# Recent Advances in 900 V to 10 kV SiC MOSFET Technology

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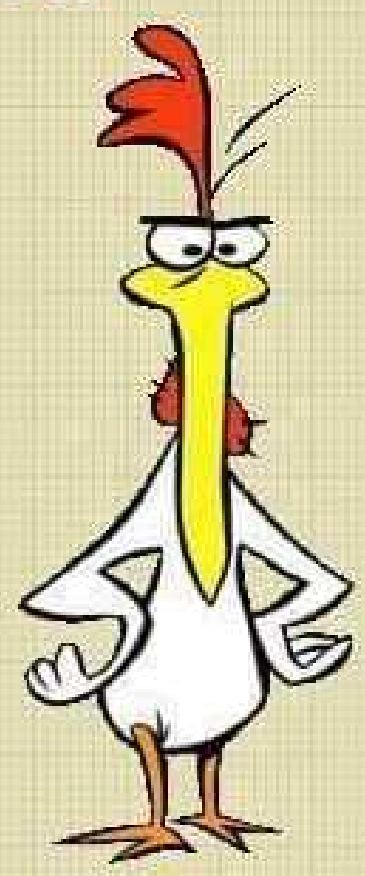
I wonder why we are so so obsessed with trying to find intelligent life on other planets, when we can't even find intelligent life here?



# OUTLINE



- Cree/Wolfspeed Gen 3 MOSFETs
  - Specific $R_{DSON}$ of 900V-1700V MOSFETs
  - Rel data for smaller (65mOhm) 900V MOSFETs
- 900V, 10mOhm SiC MOSFET chip characteristics
  - Static, dynamic, short-circuit, reliability
- 1.2kV & 1.7kV Gen 3 SiC MOSFETs
- 3.3kV & 6.5kV SiC MOSFETs
  - DC over temperature (3.3kV)
  - Dynamic characteristics at temperature (3.3kV)
- 10kV SiC MOSFETs
  - DC over temperature
  - Dynamic characteristics at temperature
- Summary

CREE™

Power and RF Division

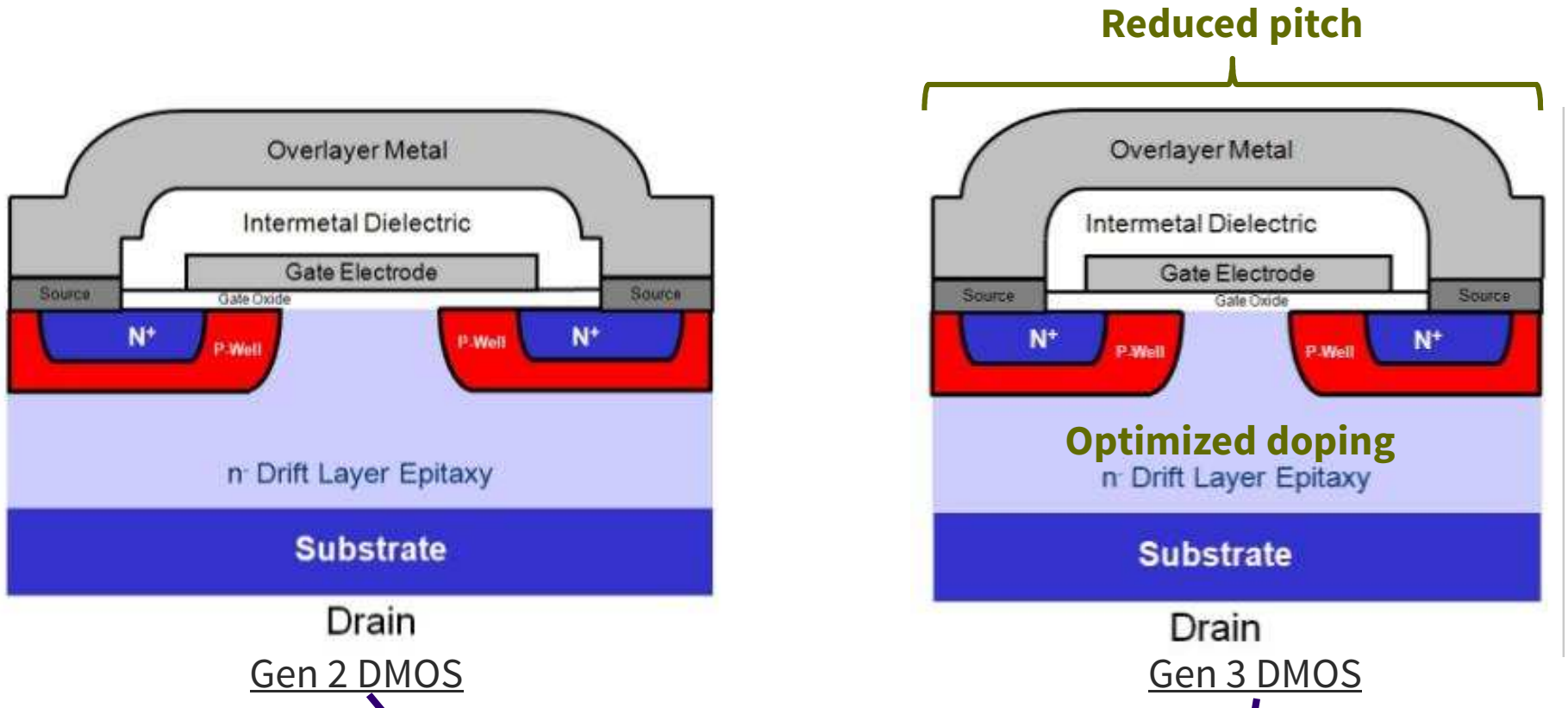
Wolfspeed™

A CREE COMPANY

# Cree/Wolfspeed
# Gen 3  SiC MOSFETs

# 900V "GEN 3" RELEASED IN 2015; NOW SCALING TO 10mΩ CHIP





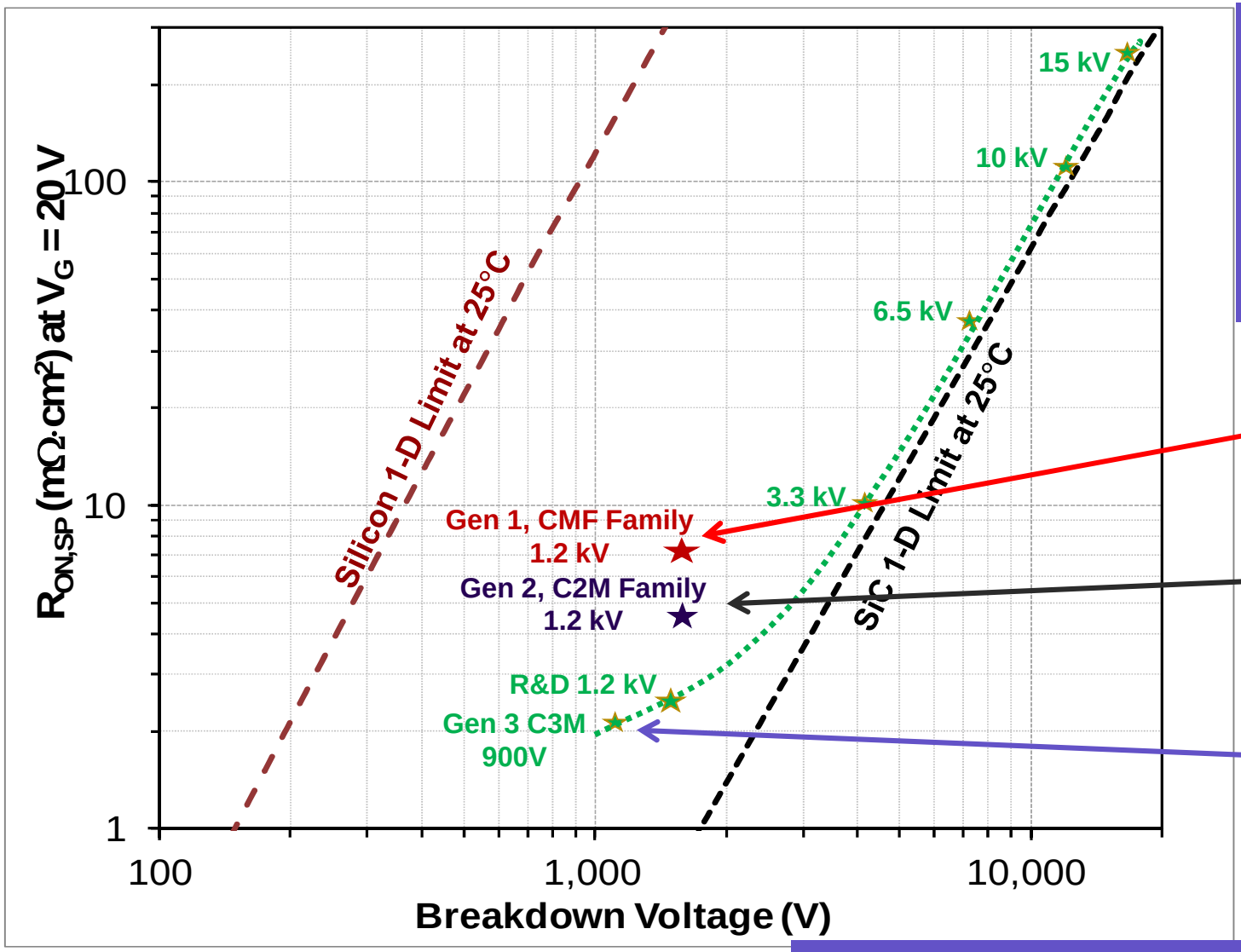

Commercially released in **2013** as "C2M" product family at 1.2-1.7kV

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

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

# NEXT-GEN SiC DMOS LOWERS $R_{ON,SP}$ DRAMATICALLY






- Gen 3 SiC DMOS has lowest $R_{ON,SP}$ in market
- Gen 3 SiC DMOS has lower $R_{ON,SP}$ than trench SiC MOSFET

**2011 release (1200V)**

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

**2015 release (900V) 2.3mΩ·cm²**

New 900V SiC MOSFET released is 2.3mΩ·cm²

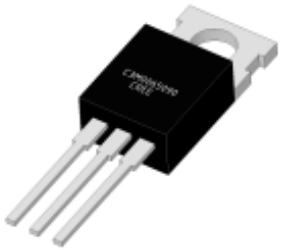
# CREE SiC MOSFET PORTFOLIO SUMMARY



| | 1700V | | 1200V | | | | | 900V | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $R_{DS(on)}$ | 45mΩ | 1Ω | 25mΩ | 40mΩ | 80mΩ | 160mΩ | 280mΩ | 10mΩ | 65mΩ | 120mΩ | 280mΩ |
| $I_{D(MAX)}$ | 60A | 3A | 90A | 60A | 36A | 19A | 10A | 100A | 36A | 23A | 11.5A |
| TO-247-3 | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● |
| TO-220-3 | | | | | | | | | ● | ● | ● |
| TO-263-7 | | ● | | | | | | | ● | ● | ● |
| Bare Die | ● | | ● | ● | ● | ● | | ● | ● | ● | |

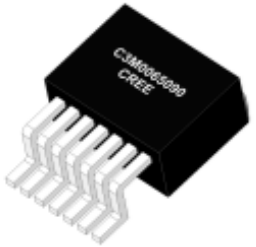
● = In Development ● = Commercially Released

NEW 900V Gen 3 TECHNOLOGY



TO-220-3

TO-247-3



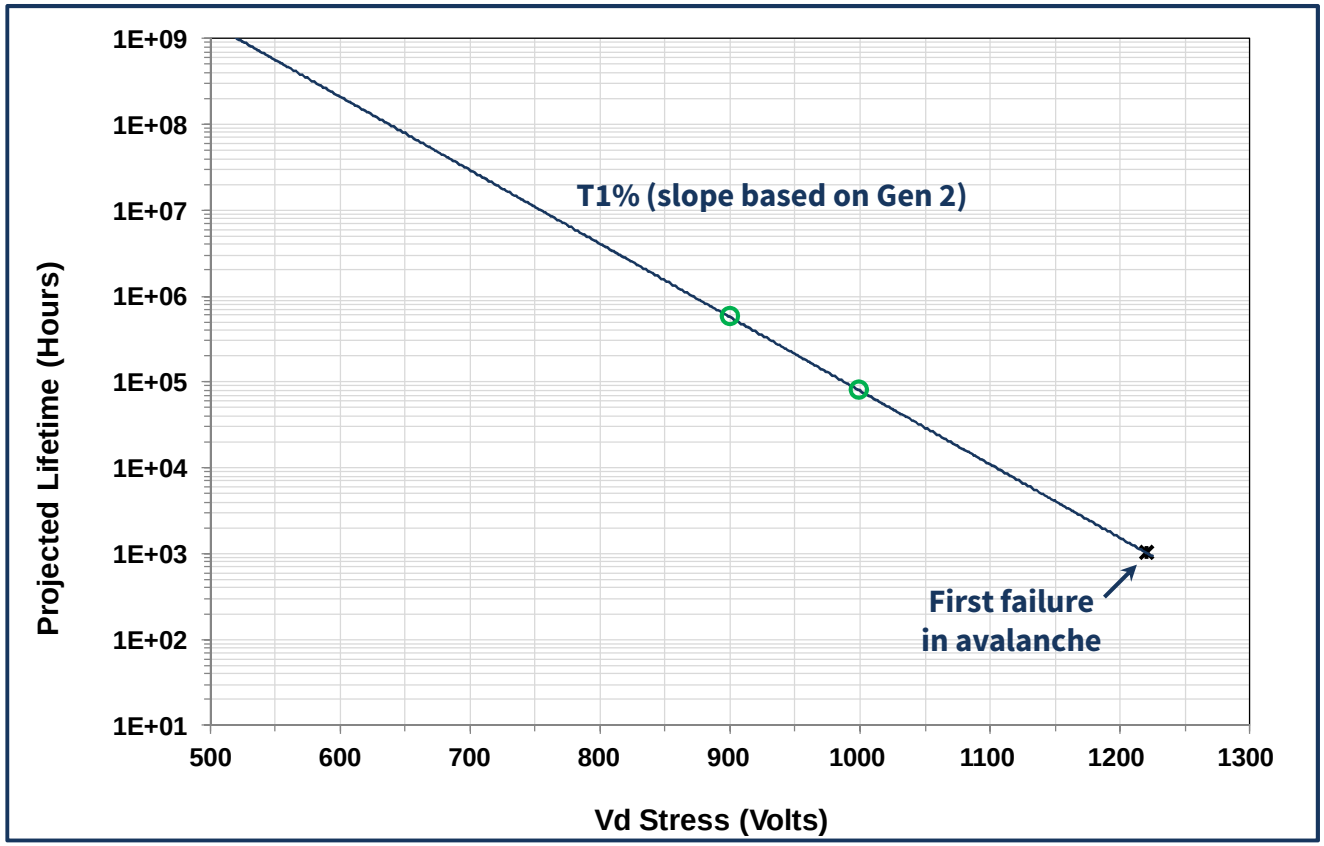
TO-263-7

pcim EUROPE

Nuremberg, 10 – 12 May 2016

# LIFETIME PROJECTIONS FOR C3M065090 (900V, 65mOhm)

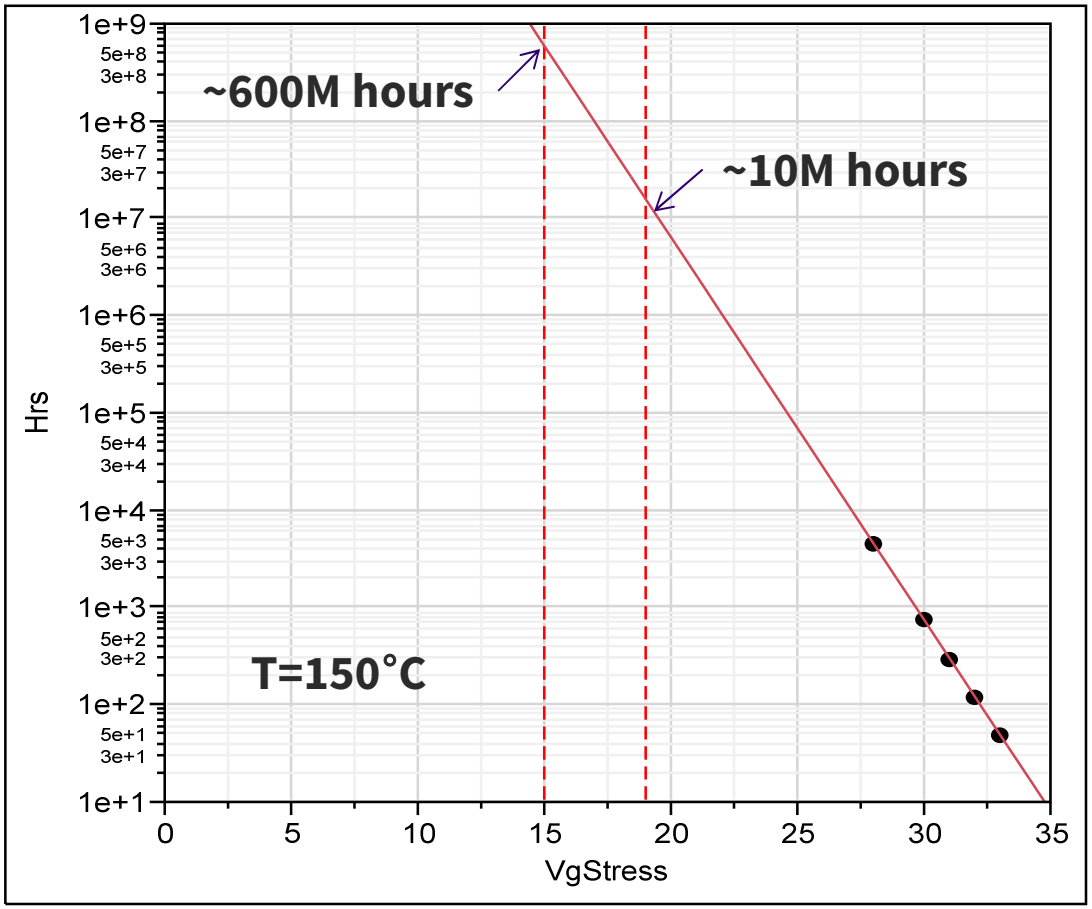





- 900V rating results in 65 years before the first projected 1% of failures
- At 1kV continuous voltage, projected failure time for first 1% is 9 years
- Avalanche rated: zero fails in 1,000 hours at 50 µA, V > 1200V

# LIFETIME PROJECTIONS FOR C3M065090 GATE OXIDES



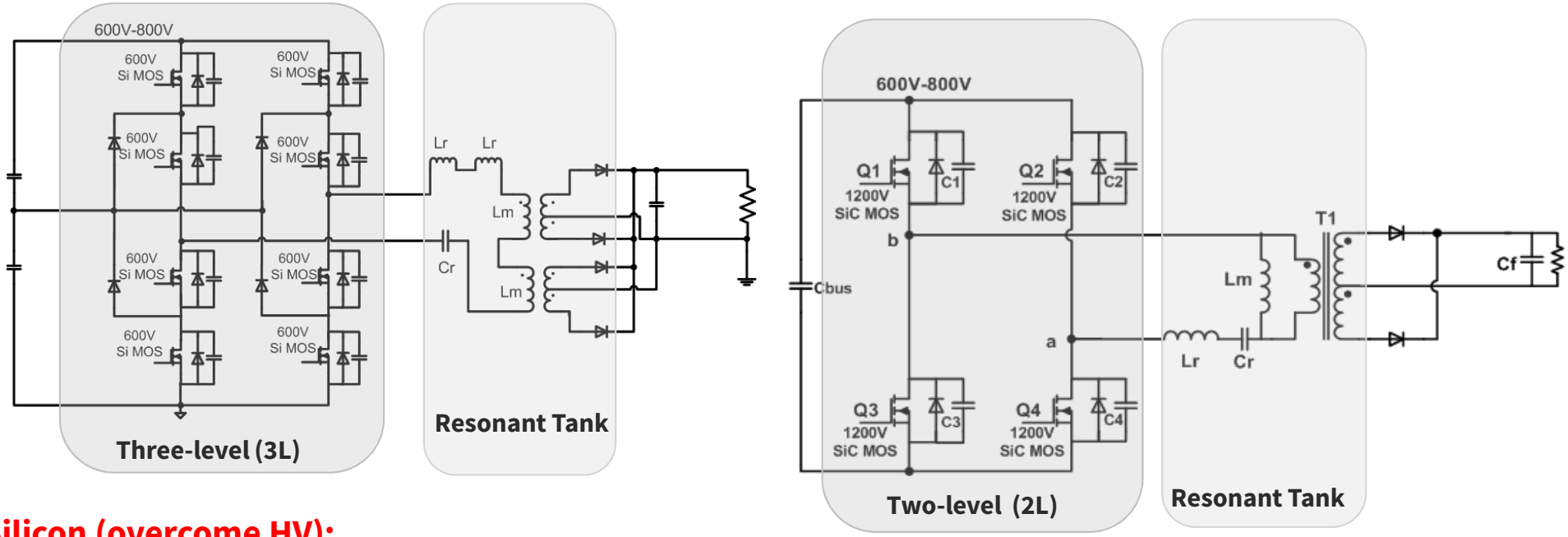



- **Extrapolated $V_{GS}$ lifetime of ~600M hours at +15V (DC recommended operating point)**
- **Passed AEC-Q101 qualification of 3 lots x 77 parts with Ø fails in 1,000 hrs at $V_{GS}$=15V, 150C**

# SIMPLIFY DC FAST CHARGERS:



## FB LLC RESONANT CONVERTER




**Silicon (overcome HV):**

600V MOS to get >800V DC Link

**Three-level LLC Full bridge**

Typical switch **100 kHz – 200 kHz**

☹ Complicated topology and control

☹ Additional clamp diodes

Si to SiC

**Silicon Carbide:**

900V SiC MOS (reliable up to 1kV)

**Two-level FB ZVS LLC resonant**

Target switch **>200 kHz – 400 kHz**

☺ Reduce BOM cost by **20%** & ↑ efficiency

☺ Simplify the converter design

☺ Reduce resonant tank size

# COST COMPARISON BETWEEN SILICON, SiC, AND GaN



| Voltage Rating & Technology | Part # | On-resistance & Current at Tc = 100C | Distribution price per 100 |
|---|---|---|---|
| 900V Silicon | IPW90R120C3 | 120 mohm 23 A | $11.50 |
| 900V Silicon Carbide | C3M0065090J | 65 mohm 23 A | $9.62 |
| 650V GaN | GS66508P-E05-TY | 50 mohm 23 A | $27.07 |

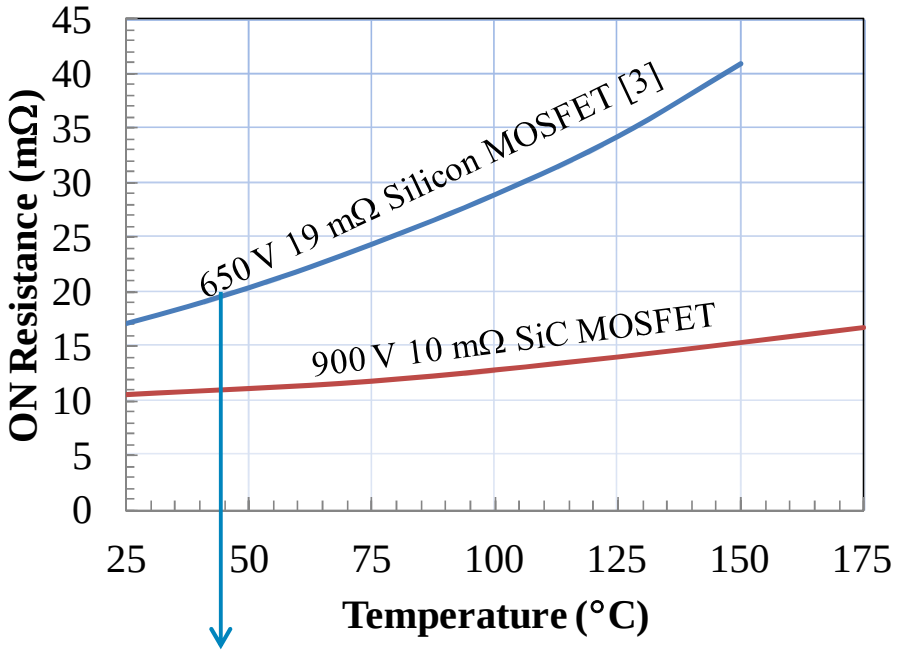
For High Speed Switches, SiC is currently the least expensive at 900V

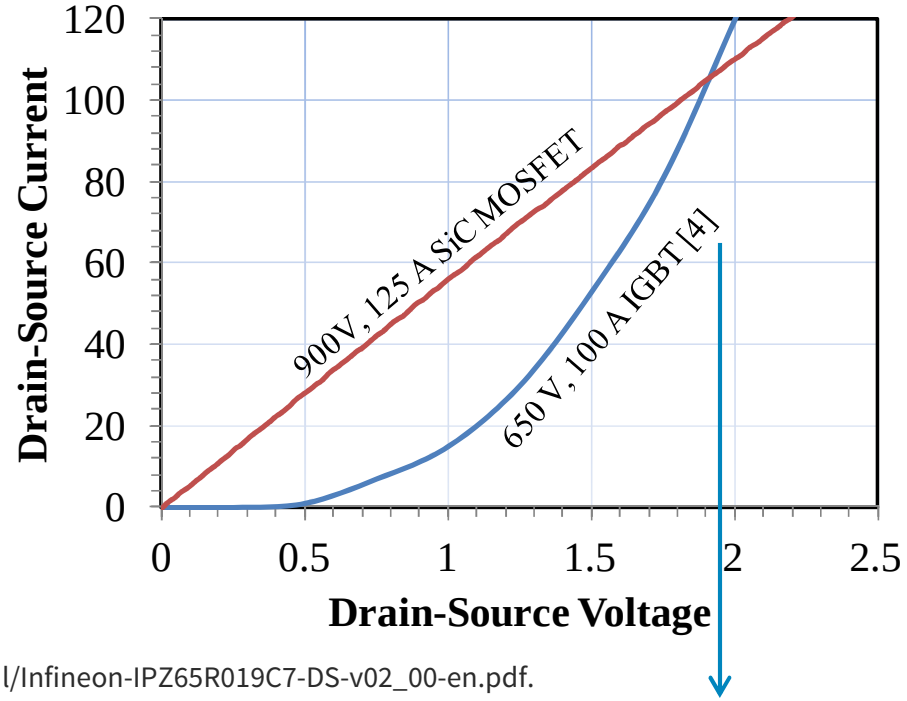
# 900V, 10mOhm SiC MOSFET
# Die Characteristics

# 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



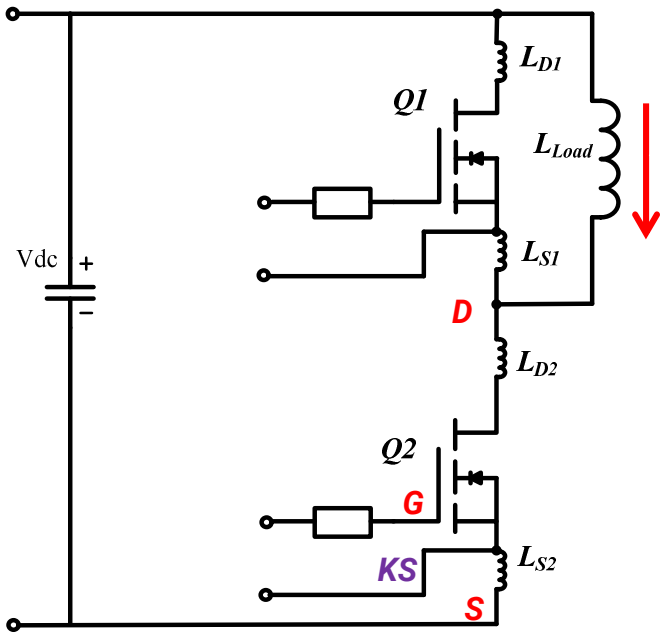

Infineon 650V, 19mΩ MOSFET, part number IPZ65R019C7, http://www.infineon.com/dgdl/Infineon-IPZ65R019C7-DS-v02_00-en.pdf.

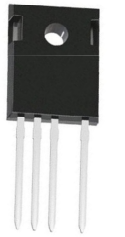
Infineon 650V 100 A IGBT, Part No. IGZ100N65H5, http://www.infineon.com/dgdl/Infineon-IGZ100N65H5-DS-v02_01-EN.pdf.

# 900V 10mΩ SiC MOSFET DYNAMIC 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

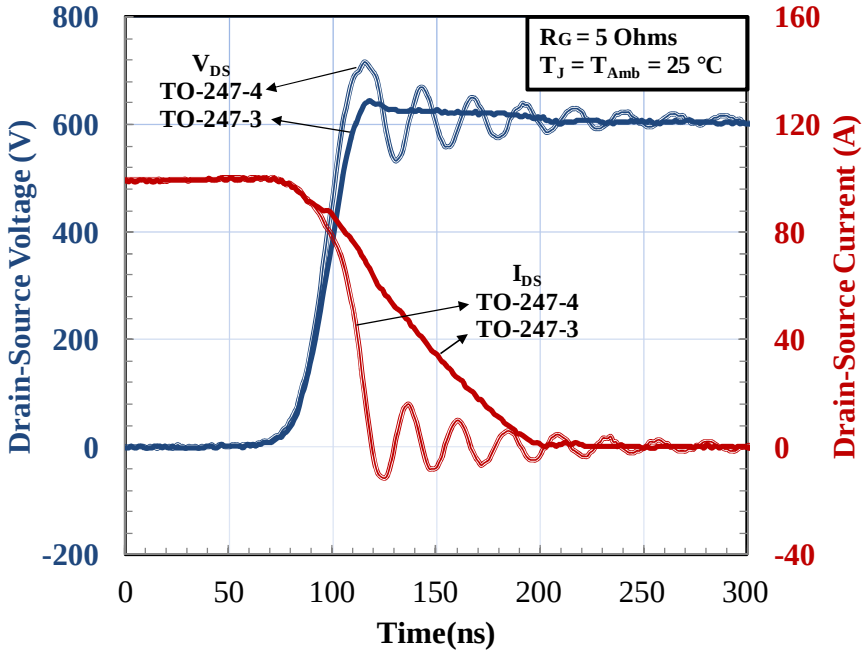
TO-247-3

# 900V 10mΩ SiC MOSFET SWITCH WAVEFORMS (600V, 100A)

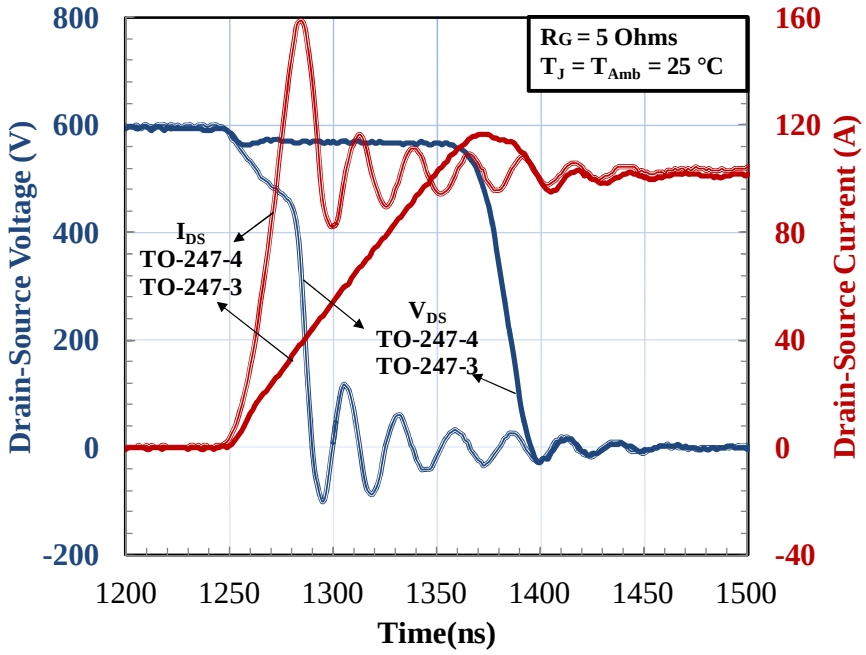


- **LEFT: Comparison of Turn-OFF for 900V, 10 mΩ SiC MOSFET in TO-247-3 and TO-247-4 packages ($R_G$=5Ω, $V_{GS}$=-4V/+15V)**
- **RIGHT: Comparison of Turn-ON for 900V, 10 mΩ SiC MOSFET in TO-247-3 and TO-247-4 packages ($R_G$=5 Ω, $V_{GS}$=-4V/+15V)**

## Turn-OFF




## Turn-ON

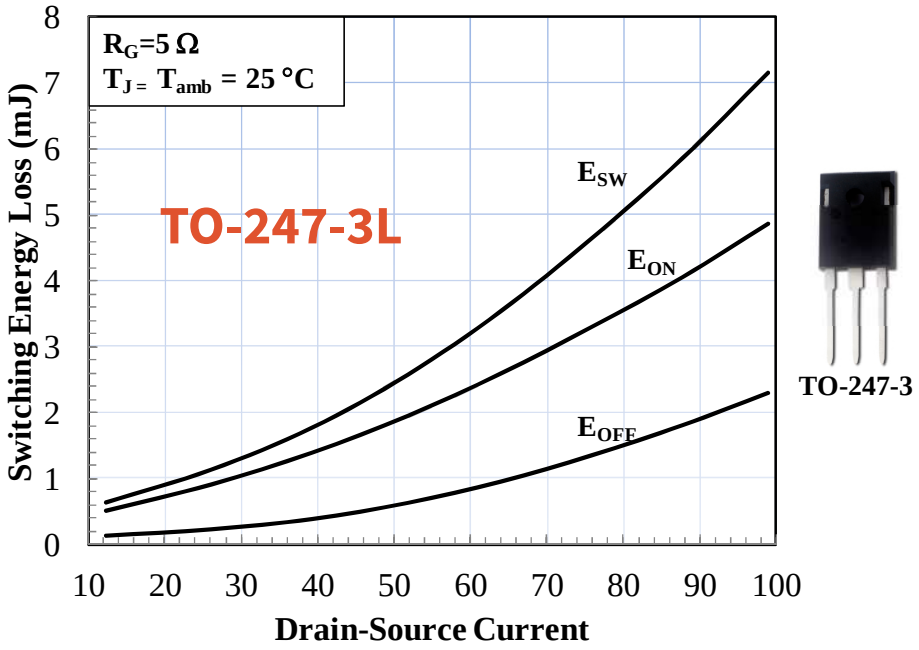


# 900V 10mΩ SiC MOSFET SWITCHING ENERGIES



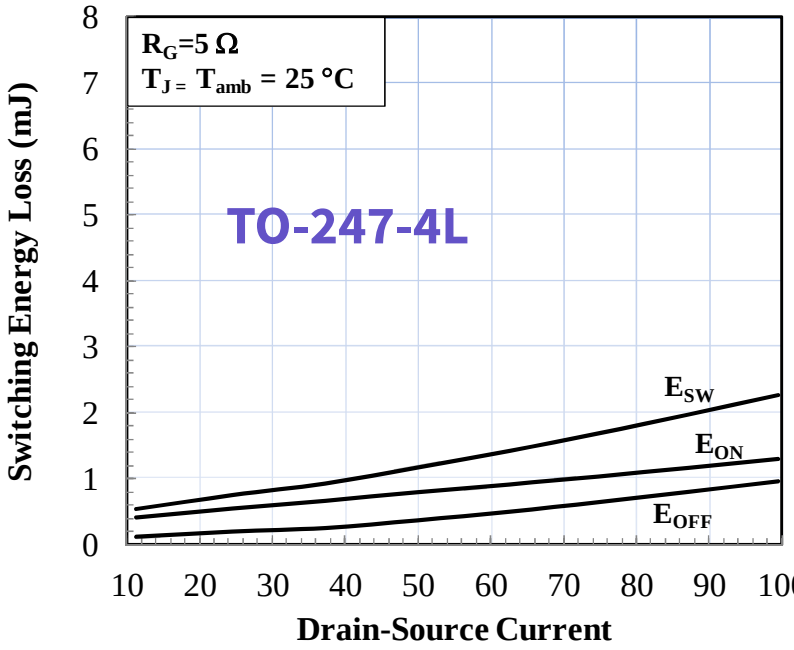
## ~3.5X lower switching energy with Kelvin Source contact

- **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)**






TO-247-3




TO-247-4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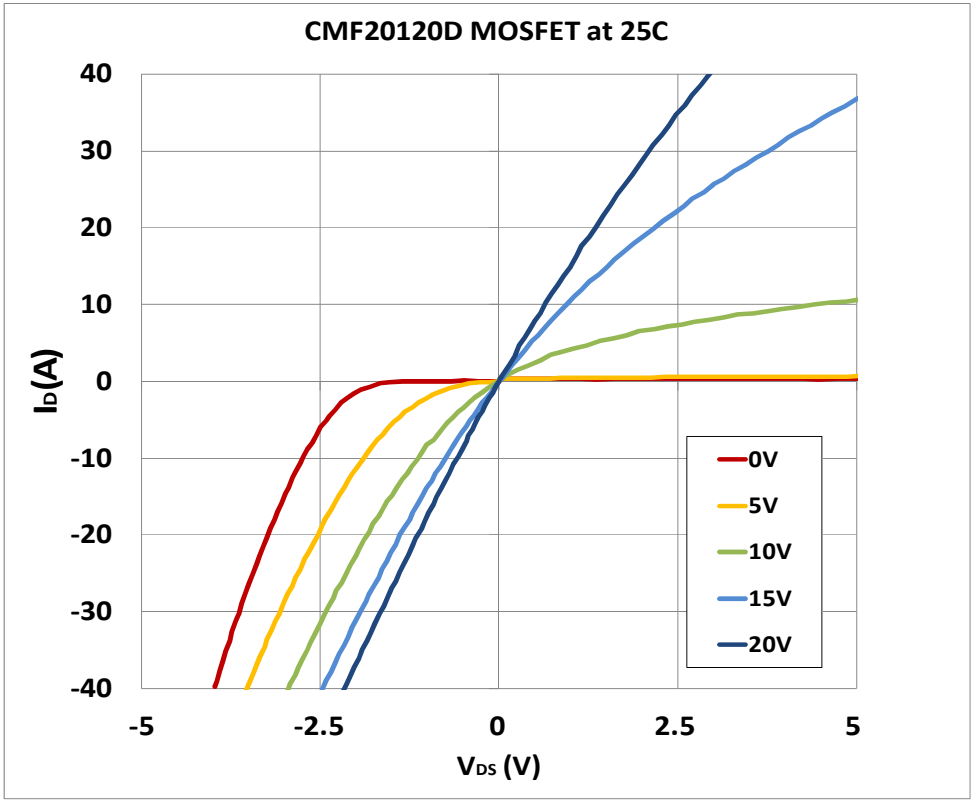
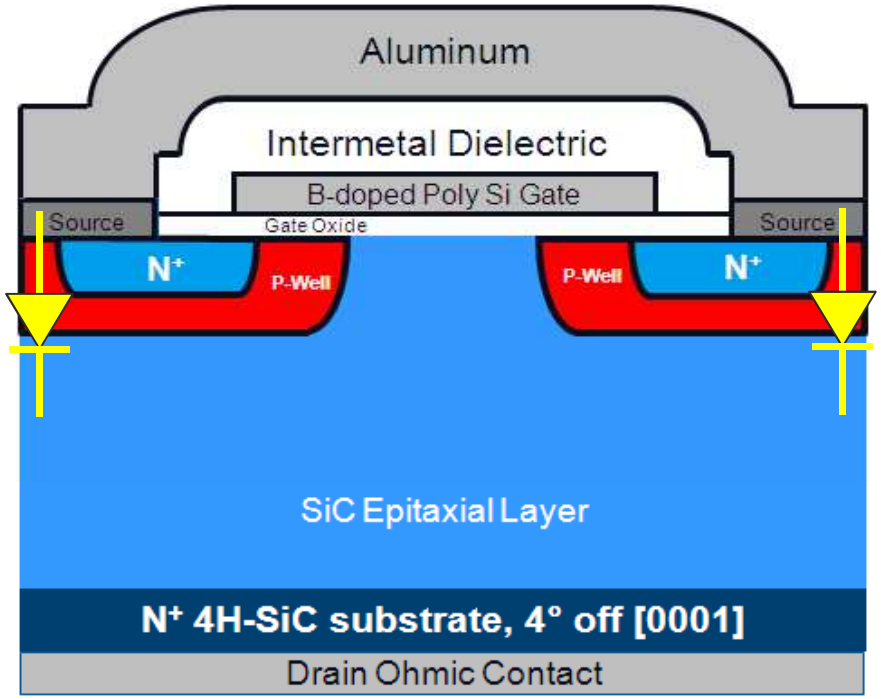
# Third Quadrant Operation – Maximizing Efficiency



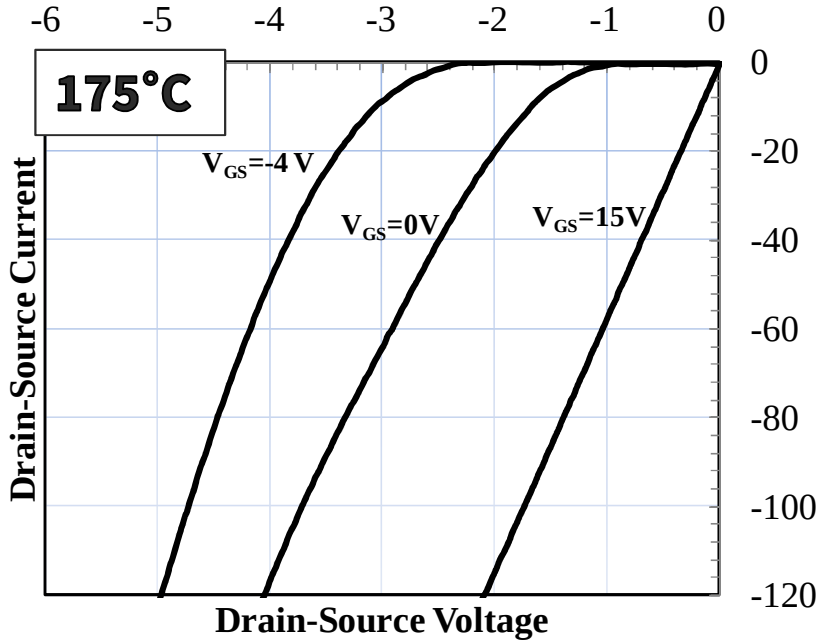



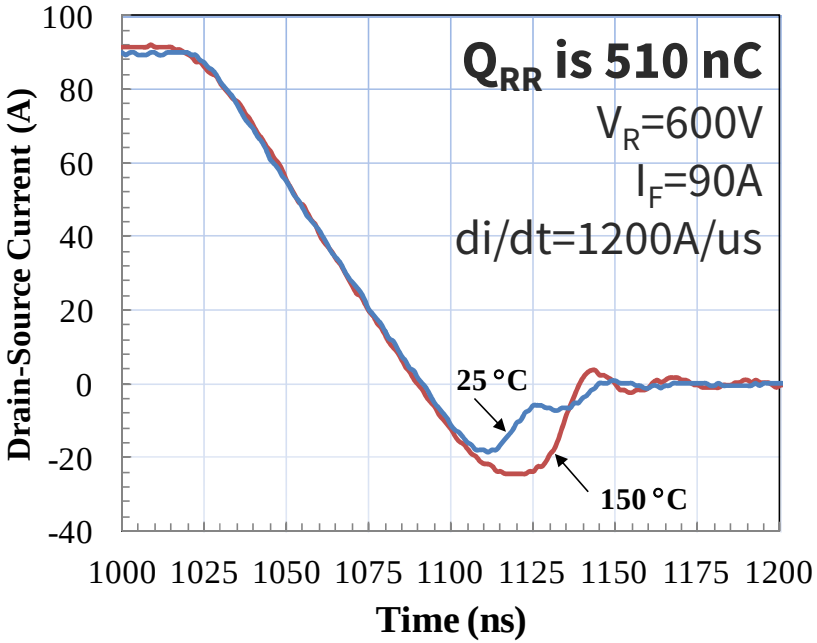

- **SiC MOSFETs Have Built-In Body Diode That Can Be Exploited In Applications Requiring Antiparallel Conduction**
- **Third Quadrant IV Characteristics are Parallel Combination of SiC MOSFET and PN diode**
- **Applying Positive Gate Bias Turns the SiC MOSFET Fully On**
- **Conduction is Symmetric for Positive and Negative $V_{DS}$ – Synchronous Rectification**

# 900V 10mΩ SiC MOSFET BODY DIODE CHARACTERIZATION



- LEFT: 3rd Quadrant characteristics of the 900V, 10 mΩ MOSFET at 175°C
- RIGHT: Reverse recovery waveforms of the 900V, 10 mΩ MOSFET at 25°C and 150°C
- Body diode with 3rd quadrant an excellent option for bidirectional flow
- Reverse recovery time is only 56 ns.



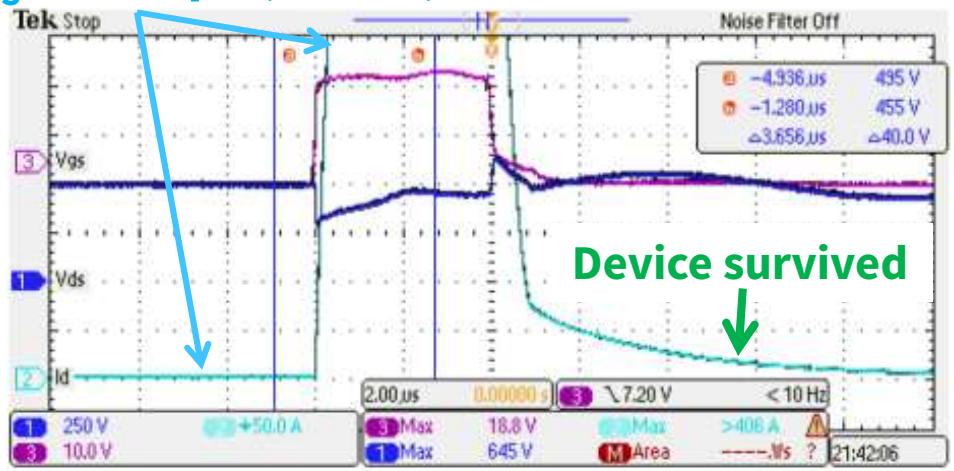



# SHORT-CIRCUIT TESTING OF 900V, 10mOHM SiC MOSFET IN TO-247-3L



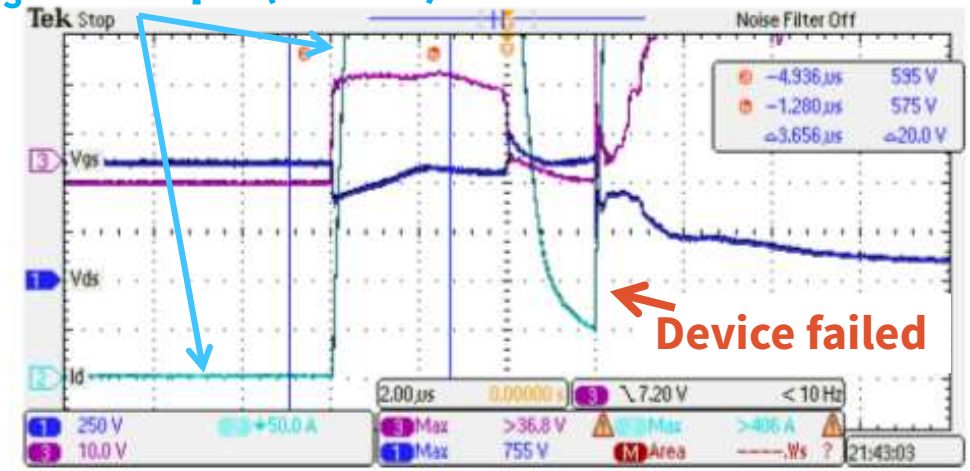
- Tested 4us with $V_{GS}$ = 19V
- $I_{DS}$ was not captured on scope, but was >406A
- At $V_{DS}$ = 500V, peak voltage was 645V, and device survived
- At $V_{DS}$ = 600V, peak voltage was 755V, and device failed
- Consistent with or above typical commercial SiC MOSFETs capability

$I_{DS}$ off scope (>406A)




$V_{DS}$=500V; $t_{SC}$=4us; $V_{GS}$=+19V

$I_{DS}$ off scope (>406A)



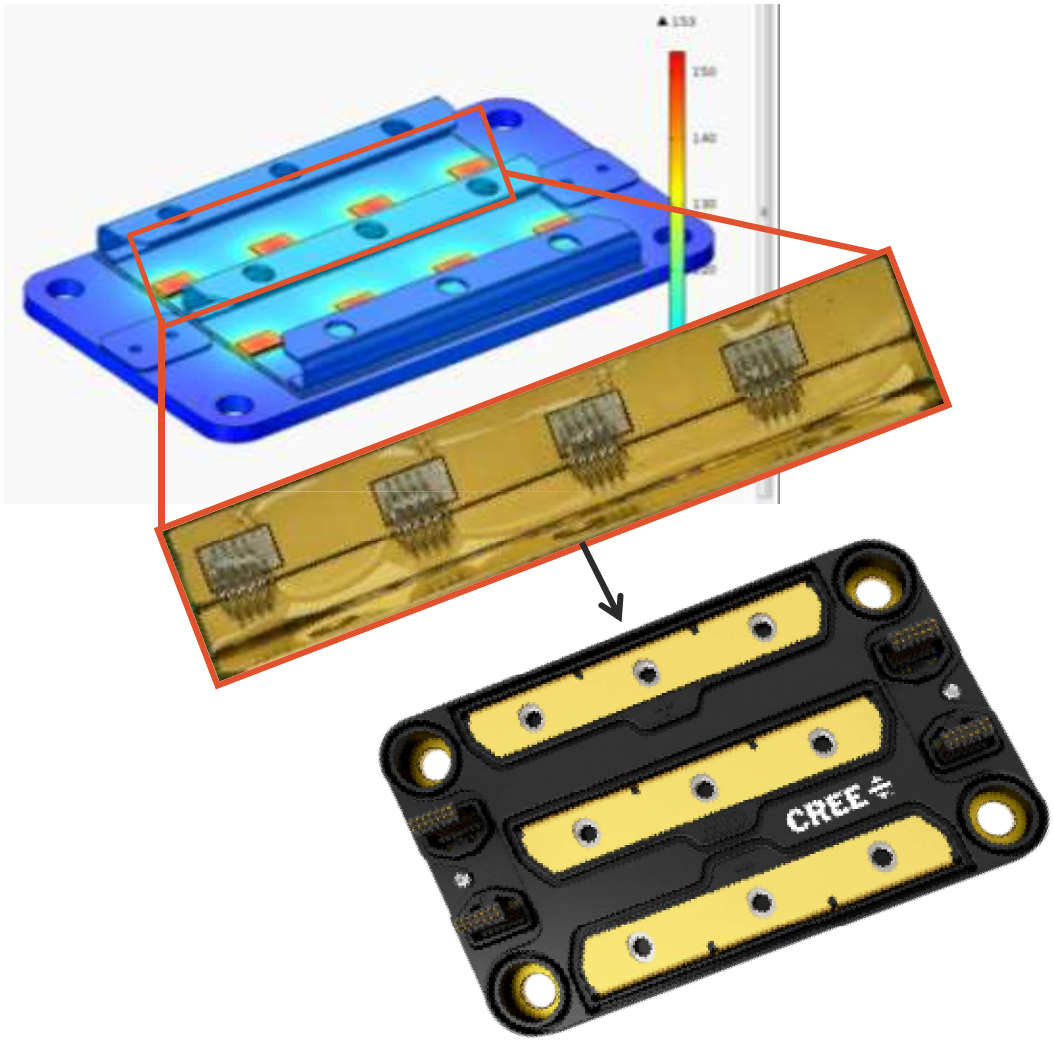

$V_{DS}$=600V; $t_{SC}$=4us; $V_{GS}$=+19V

Test results courtesy of: NC STATE UNIVERSITY

# 900V SiC MOSFET Half-Bridge Module Characteristics

# 900V, 400-800A, SiC HALF-BRIDGE POWER MODULES





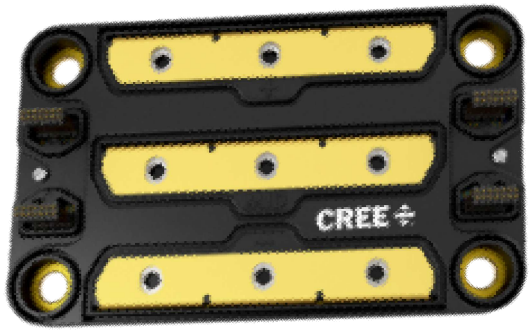

- **Assembled 900V, 10mΩ SiC MOSFET chips in ½ - bridge module**
  - **4 chips/switch pos. – 2.5mΩ module**
  - **8 chips/switch pos. – 1.25mΩ module**

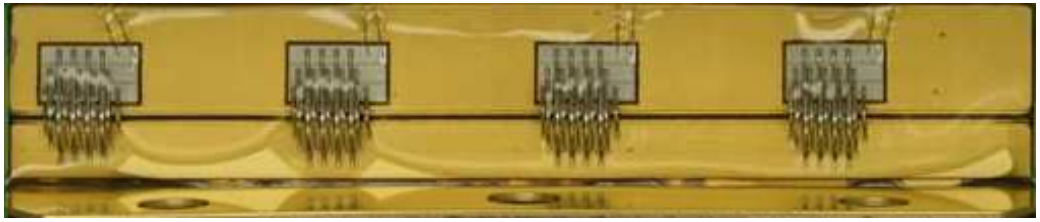
- **HTRB (150°C) completed**
  - **6 modules (48 MOSFETs)**
  - **1000 hrs; Zero failures**
- **HTRB (175°C) completed**
  - **5 modules (same modules as 150˚C test)**
  - **850 hrs; Zero failures**

# BENCHMARK 900V SiC & 650V Si POWER MODULES



- 900V SiC XAB350M09HM3 compared with 650 V EconoDUAL3 Si IGBT
- 250 V higher blocking voltage
- 10-20x lower body diode recovery, gate charge, and reverse transfer capacitance.
- Symmetrical 3rd quadrant conduction
- Lower on-state losses

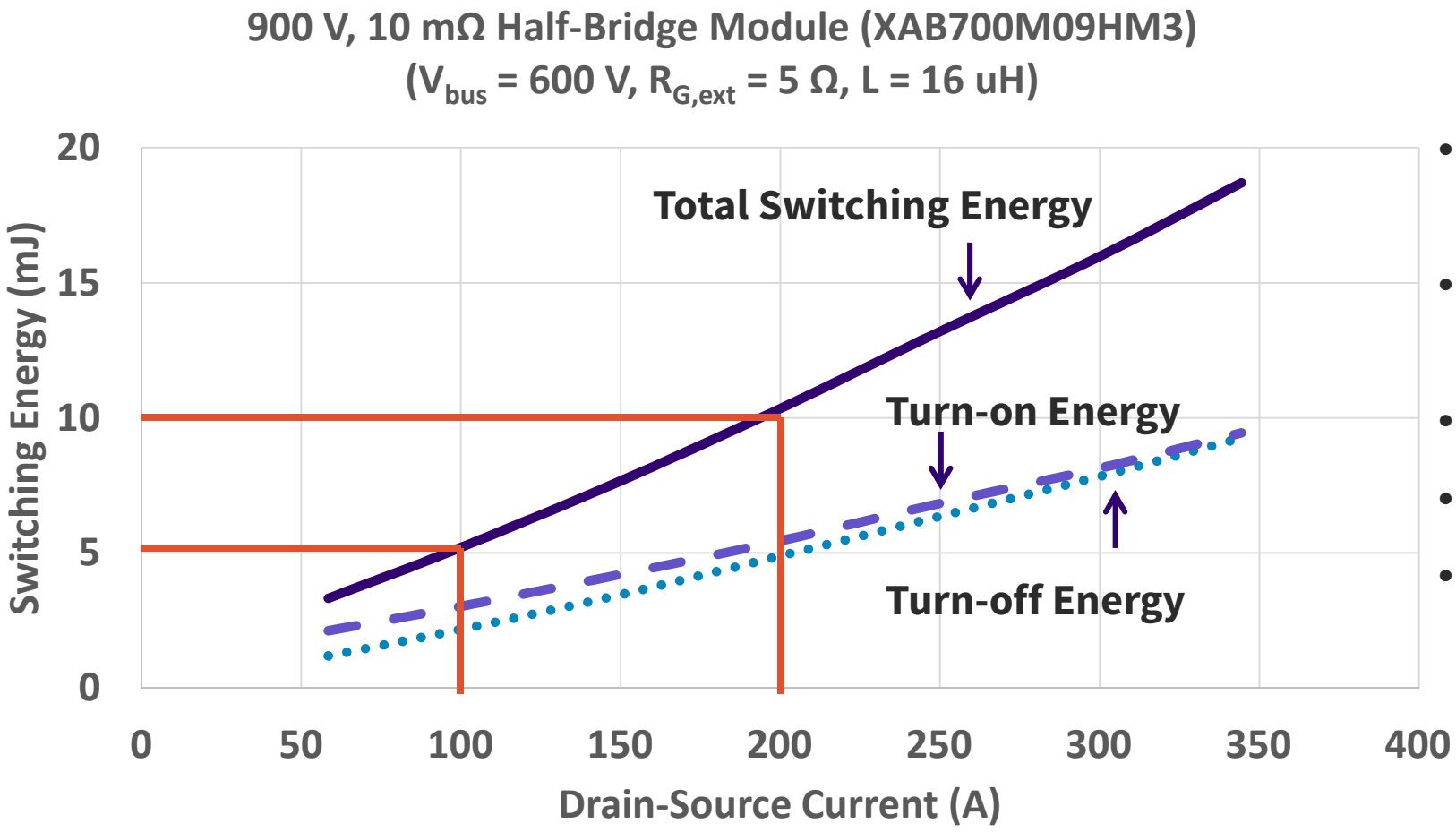


| Parameter | Wolfspeed XAB350M09HM3 | silicon FF450R07ME4_B11 |
|---|---|---|
| Package | HT-3000 (custom) | EconoDUAL3™ |
| Blocking voltage (V) | 900 | 650 |
| $T_{J,MAX}$ (°C) | 175 | 150 |
| $R_{DS,\ ON}$ (mΩ) (25°C/150°C) | 2.5 / 3.6 | N/A |
| $I_{DS}$ @ 150°C (A) | 405 | 430 |
| $Q_G$ (nC) | 648 | 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 (18pF x 4) | 820 |

# 900V, HALF-BRIDGE – 4 DIE/SWITCH; SWITCHING ENERGY





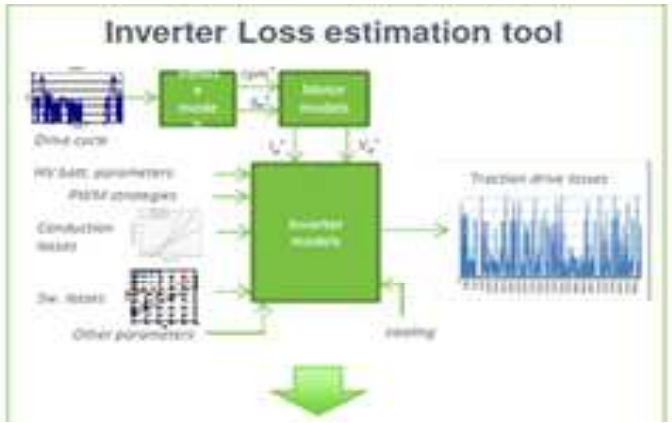

- 900V SiC XAB350M09HM3
- 4 MOSFETs / switch
- Switching 600V
- $E_T$ =**5mJ @ 100A**
- $E_T$ =**10mJ @ 200A**

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

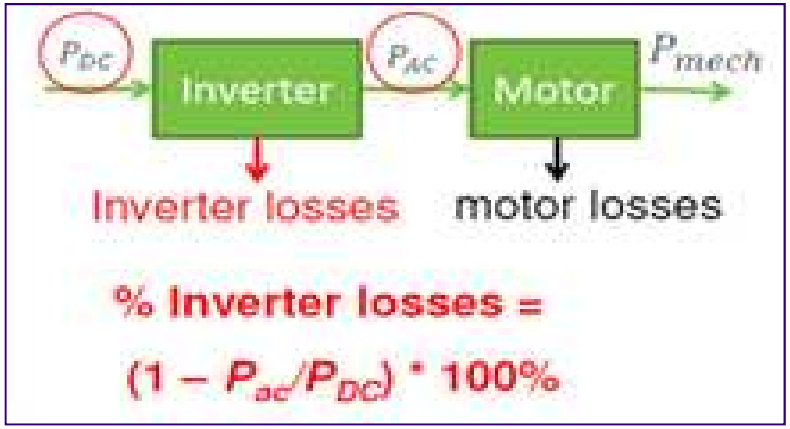
# IMPACT OF 900V SiC IN EV

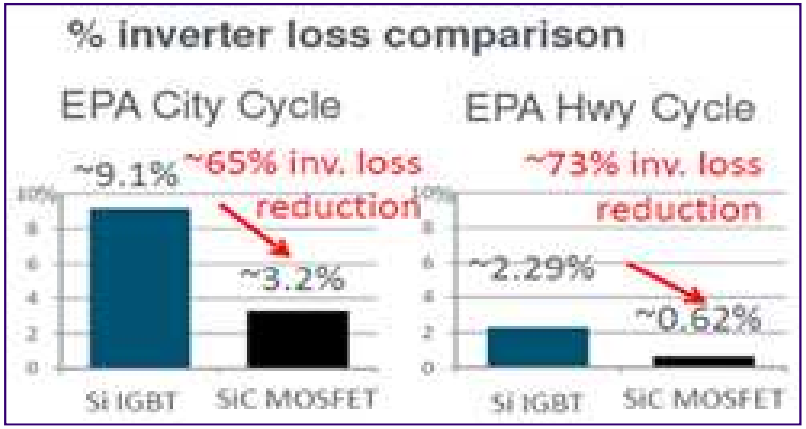


## Compared with Si inverter, SiC reduces inverter losses ~67% in combined EPA drive cycle




- 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 with SiC MOSFETs



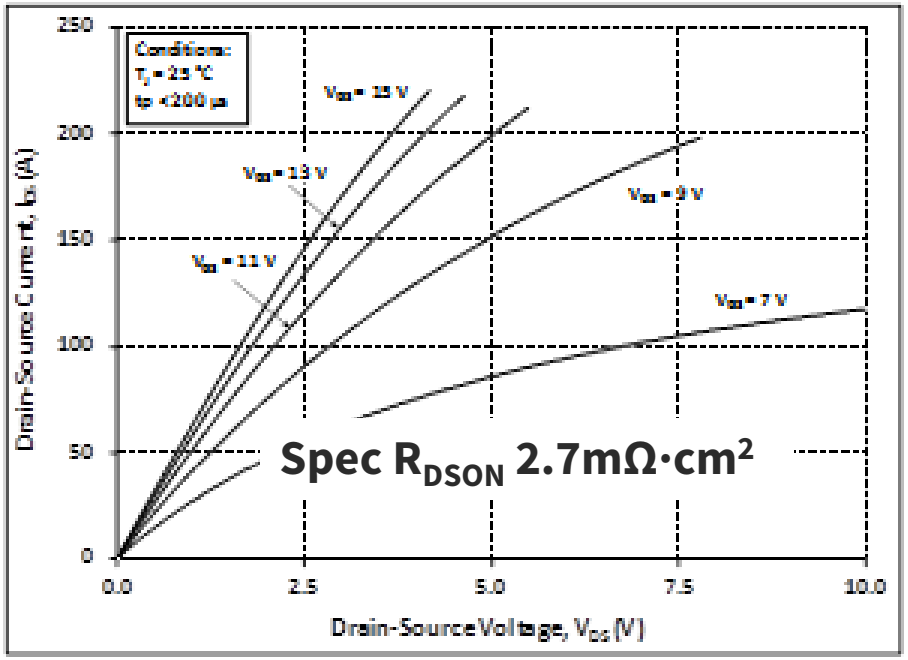

**Simulation data courtesy of Ford Motor Company, based on measured results of Wolfspeed 900V, C3M 10mOhm SiC MOSFETs**

# 1200V and 1700V SiC MOSFET data

# 1.2kV & 1.7kV GEN 3 SiC MOSFETs

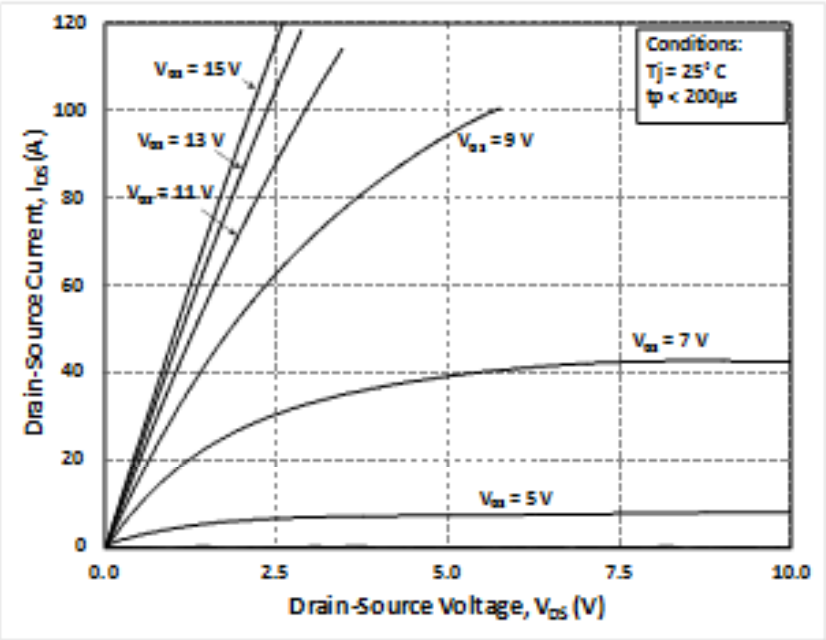


## 1.2kV SiC MOSFET




- Nominally a 75A SiC MOSFET
- $R_{DSONmax}$ at room temp ~**16mΩ**
- $R_{DSONmax}$ at 90˚C ~**21mΩ**

## 1.7kV SiC MOSFET

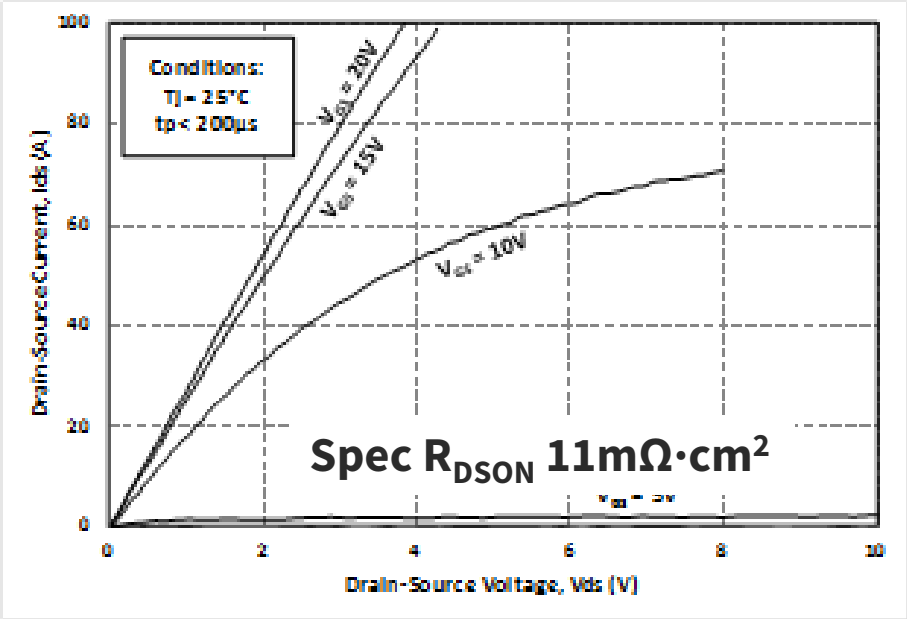



- Nominally a 67A SiC MOSFET
- $R_{DSONmax}$ at room temp **~20mΩ**
- $R_{DSONmax}$ at 90˚C ~**28mΩ**

# 3300V and 6500V SiC MOSFET data

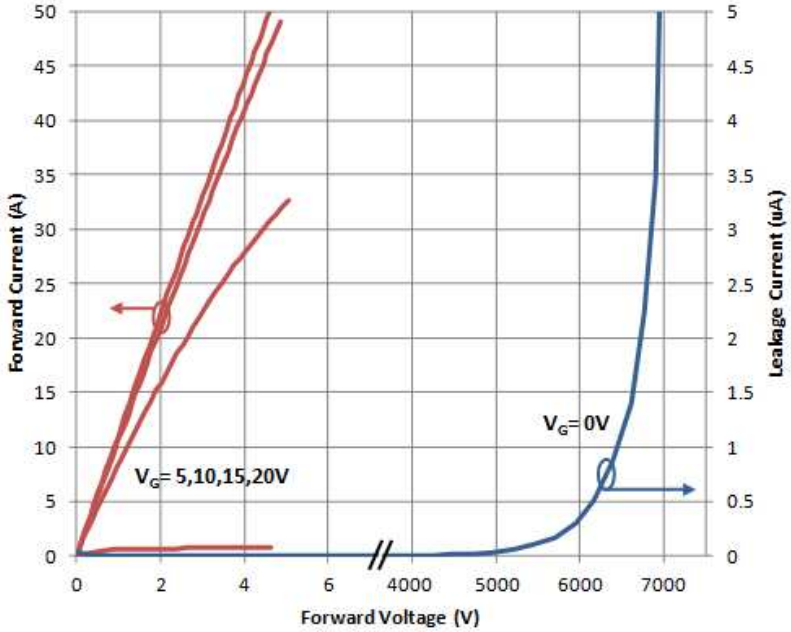
# 3.3kV & 6.5kV GEN 3 SiC MOSFETs

## 3.3kV SiC MOSFET




- Nominally a 40A SiC MOSFET
- $R_{DSONmax}$ at room temp **~41mΩ**
- $R_{DSONmax}$ at 90˚C **~98mΩ**

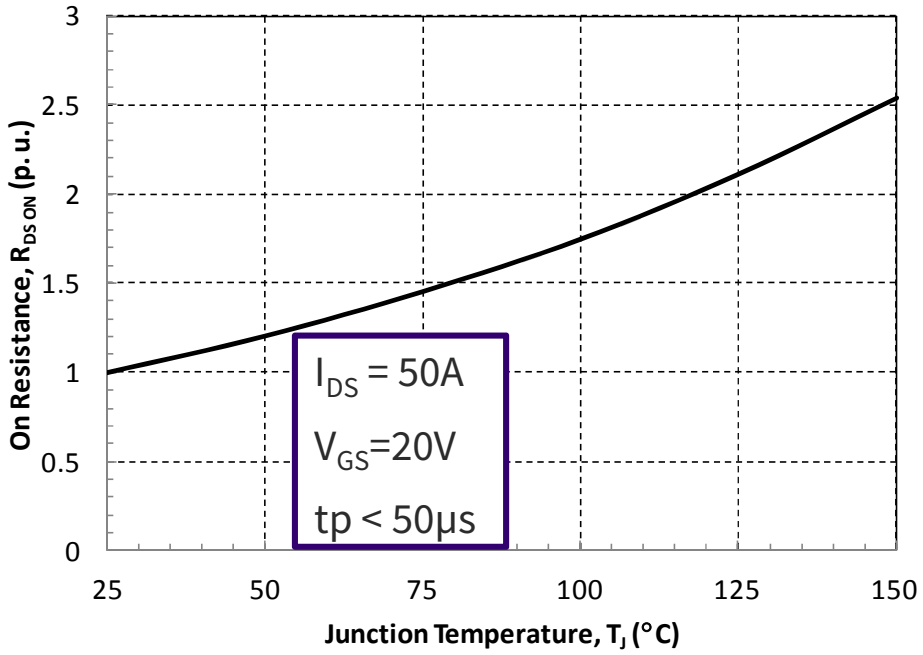
## 6.5kV SiC MOSFET



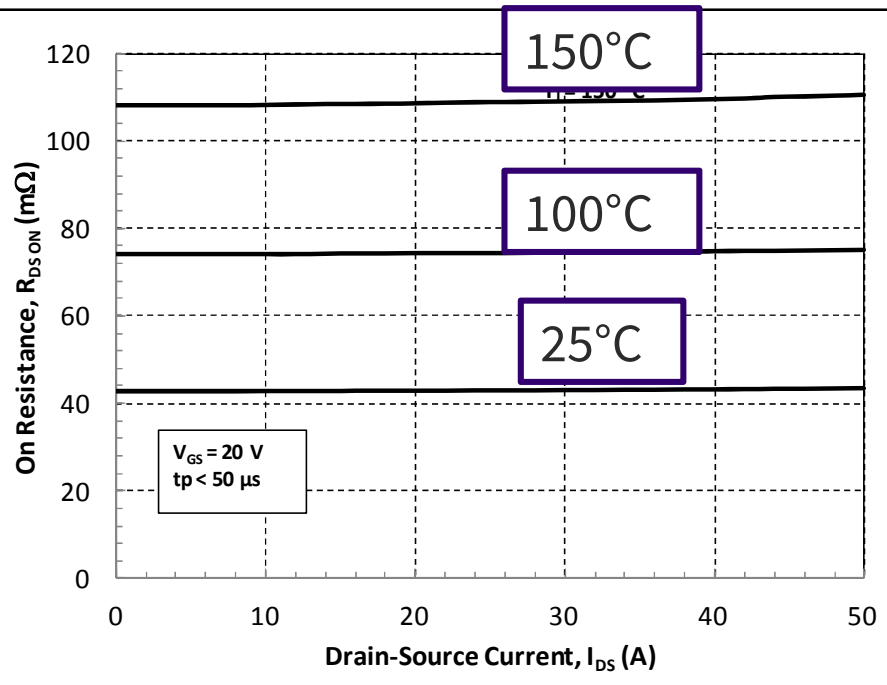

- Nominally a 20-30A SiC MOSFET
- $R_{DSONmax}$ at room temp **~100mΩ**
- $R_{DSONmax}$ at 90˚C **~171mΩ**

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






Normalized On-Resistance vs. Temperature



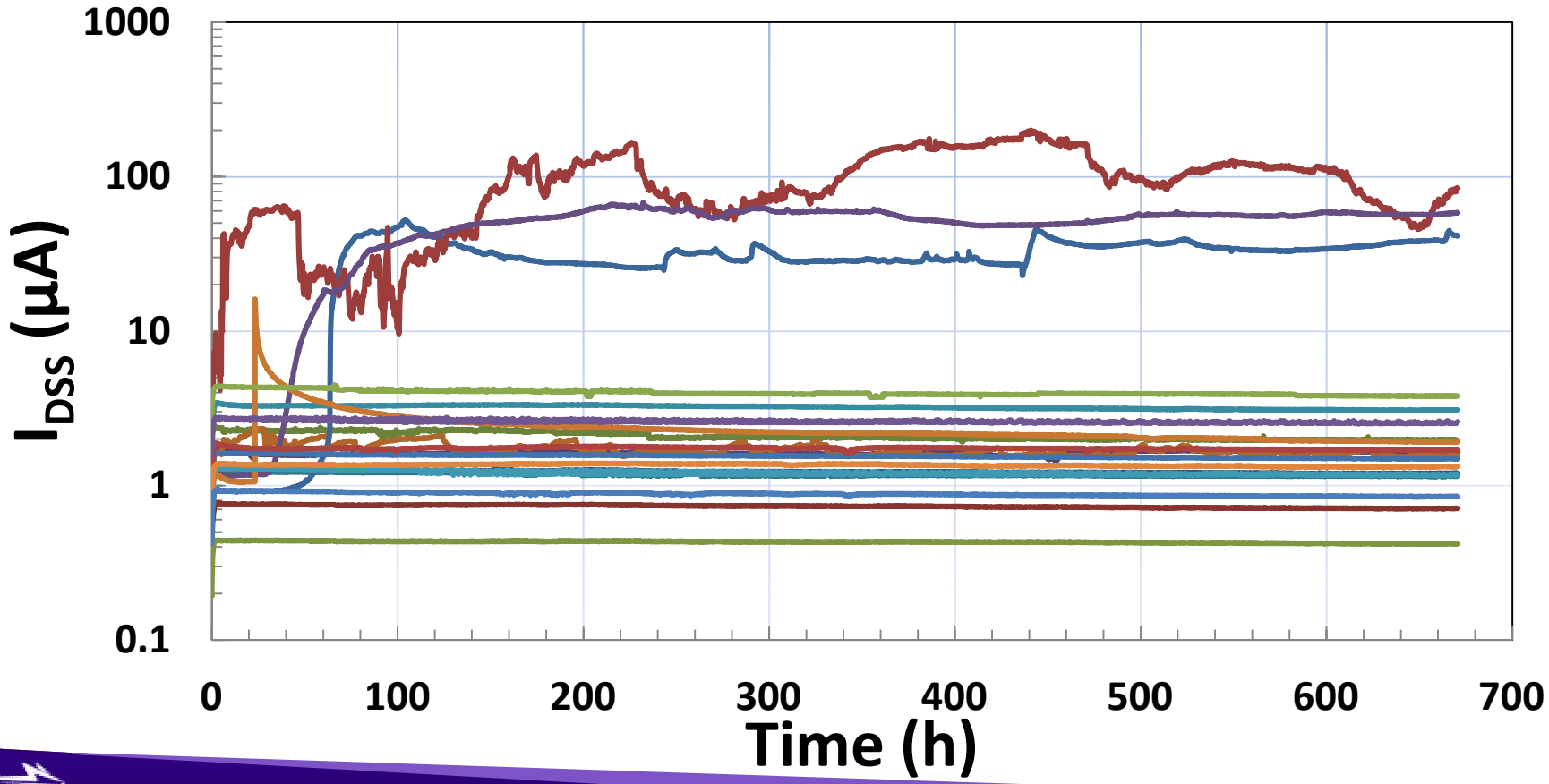

On-Resistance vs. Drain Current

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

# GEN3 3.3kV 45mΩ SIC MOSFET-INITIAL HTRB DATA

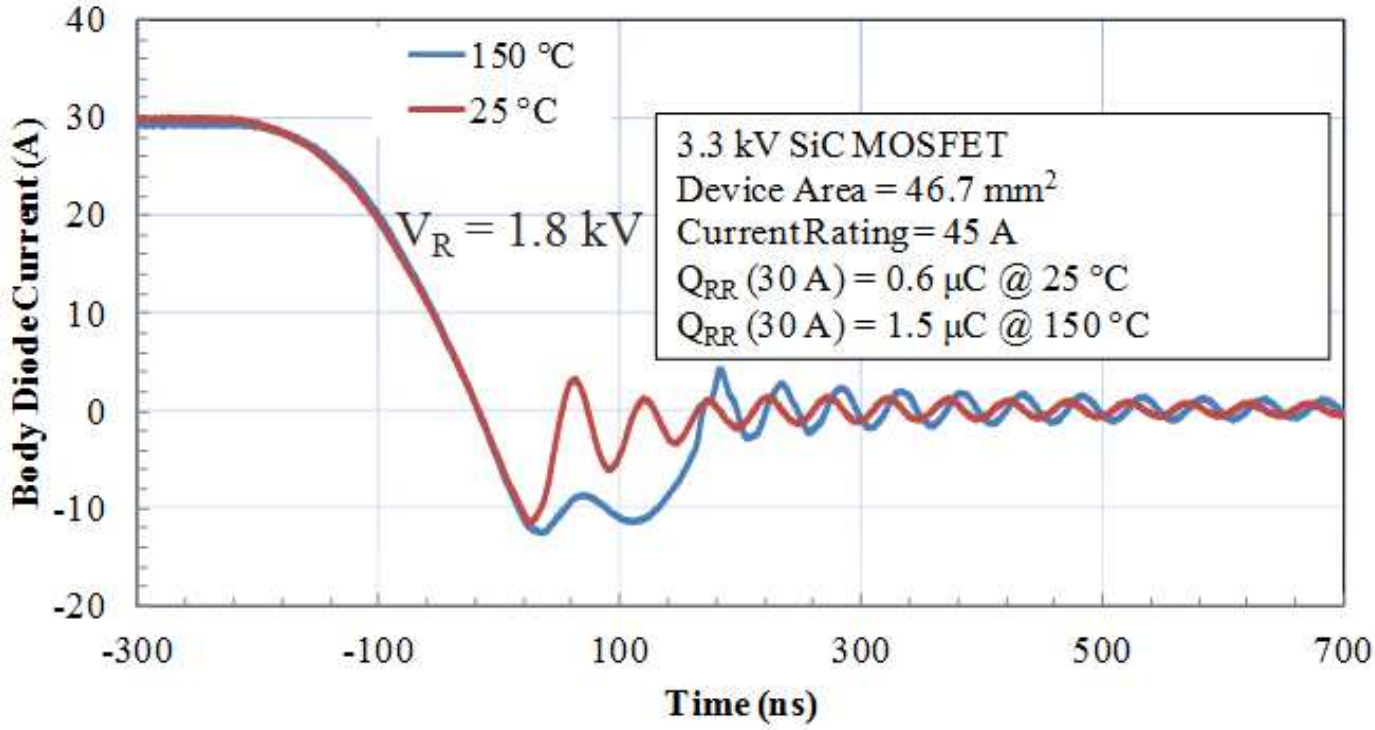


- Accelerated HTRB Testing (3.3kV – at 150°C ) of Gen3 3.3kV/45mΩ SiC MOSFET
- No Accelerated HTRB Failures Observed Up To 660 Hours



# 3.3kV, 45mΩ SiC MOSFET CHIP BODY DIODE

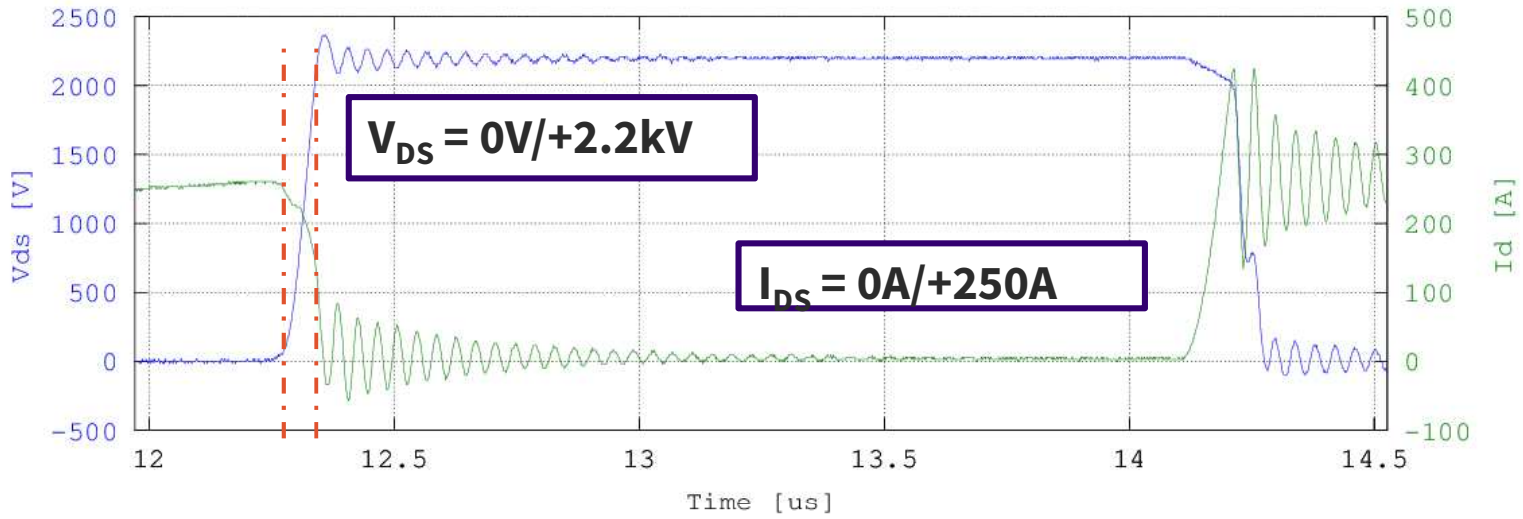


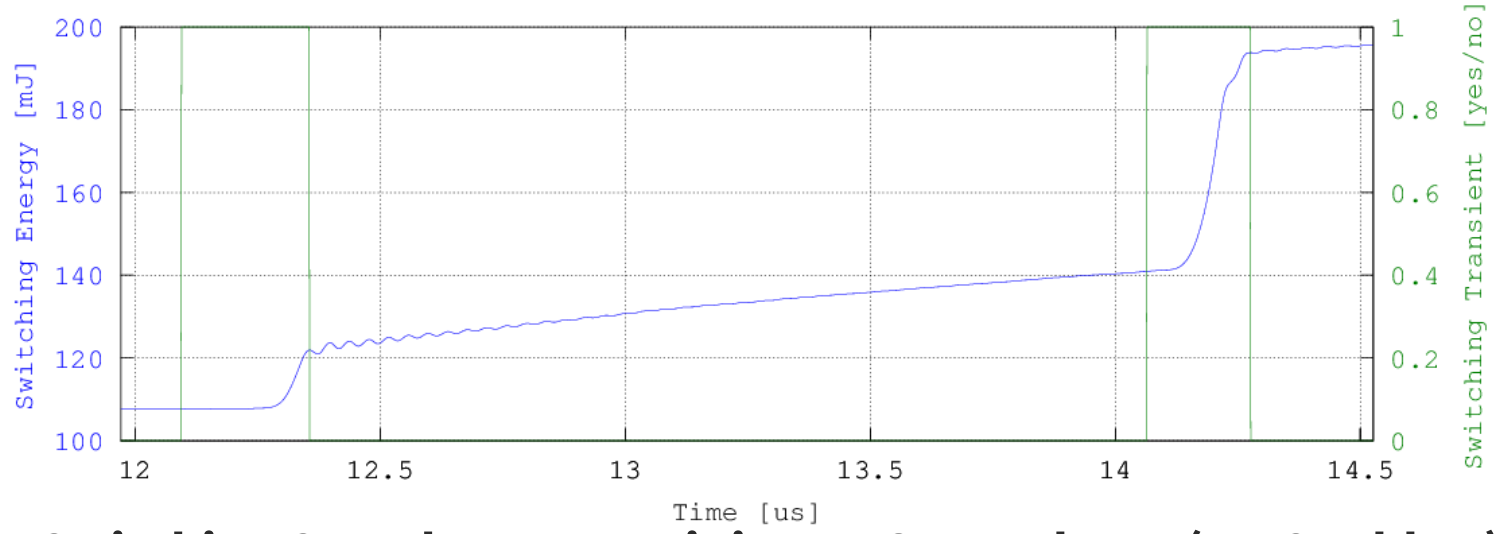



- **SiC body diode can eliminate external anti-parallel SiC diode**
- **Elimination of external anti-parallel diode saves cost and space**
- **Third quadrant operation of MOSFET possible for additional savings**

# GEN3 3.3KV SIC MOSFET
# 250A/2.2KV SWITCHING EVENT WITH RG-EXT = 2.5 Ω





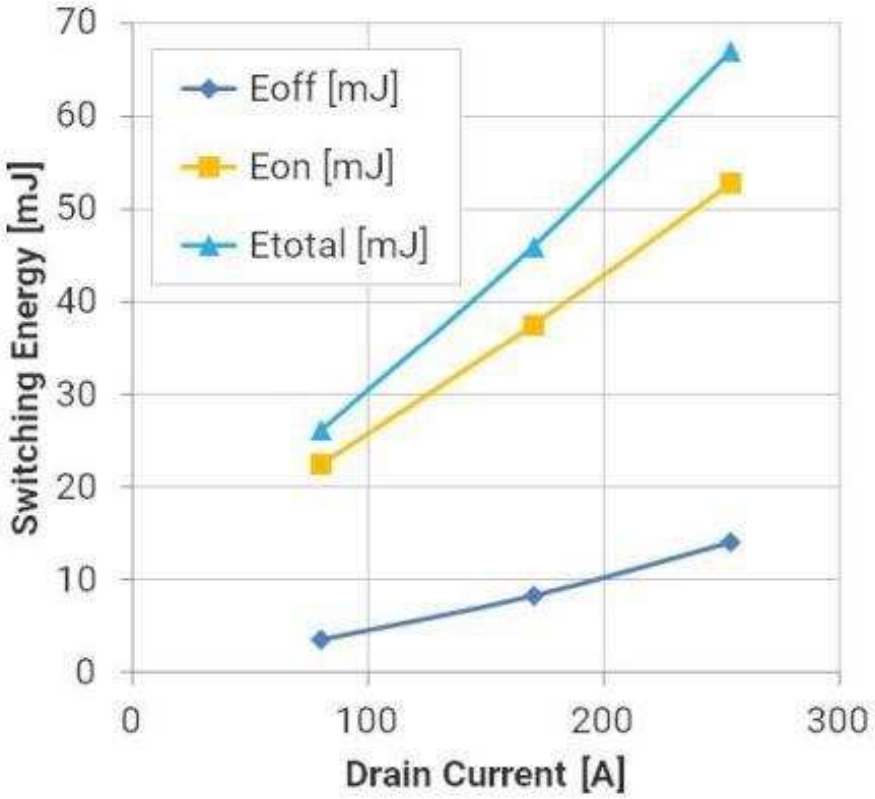




**Switching Speed <150ns; Minimum Overvoltage (No Snubber)**

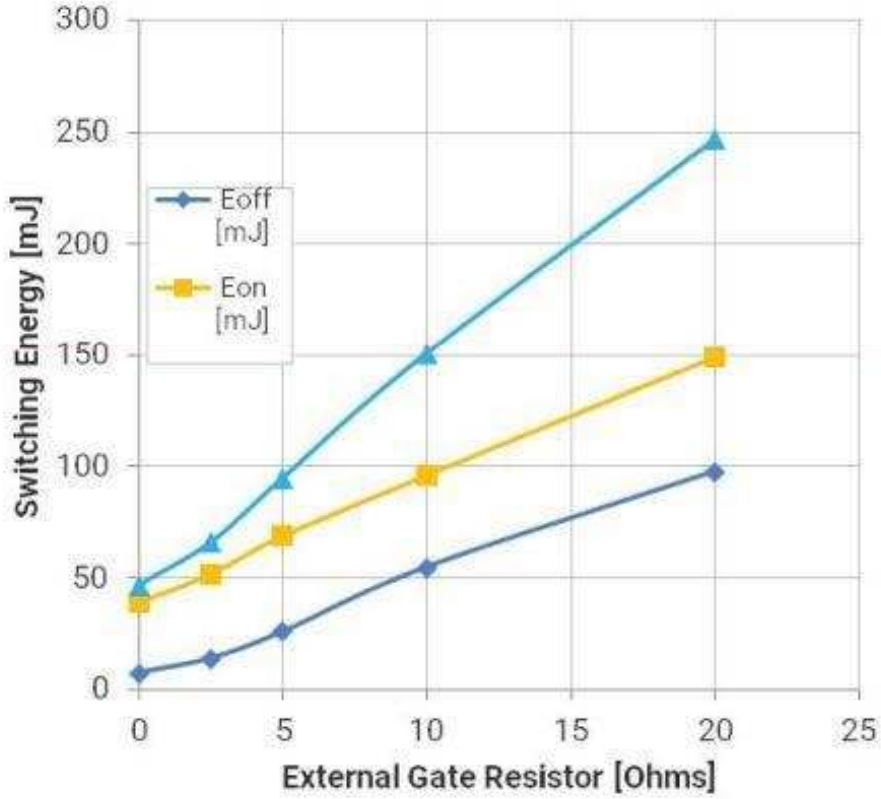
# 3.3kV SIC MOSFET SWITCHING LOSS PERFORMANCE @ 25°C

## 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**

# 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.**

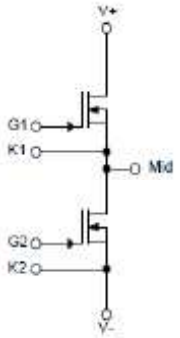
## 3.3 kV SiC HALF-BRIDGE POWER MODULE

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 | |

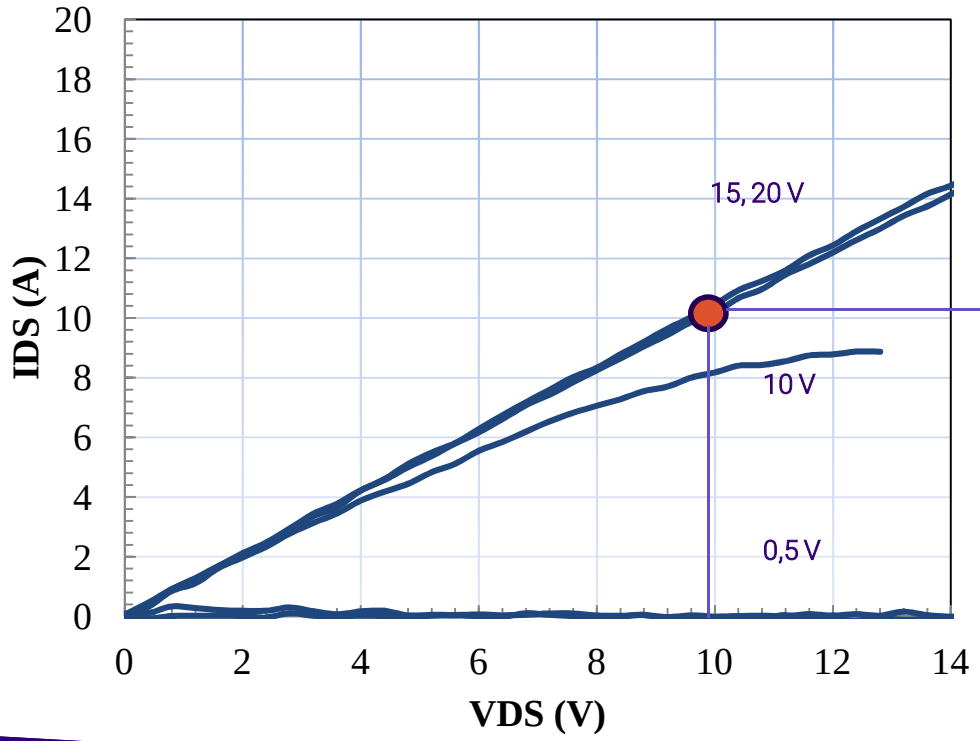
# 10kV SiC MOSFETs

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

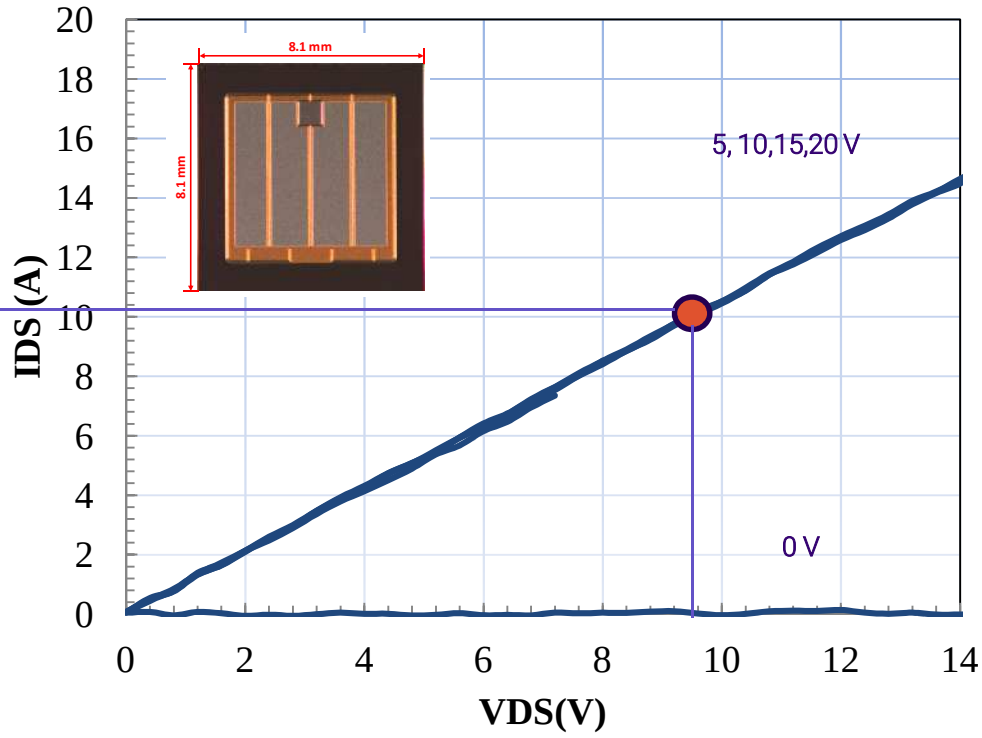


- Very Small Difference in On-Resistance ($R_{DS,on}$) at 150 °C
- Enhanced Short Circuit 10 kV SiC MOSFET has Higher Threshold Voltage

**Enhanced Short Circuit Gen3 10kV/350mOhm SiC MOSFET**

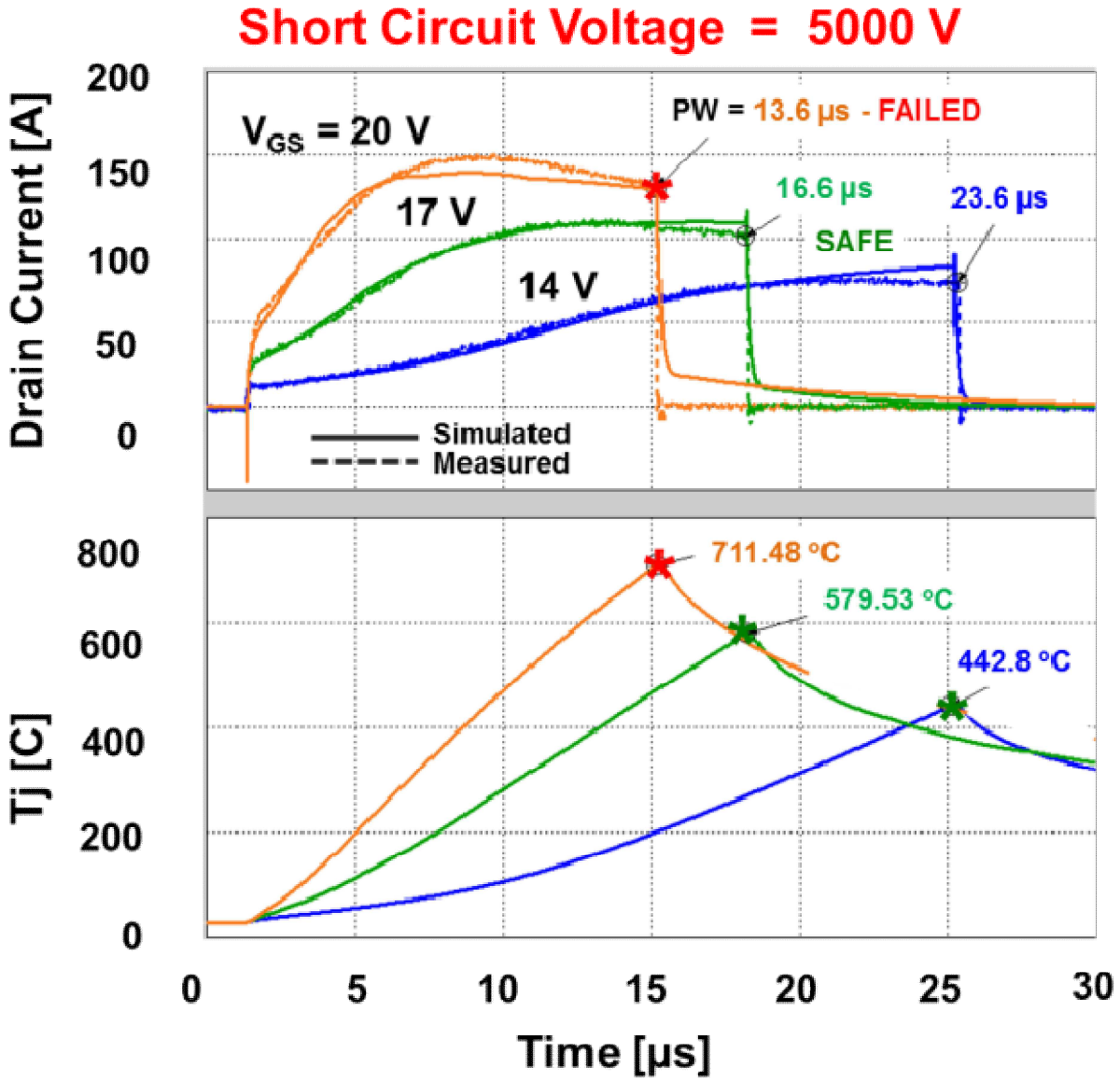



**Baseline Gen3 10kV/350mOhm SiC MOSFET**



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



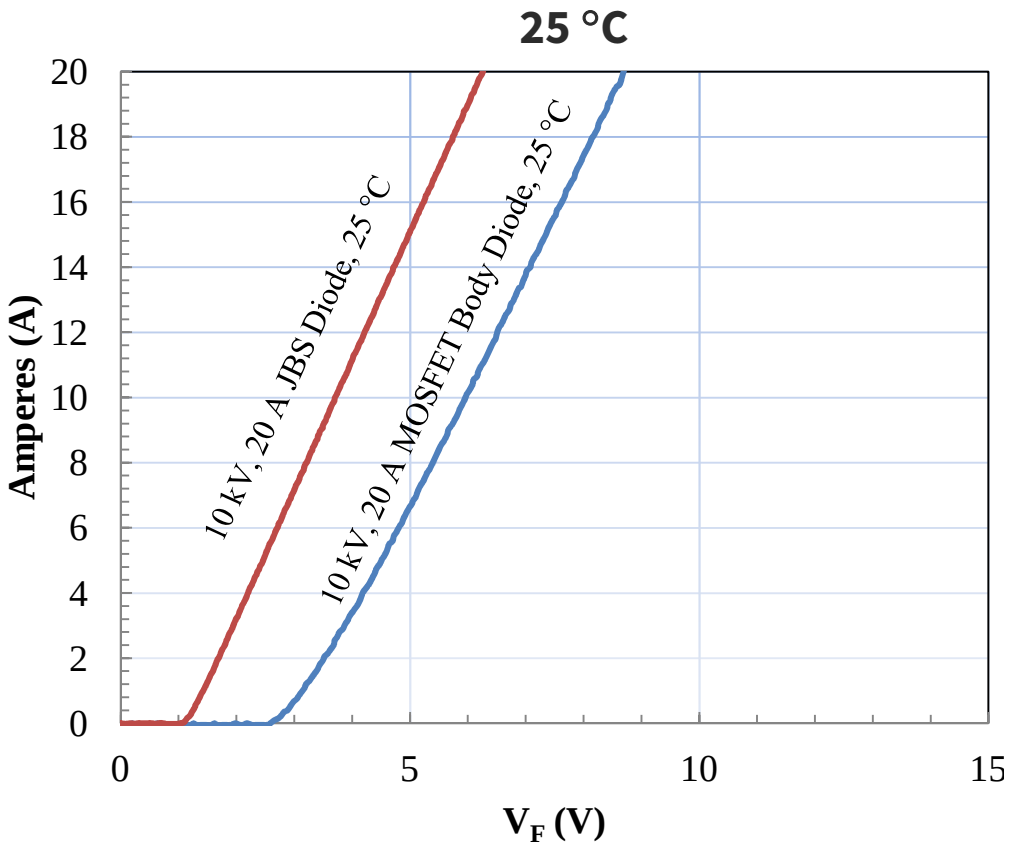


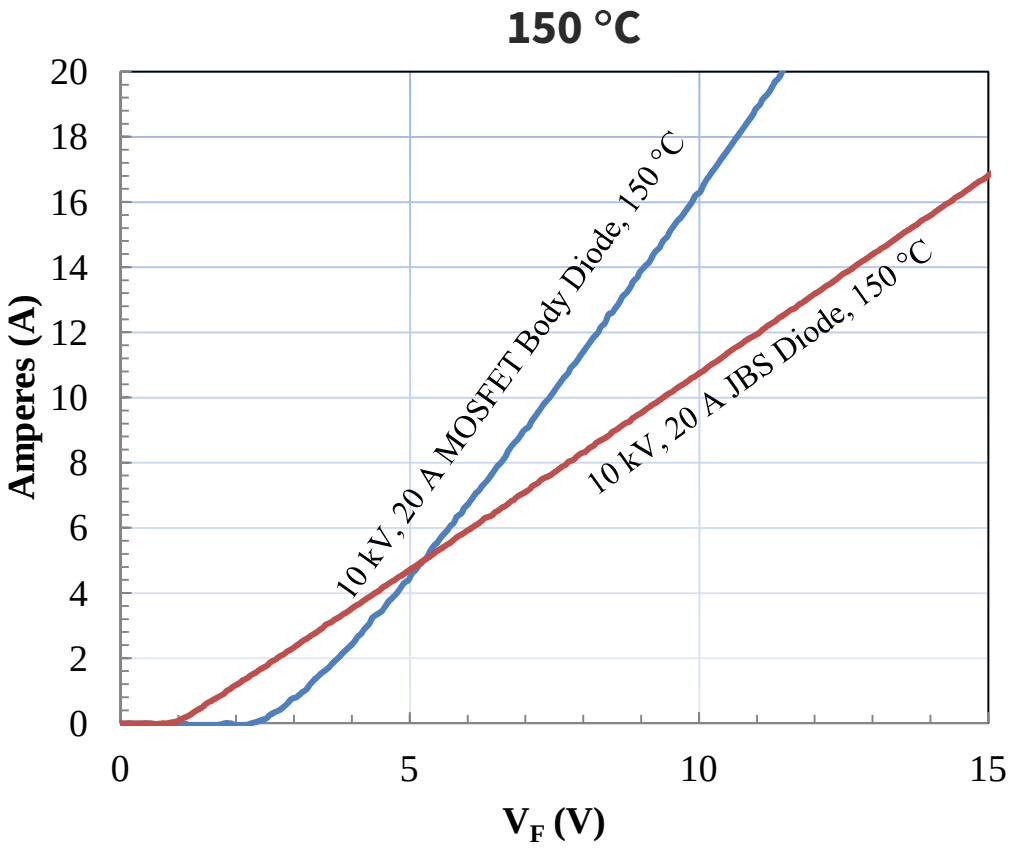

- Demonstrated Gen3 10 kV/350 mOhm SiC MOSFETs Capable of Sustaining Short Circuit Current For > 13 µsec at 5000V
- Measurement and Simulation Courtesy of Al Hefner at NIST

# 10 kV SIC MOSFET BODY DIODE STATIC CHARACTERISTICS



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

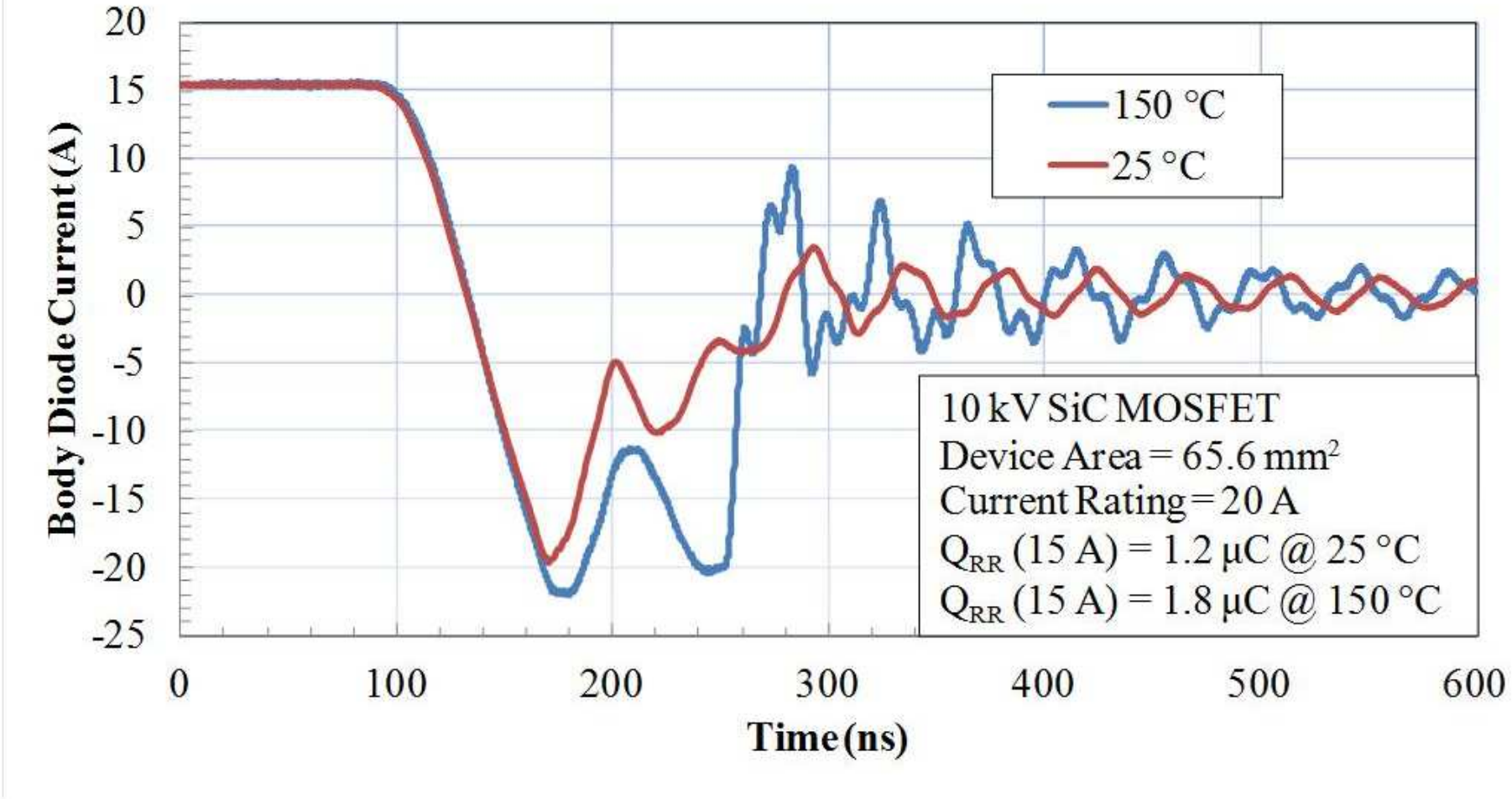


# Gen3 10kV/350mOhm SiC MOSFET Body Diode Switching - Body Diode Has Low Reverse Recovery Loss

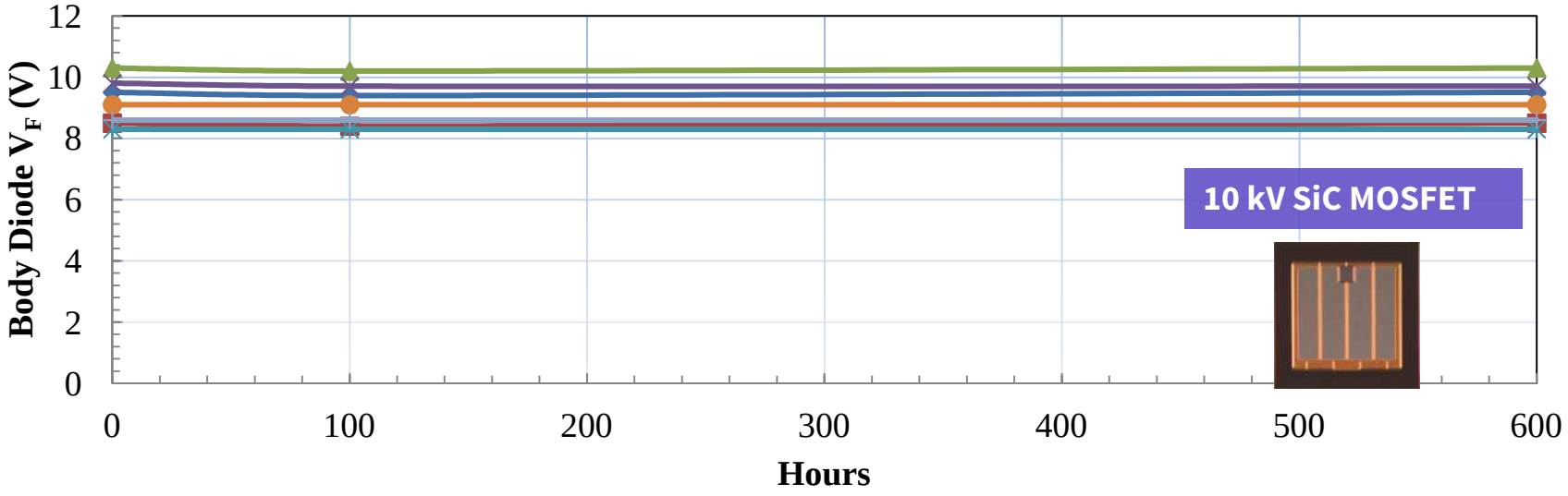


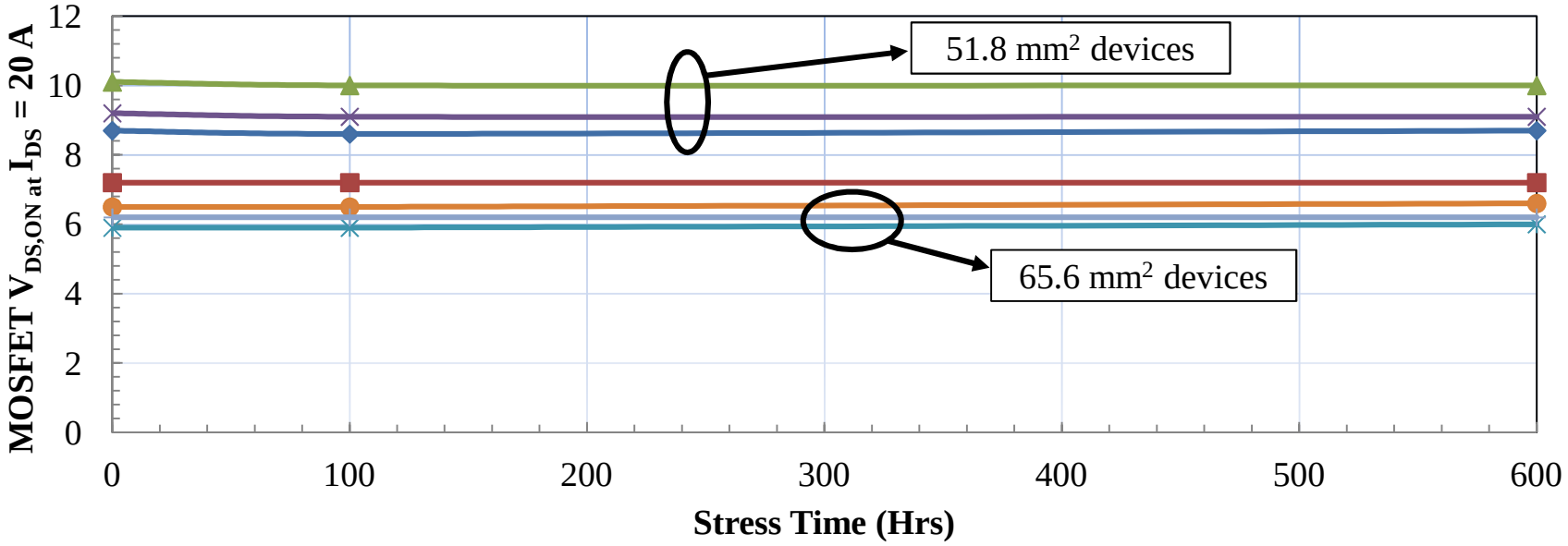
- **Body Diode Has Excellent Dynamic Characteristics ⇒ Low Reverse Recovery**



# Gen3 10kV/350mOhm SiC MOSFET Body Diodes Exhibit Stable Performance Under Constant Bias Stress

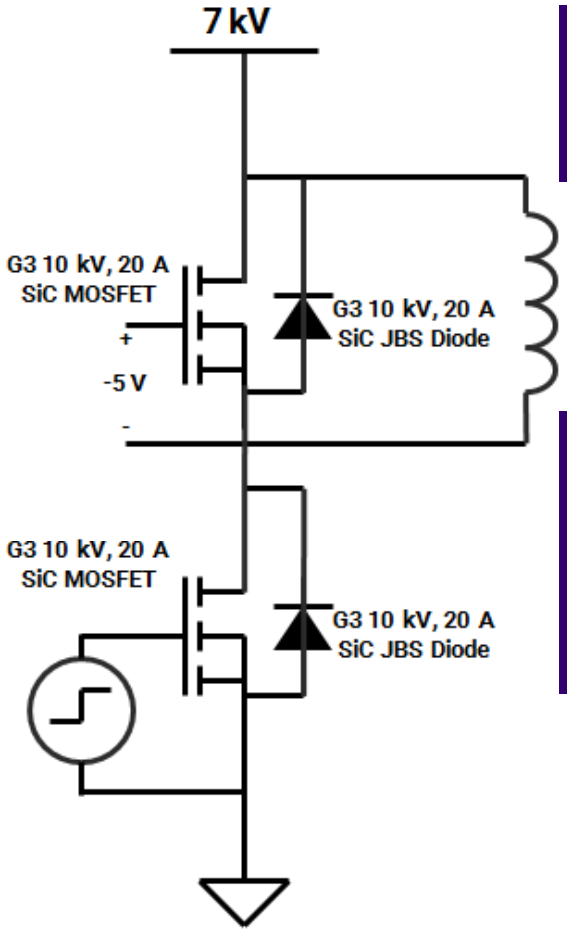




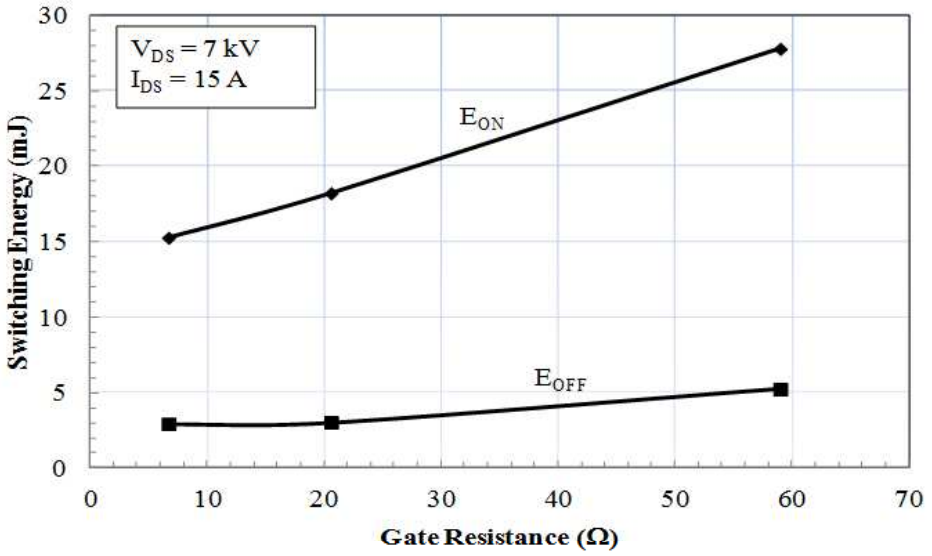
# ½ BRIDGE CONFIGURED MEASURED SWITCHING ENERGIES AND WAVEFORMS

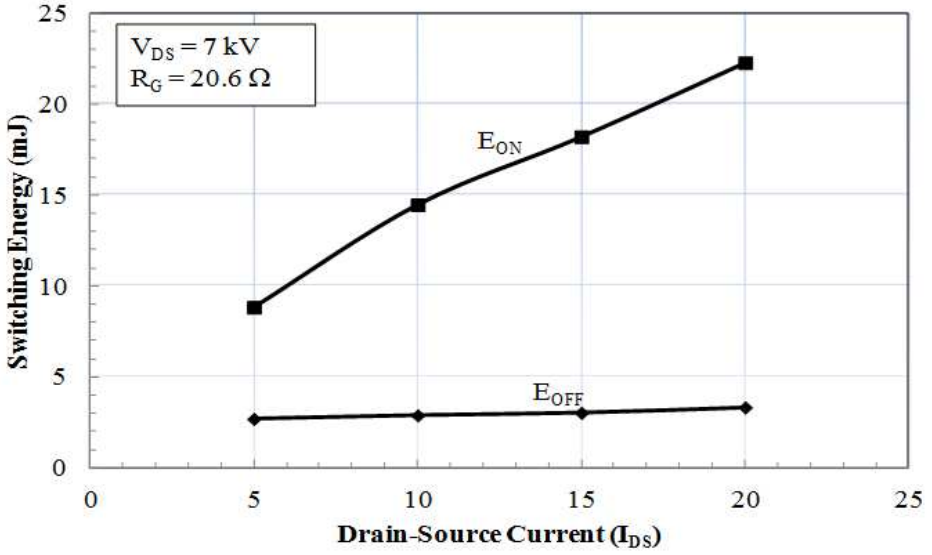





**$E_{TS}$ measured 10-33mJ**

**$E_{TS}$ =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.**

# SUMMARY 900V TO 10kV GEN 3 SiC MOSFETS

- SiC MOSFETs released in 2011
- > 20 SiC MOSFET discretes in market
- Gen 3 SiC MOSFETs entering market

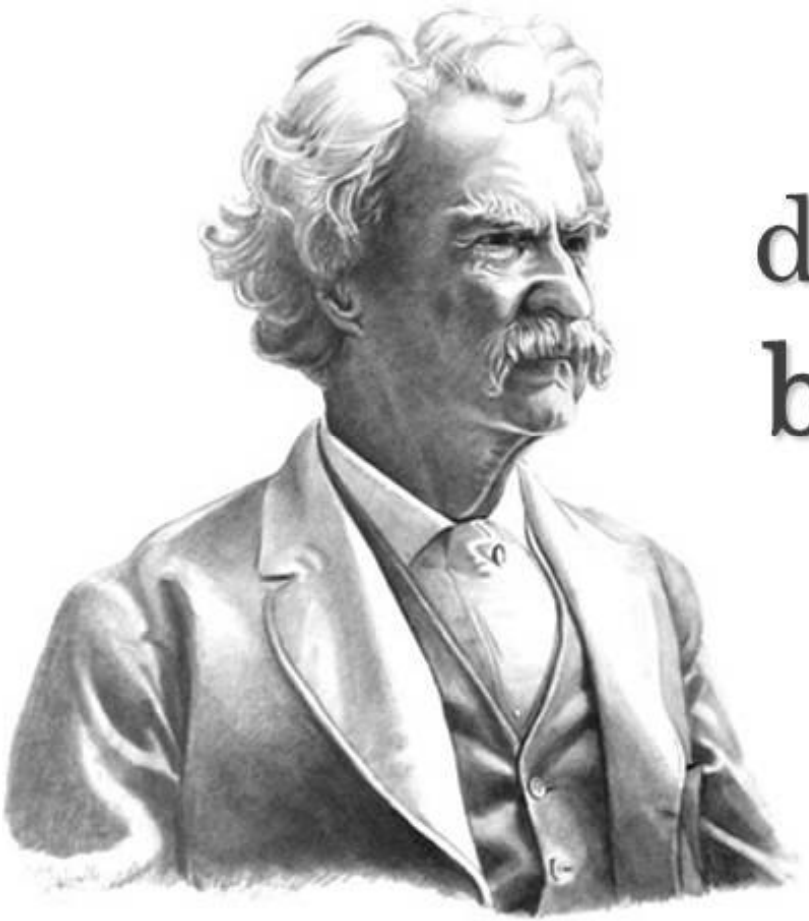
| $V_{DSmax}$(V) | Chip $R_{DSON}$ (mΩ) | Comments |
|---|---|---|
| 900 | 10 | 65mΩ released 2015 |
| | | Engineering samples |
| 1200 | 16 | Engineering samples |
| 1700 | 20 | Engineering samples |
| 3300 | 41 | Engineering samples |
| 6500 | 100 | Engineering samples |
| 10000 | 350 | Engineering samples |


900-1700V low-profile 62mm


900-1700 V low profile

3.3-6.5 kV Half-Bridge

10kV XHV-6 Half-bridge



# History

doesn't repeat itself,

but it does rhyme.

Mark Twain

# Questions or Discussion?


## Acknowledgment

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*EV drive cycle data analysis based on measured 900V SiC MOSFET data provided by Dr. Chingchi Chen and Dr. Ming Su, Ford Motor Company*


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