOSFETs switching losses are 10-15x lower than 3.3kV Si IGBTs**

Reference: J. Casady, et al (ECCE 2015)

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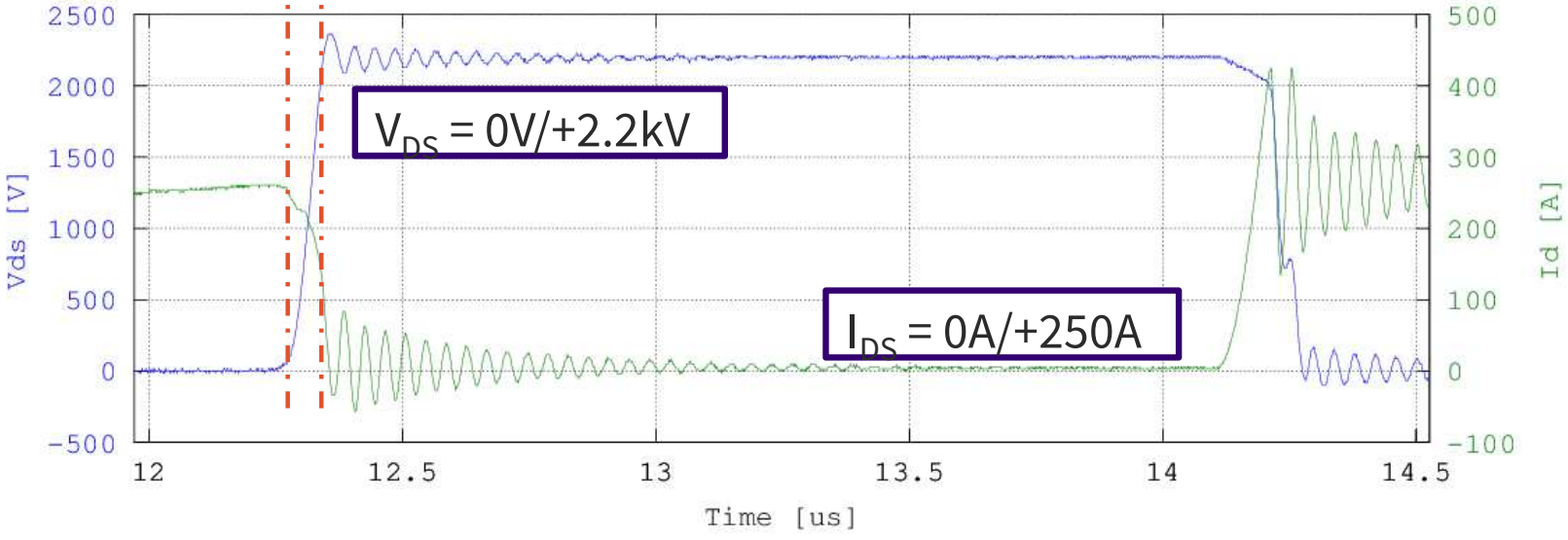
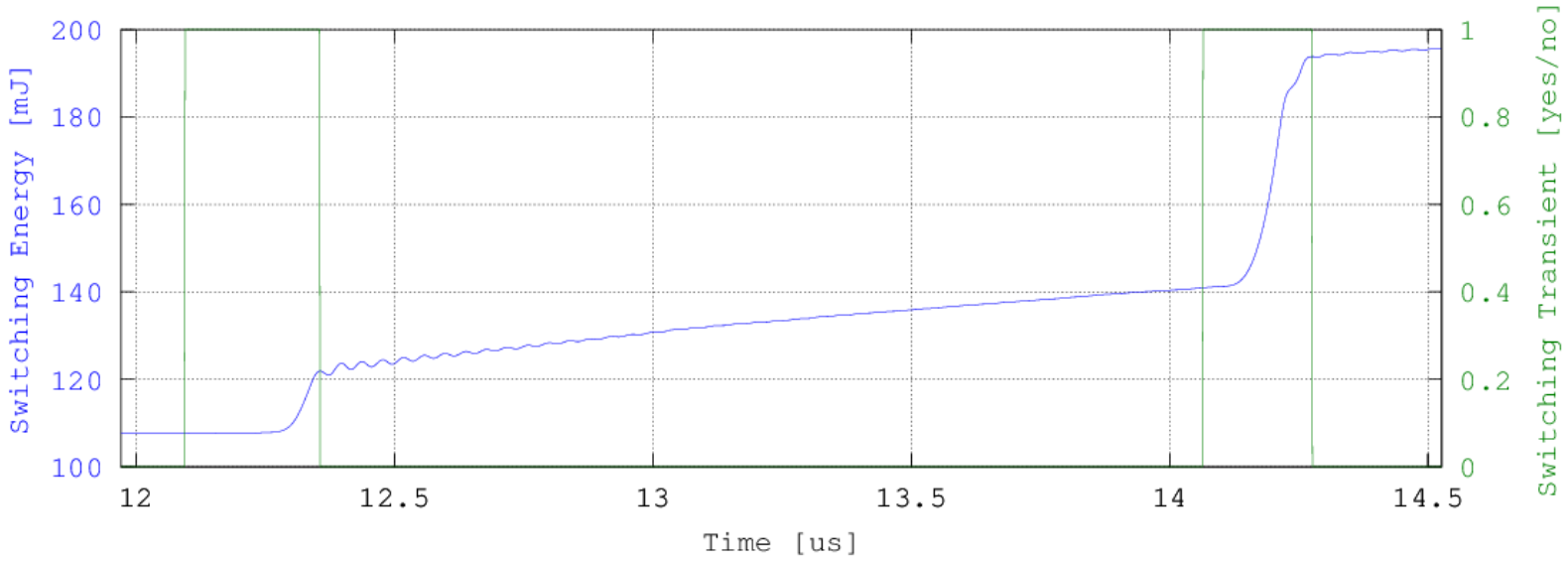
250A/2.2kV SWITCHING EVENT WITH RG_EXT = 2.5 Ω





Reference: J. Casady, et al (ECCE 2015)

Switching speed <150ns; minimal overvoltage (no snubber)

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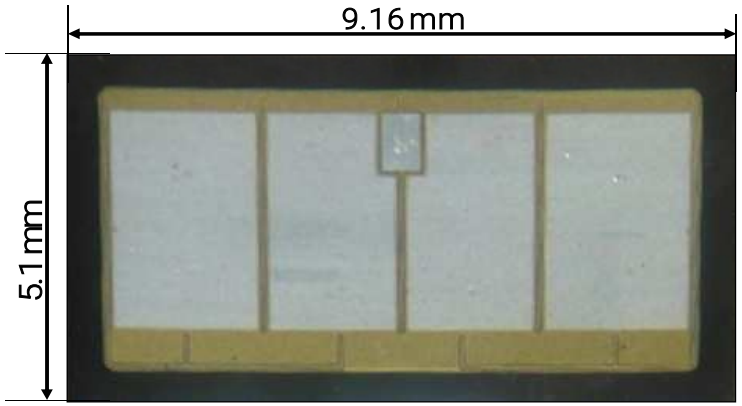
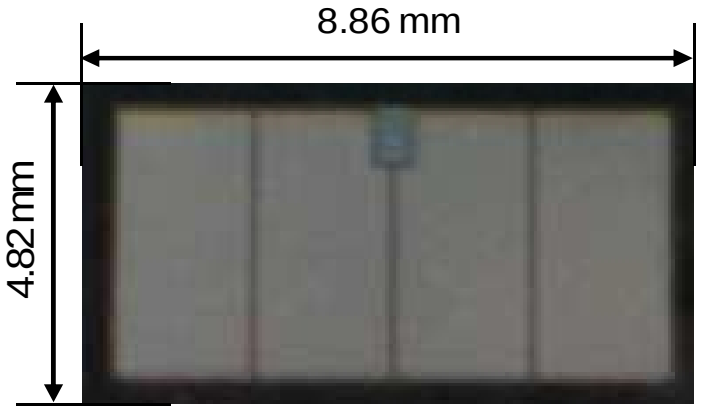
Improved Gen three 3.3kV, 40mΩ SiC MOSFET chip

IMPROVED GEN THREE 3.3kV/40mΩ SiC MOSFET

- 8.5 % Reduction in Die Size
- 13.6% Improvement in R_{DSON}



- Preliminary 3.3kV SiC MOSFET Design
- $R_{DS,ON}$ = 46.9 mΩ
- Die Area = 46.7 mm^2



- **Improved** 3.3kV SiC MOSFET Design
- $R_{DS,ON}$ = **40.5** mΩ
- Die Area = **42.7** mm^2

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SiC XHP™ STYLE MODULE - INDUSTRY STANDARD HOUSING

- Engineering Sample sales
- Up to 12 MOSFETs/ switch available
- Ultra-Fast Switching, Low Inductance (<20 nH V+ to V-)
- Companion gate driver
  - Desaturation protection, temperature sensing, programmable UVLO with hysteresis, galvanic signal isolation, & on-board isolated power supplies.

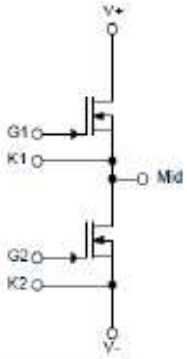
3.3 kV SiC HALF-BRIDGE POWER MODULE

N-Channel MOSFET

3.3 kV / 5.7 mΩ

FEATURES

> High Voltage: V_{DS} = 3.3 kV, $T_{J(max)}$ = 175 °C
> AS9100:Rev. C-Certified Manufacturing,
> Traceable Throughout Value Chain
> Ultra-Fast Switching, Low Inductance
> Enables High System Efficiency
> "XHP" Style Half-Bridge Power Module



APPLICATIONS

> Solid-State Transformers
> Medium Voltage Drives
> Solid-State Circuit Breakers
> Smart Grid / Grid-Tie Distributed Generation
> Energy Storage Systems

Power Module Absolute Maximum Ratings

Symbol	Parameter	Condition(s)	Value	Units
V_{DSS}	Drain-Source Voltage		3300	V
V_{GSS}	Gate-Source Voltage[1]		-8/+19	
I_D	Continuous Drain Current	T_C = 25 °C, T_J = 175 °C		A
		T_C = 125 °C, T_J = 175 °C		
P_D	Maximum Power Dissipated	T_C = 25 °C, T_J = 175 °C	2586	W
$T_{J(max)}$	Maximum Junction Temperature		175	°C
T_{stg}	Storage Temperature Range		-55 to 175	

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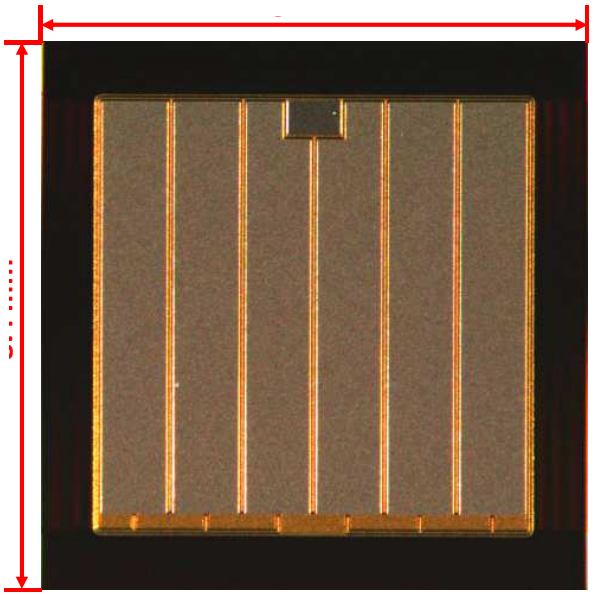
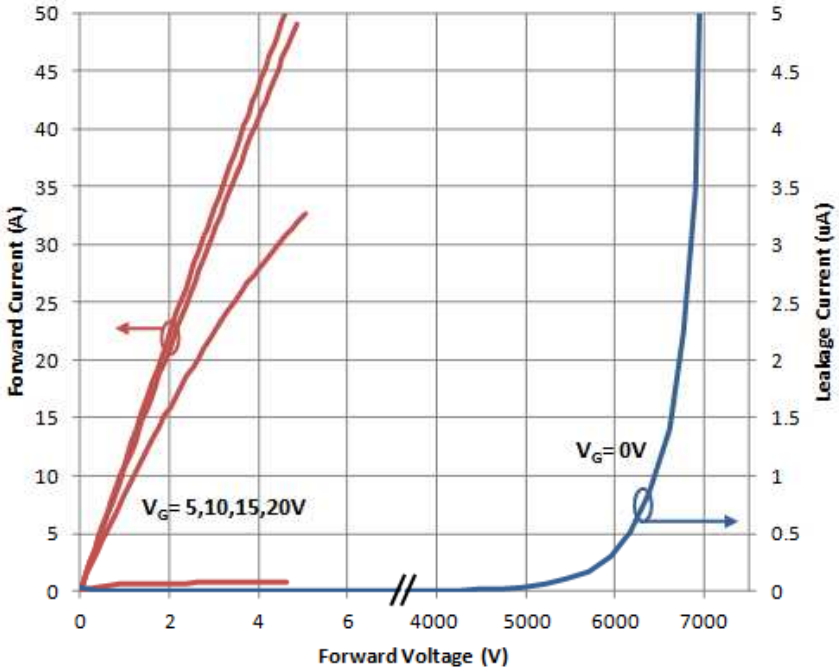
Gen three 6.5kV, 100mΩ
SiC MOSFET chip

6.5kV, 100mΩ SiC MOSFET

6.5 kV 30 A MOSFET die photo





- Nominally a 30A SiC MOSFET
- $R_{DSONmax}$ at room temp ~100mΩ
- $R_{DSONmax}$ at 90˚C ~171mΩ
  - **all parameters subject to change without notice**

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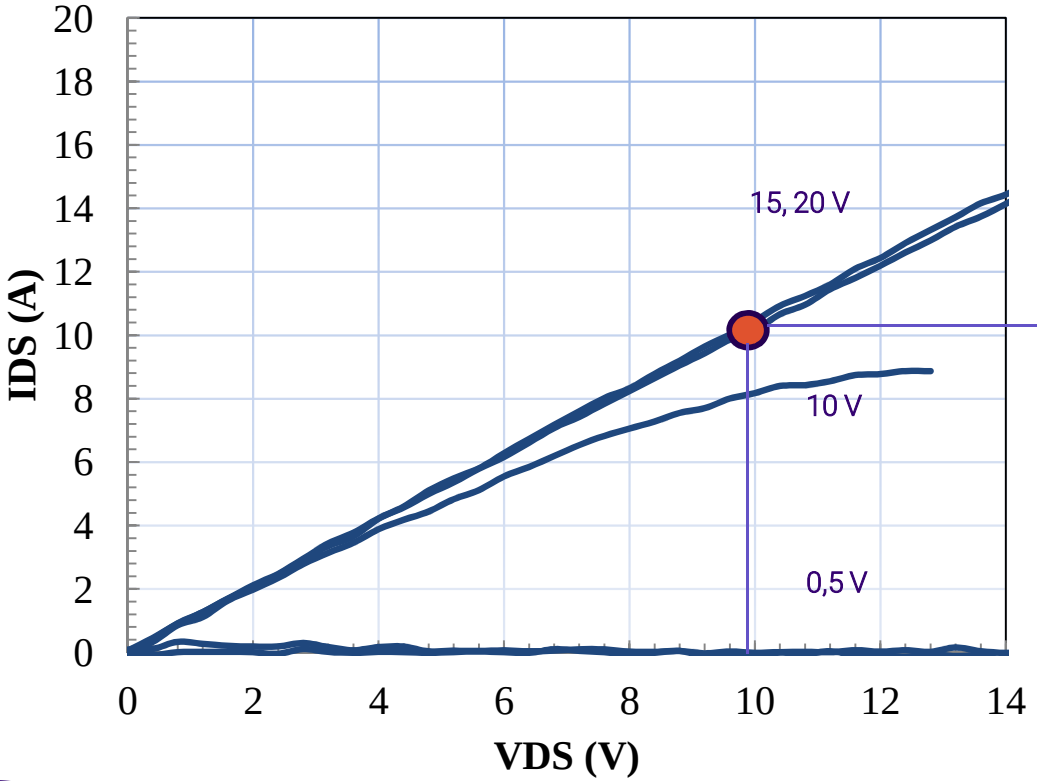
Improved Gen three 10kV, 350mΩ SiC MOSFET chip

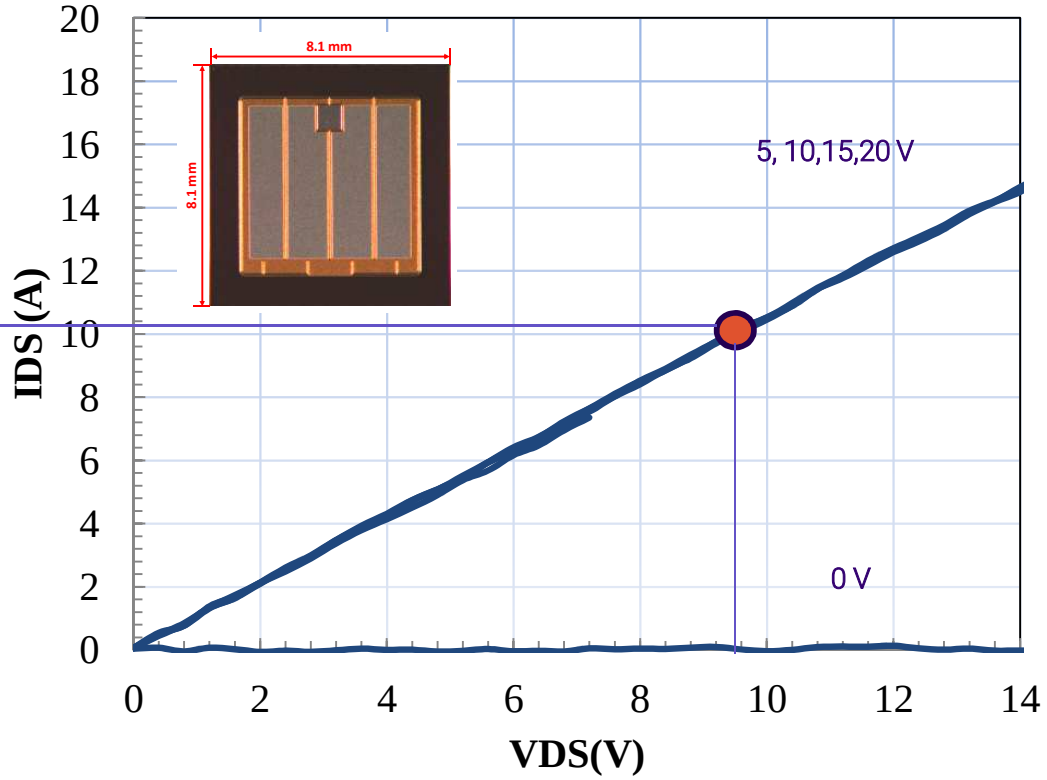
Measured I-V Characteristics at 150°C of Enhanced Short Circuit Capability and Baseline Gen3 10 kV/350 mOhm SiC MOSFETs

- Very Small Difference in On-Resistance ($R_{DS,on}$) at 150 °C
- Enhanced Short Circuit 10 kV SiC MOSFET has Higher Threshold Voltage

Enhanced Short Circuit Gen3 10kV/350mOhm SiC MOSFET



Baseline Gen3 10kV/350mOhm SiC MOSFET



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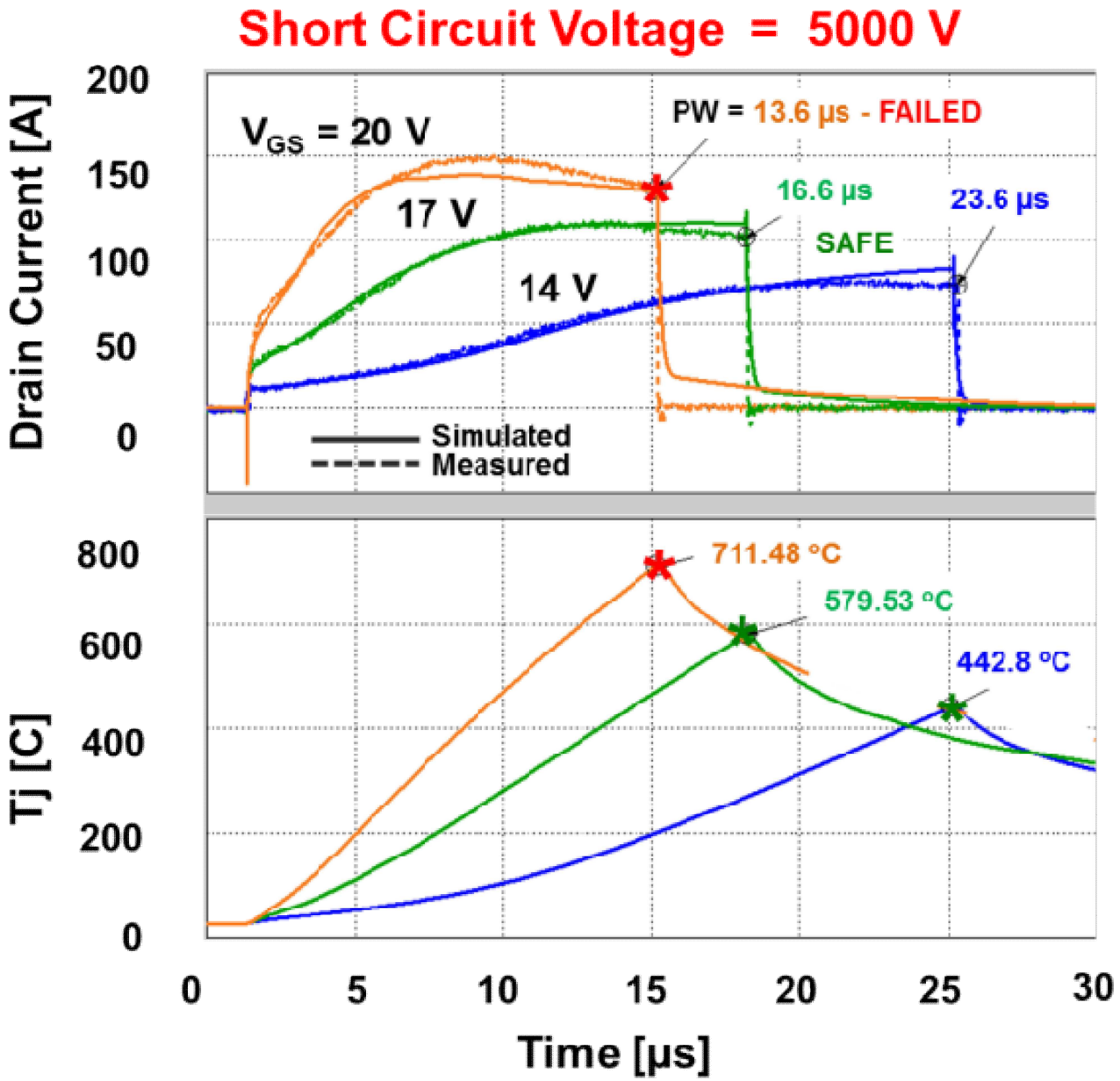
Short Circuit Simulation/Test of Gen 3 10 kV/350 mOhm SiC MOSFETs With Enhanced Short Circuit Capability



- Demonstrated Gen3 10 kV/350 mOhm SiC MOSFETs Capable of Sustaining Short Circuit Current For > 13 µsec at 5000V
- Measurement and Simulation Courtesy of Al Hefner at NIST

NIST

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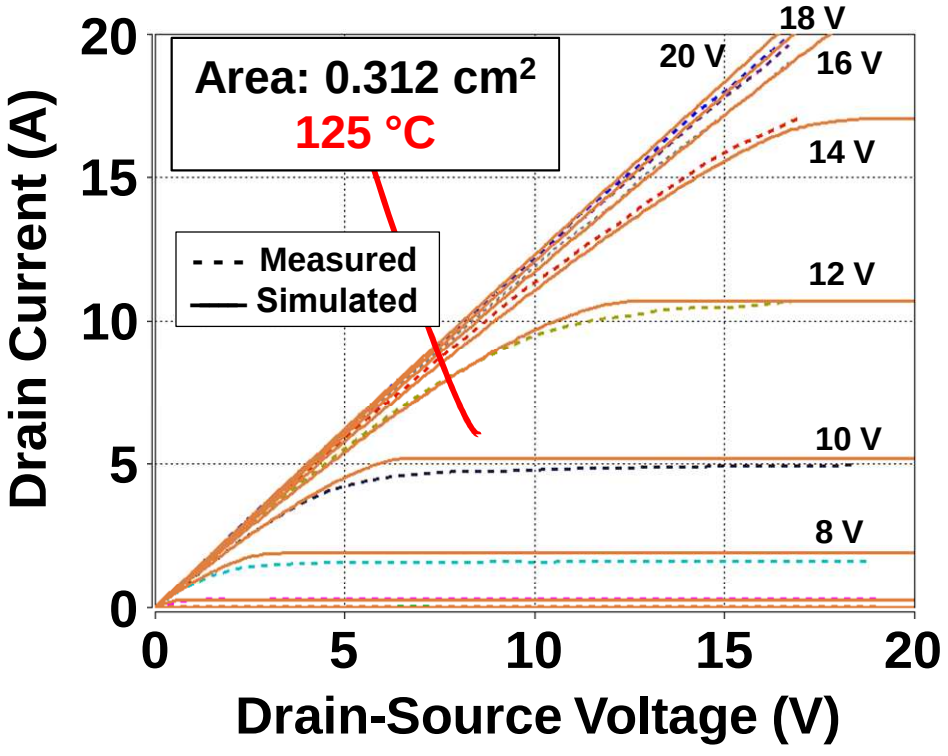
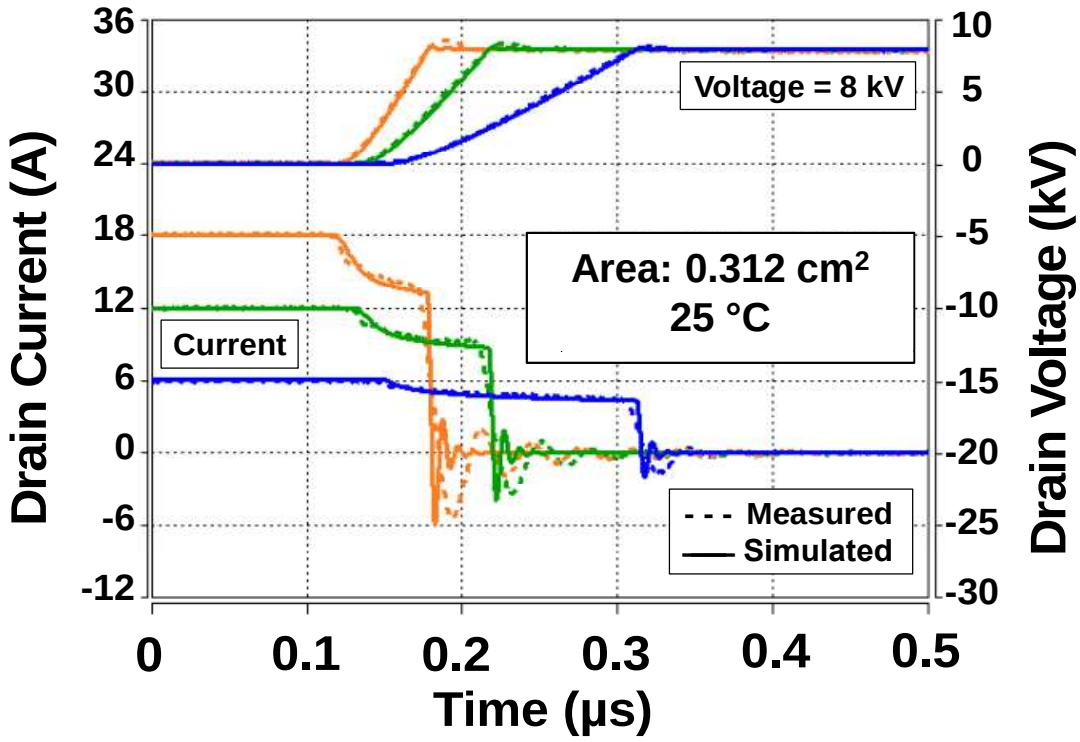
Conduction/Switching Measurements and Model of Enhanced Short Circuit Capability Gen3 10 kV/350 mOhm SiC MOSFETs

200 W/cm² @ 10A





- **Measurement and Model**

  Courtesy of Al Hefner at NIST

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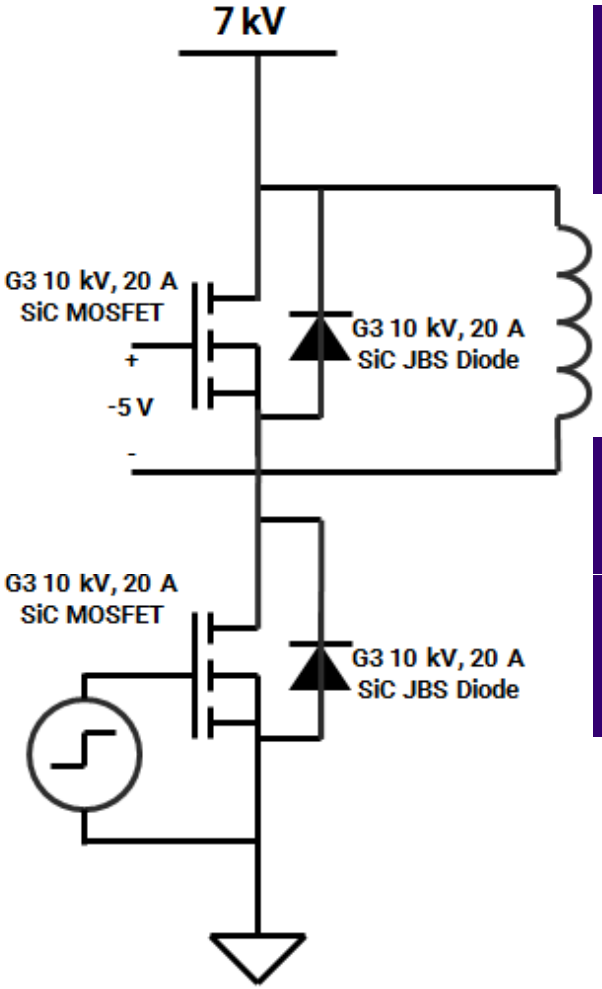
10kV Switching Measurements

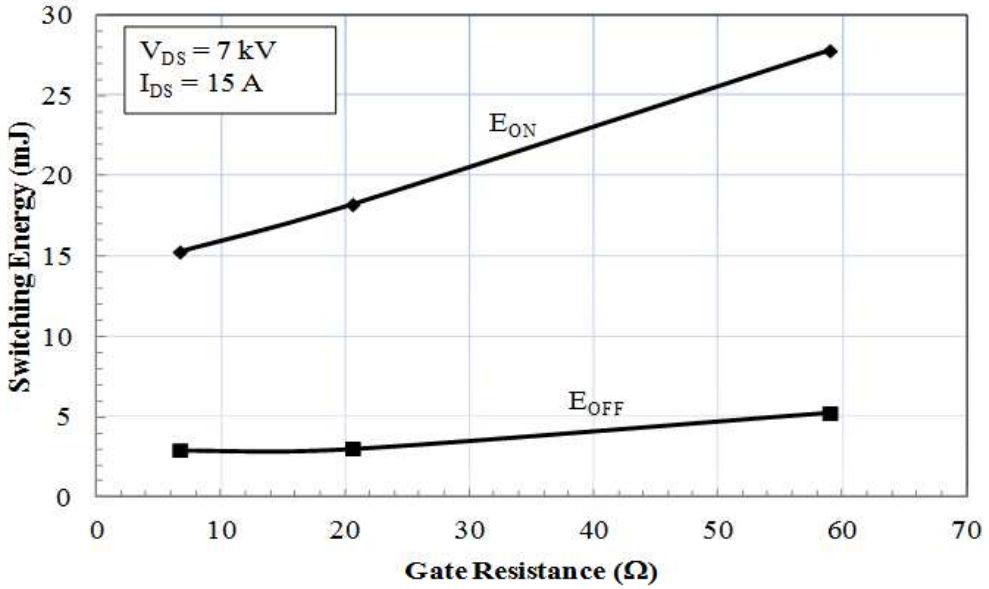
A. ½ Bridge Configured Measured Switching Energies and Waveforms
B. Boost Configured Switching Energies

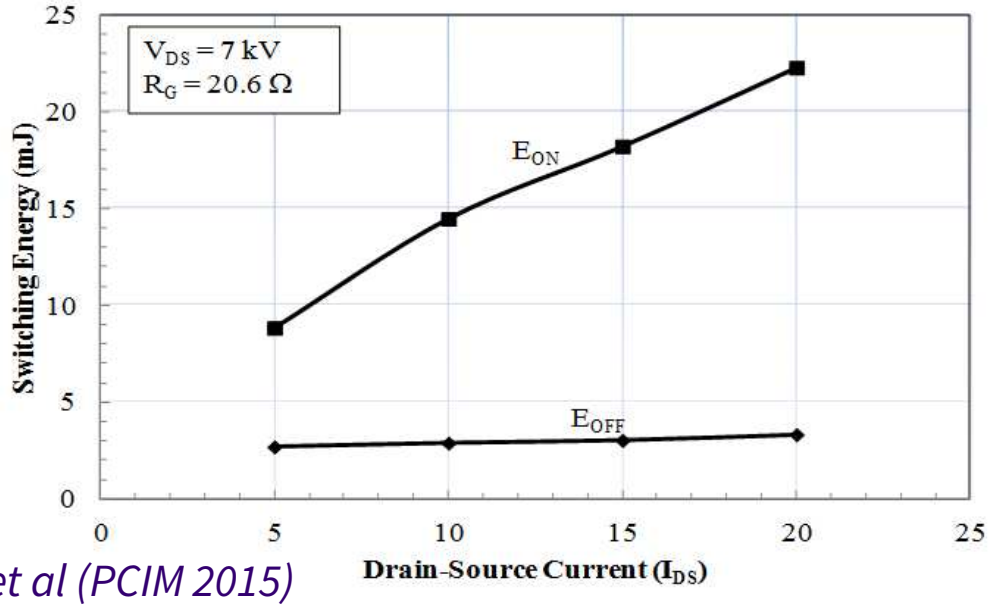
½ BRIDGE CONFIGURED MEASURED SWITCHING ENERGIES AND WAVEFORMS



E_{TS} measured 10-33mJ

E_{TS} =21mJ at 7kV, 15A, 20.6Ω R_G





½ bridge configuration used for switching measurements of a 10kV, 345mΩ SiC MOSFET in both the high position and low positions.

Reference: J. Casady, et al (PCIM 2015)

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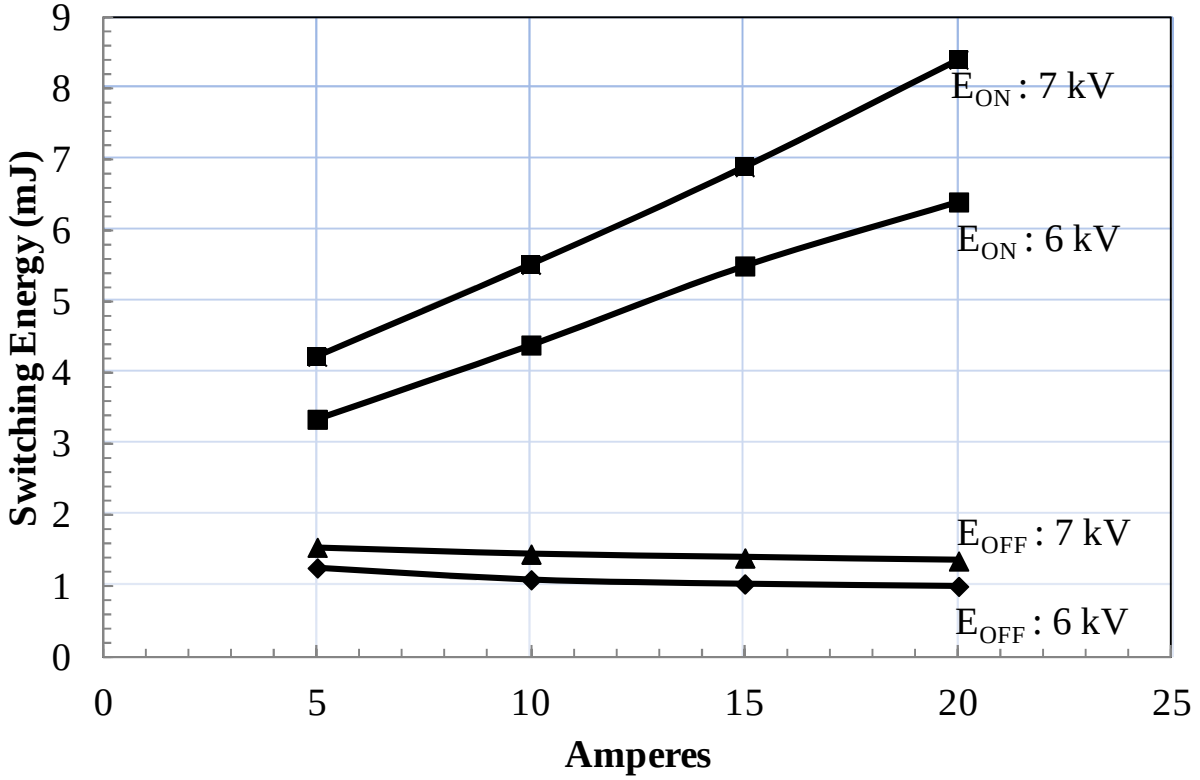
Boost Configured Switching Energies



Device	BV	$E_{SW, TOTAL}$
SiC Gen 3 10kV SiC MOSFET	10 kV	6.5 mJ @ 6kV, 15A
Silicon 6.5kV IGBT ABB 5SMX	6.5 kV	265 mJ @ 3.6kV, 25A

- **New R&D 10kV SiC MOSFETs > 40X lower switching losses than 6.5 kV Si IGBT in boost configuration**
  - **Peak switching voltage set by overshoot and cosmic ray FIT – potentially much less de-rating in SiC vs Si**

Reference: J. Casady, et al (PCIM 2015)

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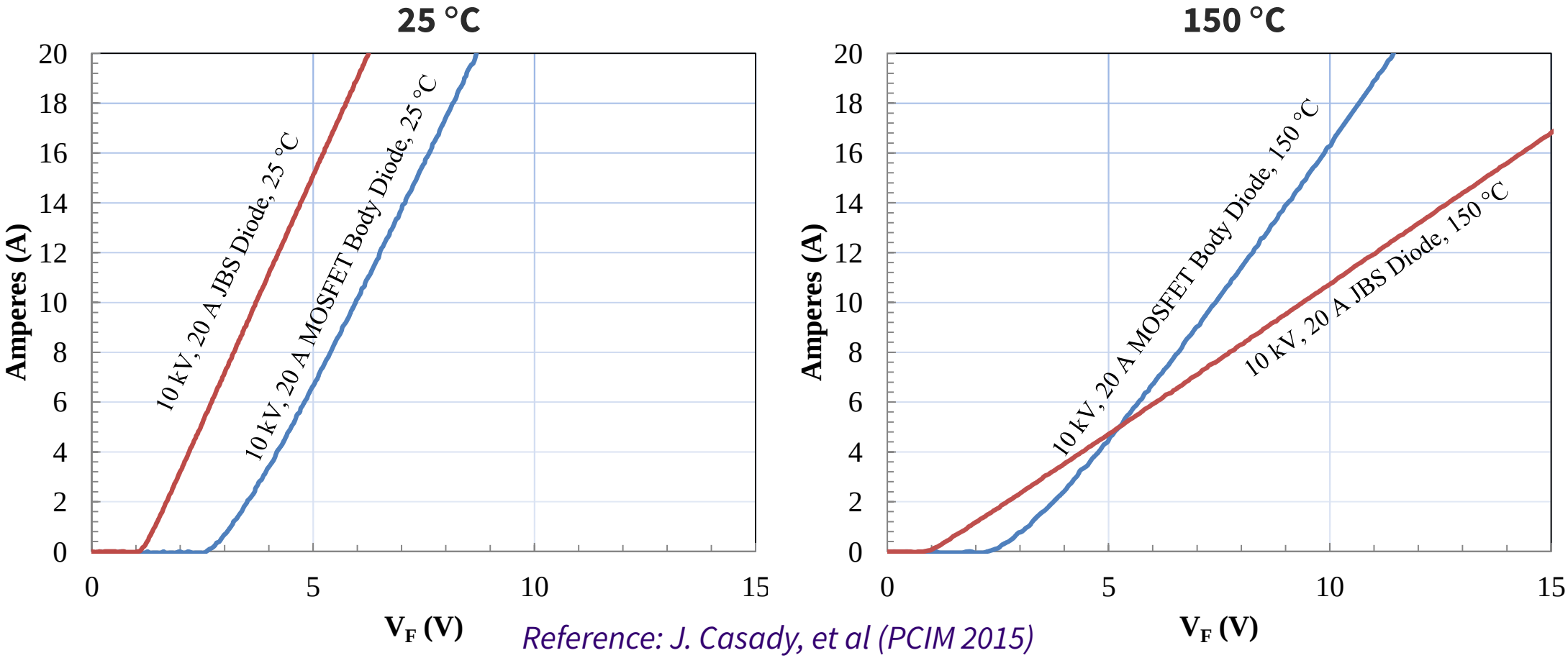
10 kV BODY DIODE STATIC CHARACTERISTICS

- 10 kV body diode is bipolar – lower resistance than a 10 kV JBS diode at high temperatures
- Reverse conducting antiparallel JBS diode can be eliminated



Reference: J. Casady, et al (PCIM 2015)

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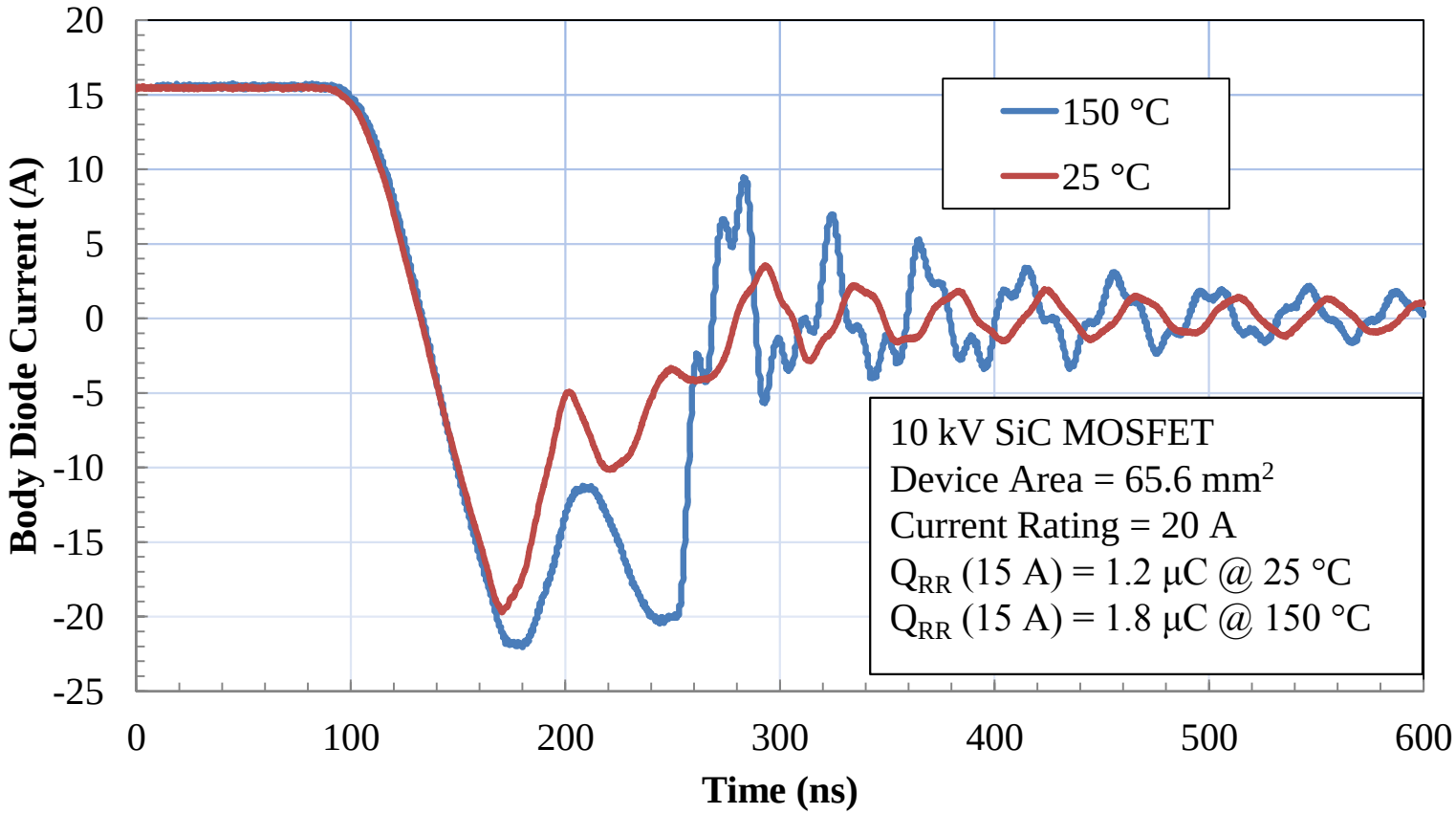
10 kV BODY DIODE REVERSE RECOVERY

- 10 kV body diodes show low reverse recovery



Reference: J. Casady, et al (PCIM 2015)

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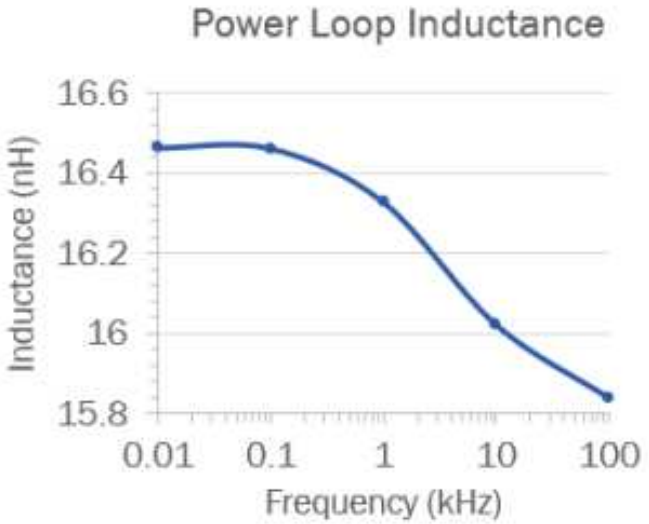
10kV SiC MOSFET XHV-6 POWER MODULE

Funded by ONR
PM: Lynn Petersen

Key Features

- 10 kV / 240 A, half-bridge power module
- 18 10 kV / 350 mΩ MOSFETs per position
- Low inductance power (~ 16 nH) and gate (~ 10 nH) loops
- Low Rjc (0.026 °C/W per half-bridge switch position)
- Can be configured as a 3-phase module
- Reworkable submodules
- Meets UL 840 and IEC 60664-1 creepage/clearance for a 15 kV module
- Mounts to standard 3x EconoDUAL footprint coldplate



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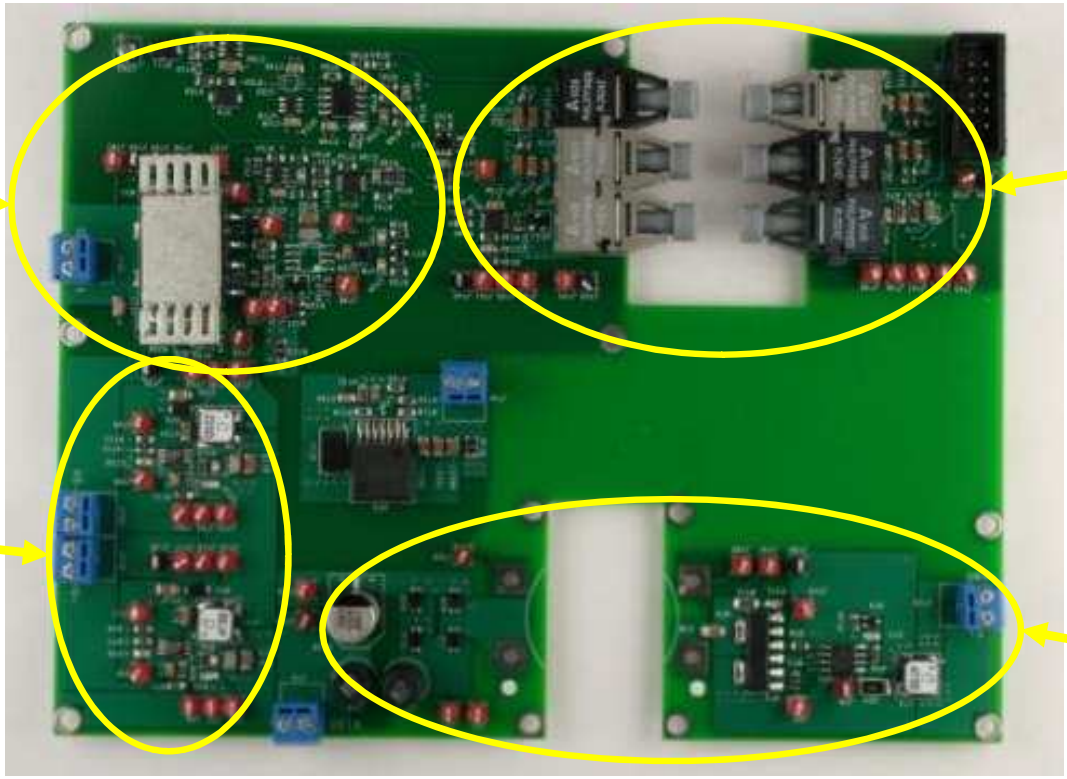
PROTOTYPE GATE DRIVER WITH TARGET >100 kV/μs CAPABILITY

Gate Driver output with custom totem pole. Max peak current >70 A

Non-Isolated DC/DC regulation
Unregulated 10-30V to +20/-5V, or +15/-4V



Fiber-optic control signals, non-isolated side would be on a separate board in final implementation

HV unregulated Isolated (>10kV) Power Supply 20-30V input to 15-30V output

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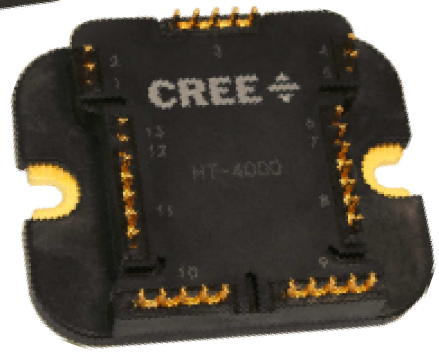
SUMMARY

- SiC MOSFETs released over 5 years ago
- Gen 3 SiC MOSFETs released beginning in 2015 at 900V;
- Gen 3 SiC MOSFETs engineering samples at 1.7kV, 3.3kV, 6.5kV and 10kV
- Modules available
  - Companion gate drivers/power supplies for all modules available
  - 1.7kV modules using Econodual™ based design
  - 3.3-6.5 kV module
    - (Infineon XHP™ standard footprint)
    - Internal design is customized to enable SiC high switching frequency operation with low loop inductance <20 nH
  - 10kV SiC MOSFET XHV-6 Power Module
    - Up to 240A, half-bridge topology

900-1700 V HT-3000 Series Half-Bridge

900-1700 V HT-4000 Series H-Bridge



3.3-6.5 kV Half-Bridge

10kV XHV-6 Half-bridge

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Leading the Pack™

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