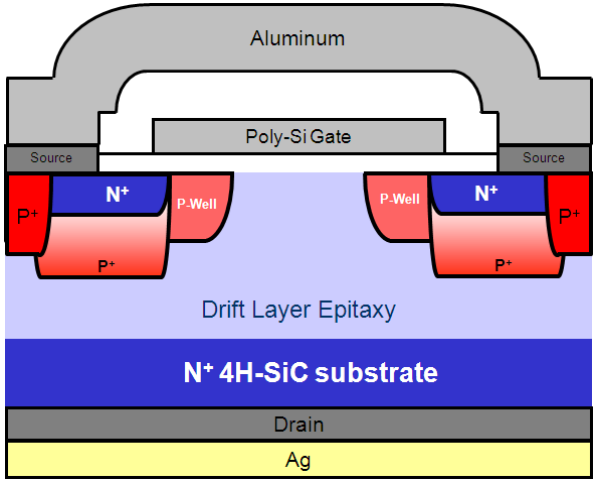
Cree's SiC MOSFETs and Modules

January, 2013

Outline

- Overview of Cree's MOSFET Portfolio
- Reliability Studies of Cree's SiC MOSFETs
- Beneficial Properties of SiC MOSFETs
- Applications
- Cree Modules

Cree's Planar SiC MOSFETs – Maximizing Reliability



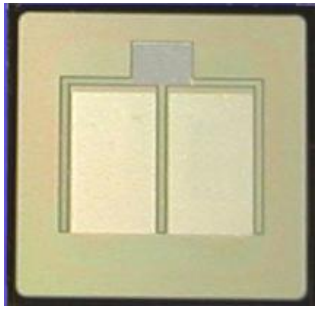
Schematic cross-Section of Unit Cell for Cree's Planar DMOSFET

- **Normally off – all reliability data taken at V_{GS} = 0V**
- **Planar structure to minimize all critical electric fields**
- **Gate oxide represents state-of-the-art for reliability and electron mobility**
- **Fully passivated and passes stringent THB requirements**

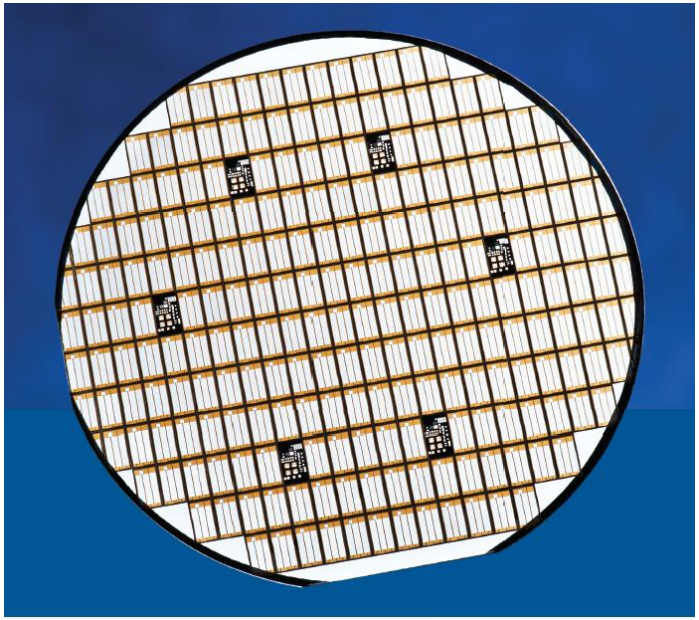
Cree's SiC MOSFET Product Portfolio

1200V SiC DMOS FET
80mΩ & 160mΩ available today

TO-247



Bare Die

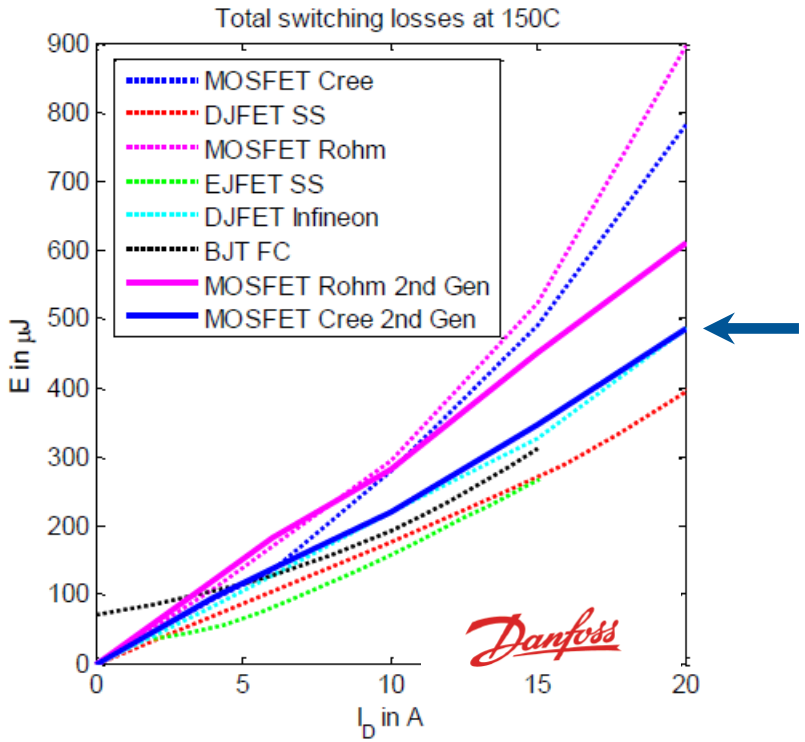


New 50 Amp Chip Set:

- **CPM2-1200-0025B: 50 Amps at 1200V**
- **CPM2-1700-0040B: 50 Amps at 1700V**

Cree's Gen 2 MOSFET: Lower Cost, Higher Performance

Lower Switching Losses



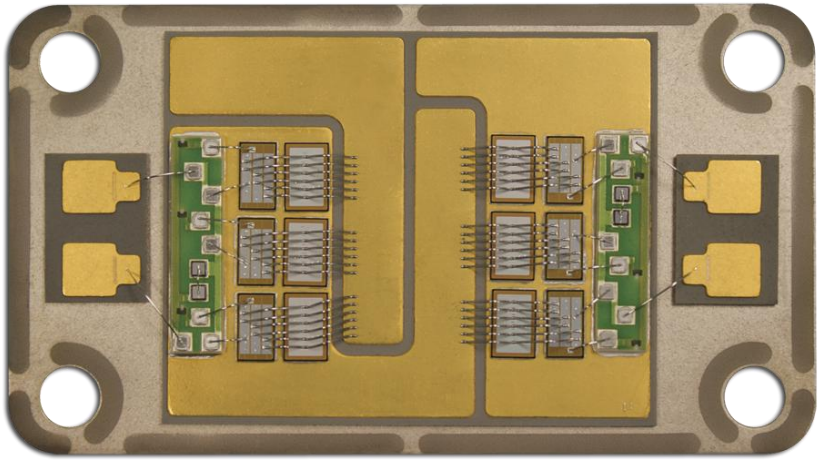
(Data presented at PCIM, May, 2012)

- **Lower Cost: 35% die shrink due to lower specific R_{on}**
- **Thinned wafer for lower thermal resistance**
- **Higher reliability due to lower critical electric fields**

Samples of 1200V Gen 2 available now: 25 mOhm and 80 mOhm

Summary of New SiC 50 Amp Chip Set

- New generation chip set for MOSFETs and Schottky diodes capable of conducting 50 Amps
- Targeted for high power module applications
- Key milestone in the evolution of SiC to open up the motor drive industry



1700V Half-Bridge Module with new SiC MOSFETs and JBS Diodes

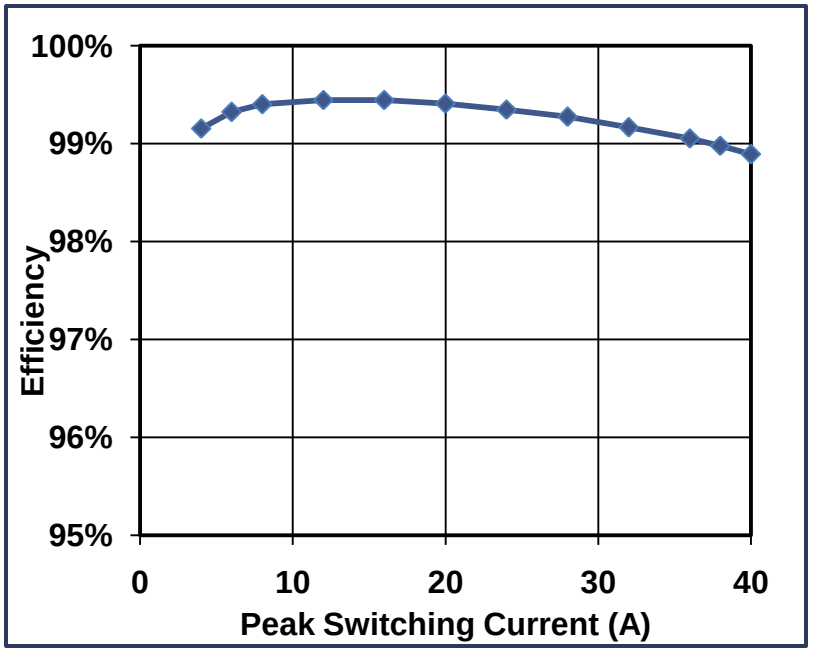
1200V 25 mOhm SiC MOSFET

Critical Device Parameters

Parameter	Value
$R_{ds\text{-}on}$ at 25°C	25 mΩ
$R_{ds\text{-}on}$ at 150°C	40 mΩ
I_R at 150°C	< 100 µA
Switching Energy Loss	2.2 mJ

- Switching loss less than 20% of comparable IGBT
- 3 times the power density

Measured Data in Hard-Switched Circuit



Freq = 32 kHz
Switch Voltage = 1000V, 50% Duty cycle

- Targeted for solar inverter, UPS and motor drive modules

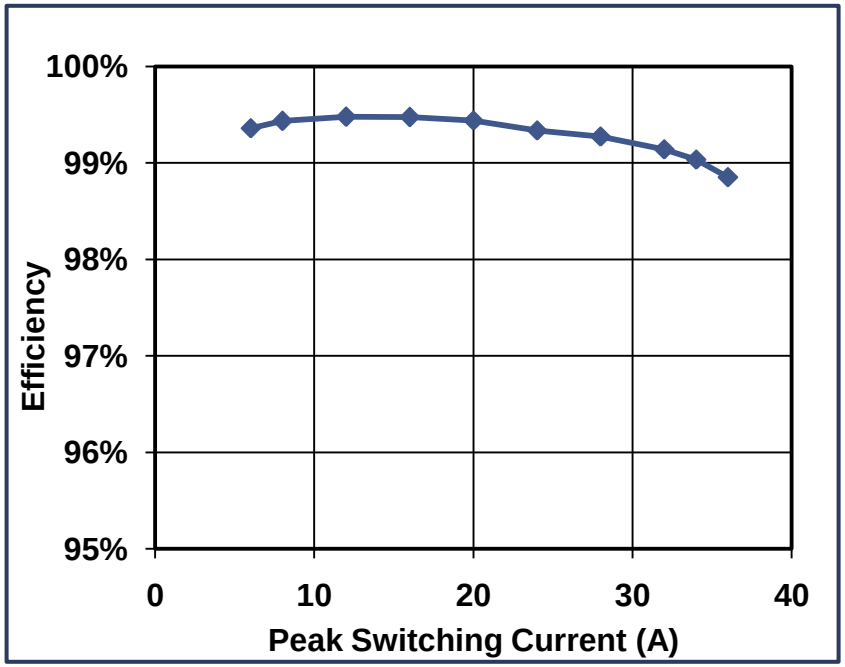
1700V 40 mOhm SiC MOSFET

Critical Device Parameters

Parameter	Value
$R_{ds\text{-}on}$ at 25°C	40 mΩ
$R_{ds\text{-}on}$ at 150°C	80 mΩ
I_R at 150°C	< 200 µA
Switching Energy Loss	< 4 mJ

- Switching loss less than 10% of comparable IGBT

Measured Data in Hard-Switched Circuit

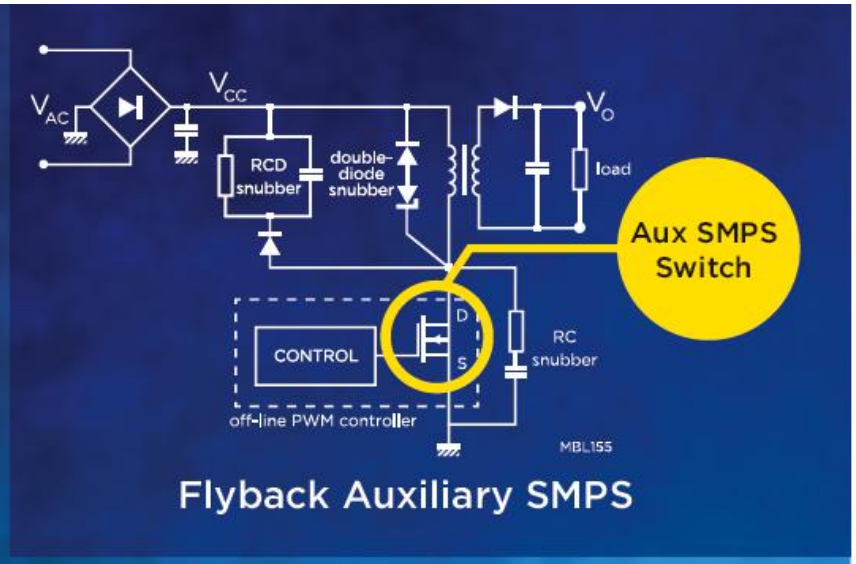


Freq = 32 kHz
Switch Voltage = 1000V, 50% Duty cycle

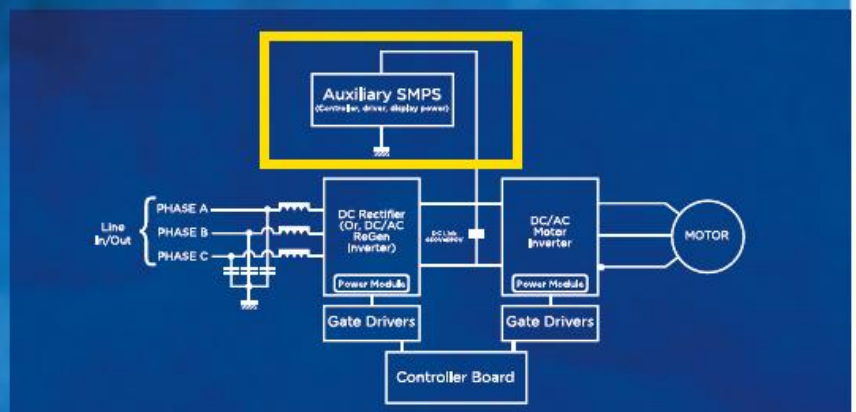
- Targeted for high power modules in 690V systems

New 1700 SiC MOSFET for Aux. Power Supplies

- Ideal for auxiliary SMPS applications in inverter based systems
- >1800V avalanche assures transient protection in noisy inverter systems
- Improves on silicon efficiency and switching frequencies
- Simplifies system electrical and thermal design
- Reduces overall system cost



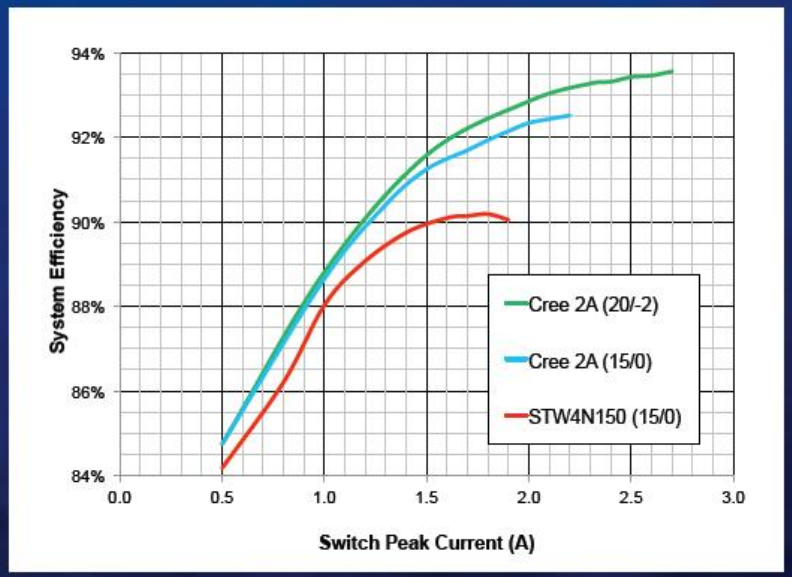
Flyback Auxiliary SMPS



1700V- 1 Ohm MOSFET available for sampling now in TO-247

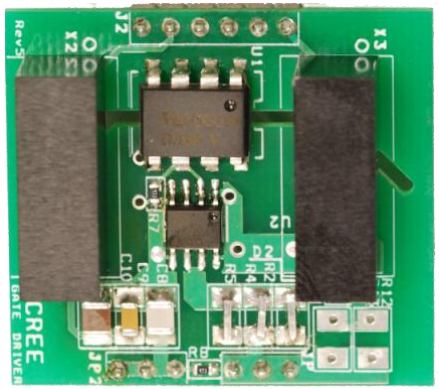
Performance of New 1700V SiC MOSFET

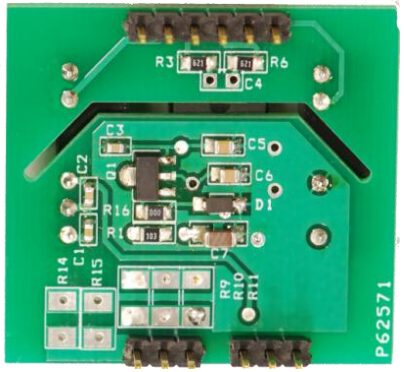
Package	TO-247
$V_{(BR)DSS}$	1700V (>1800V avalanche)
I_D @ T_J=150°C	>3 AMPs
$T_{C(max)}$	150°C



- **Optimized for auxiliary power supplies**
- **Higher reliability and lower loss than Si solutions**
- **Drop-in replacement**
- **Lower Cost**

Gate Driver Boards Available





Gate Driver: IXDN609SI

(Drivers from TI and Avago also work well with SiC MOSFETs)

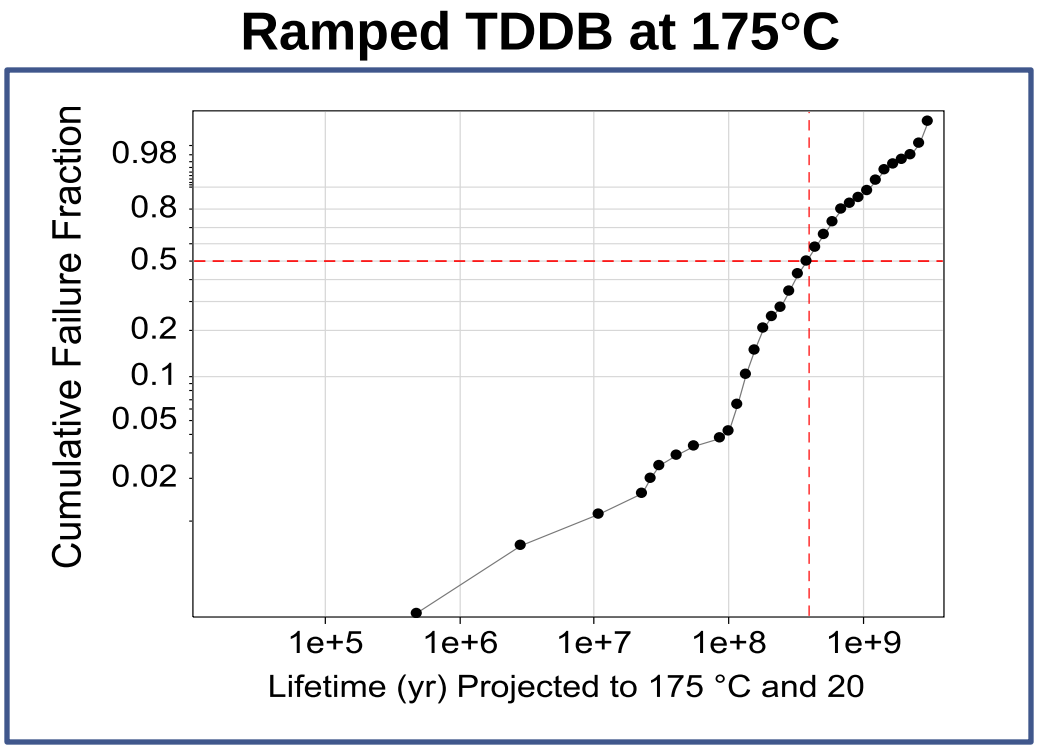
Top and bottom views of the gate driver board

- **Gate driver boards are available to help speed development effort and faster time to time to evaluation.**
- **Each board comes with large creep/strike clearance and an opto-isolator providing reliable electrical isolation and proper drive voltages.**
- **A separate output resistor network has been included to allow separate optimization of turn-on and turn-off transitions.**

Outline

- Overview of Cree's MOSFET Portfolio
- **Reliability Studies of Cree's SiC MOSFETs**
- Beneficial Properties of SiC MOSFETs
- Applications
- Cree Modules

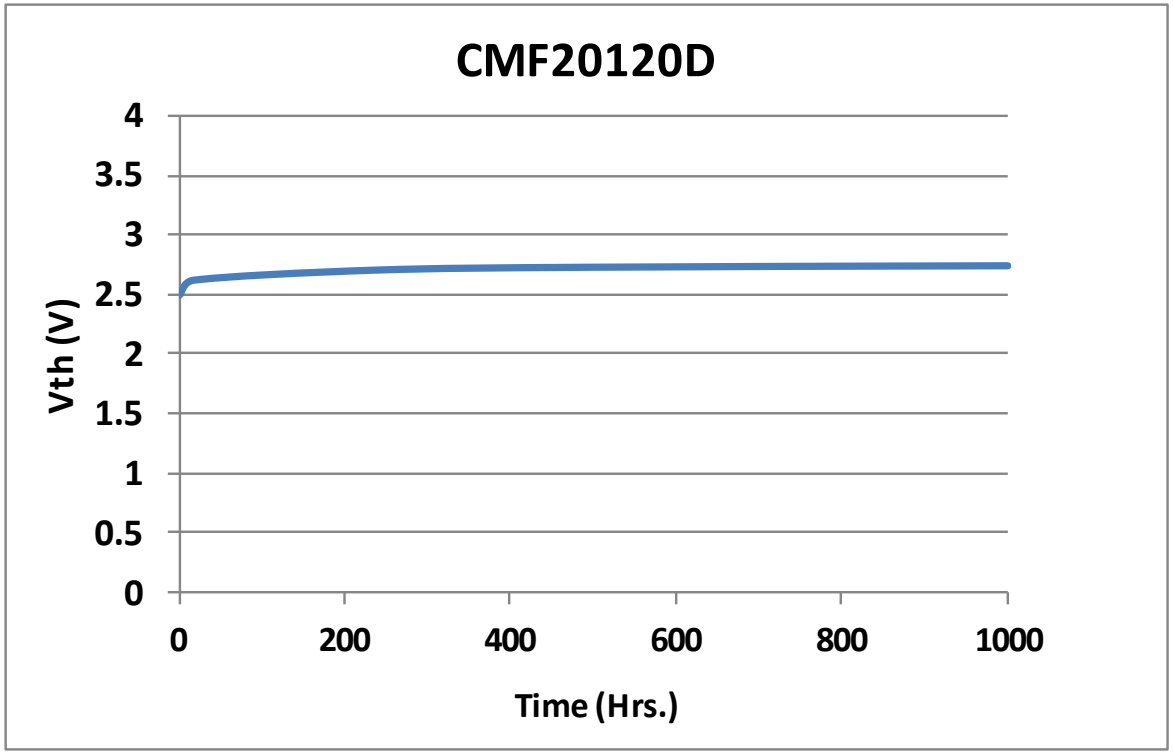
Reliability of Cree's SiC Gate Oxide

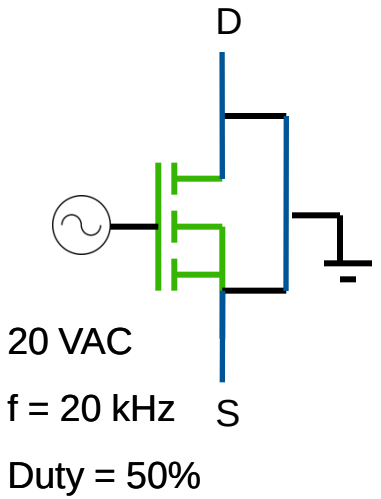


- **Projects to a MTTF of ~400 million years for SiC MOS capacitors at V_{GS} = 20 V gate bias**

Cree has solved the issues with the reliability of oxides on SiC

SiC MOSFETs Demonstrate Stable V_{TH} at 150ºC





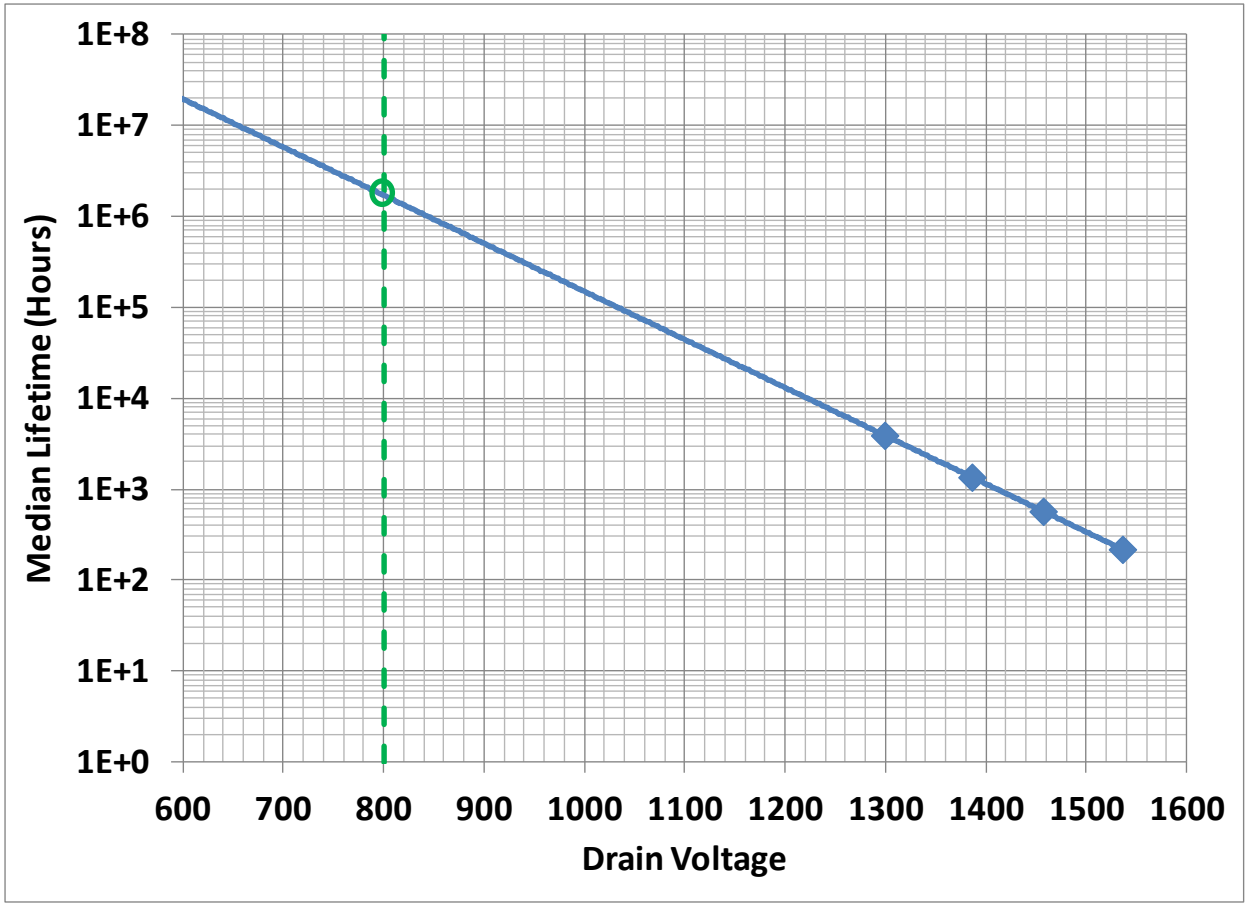
- **Only 0.25V of drift in V_{th}**
- **V_{th} drifts positive, so no issue regarding normally off condition**
- **Increase due to charge buildup; NOT a reliability issue or wear-out mechanism**

SiC MOSFET Qualification Tests at 150°C

Test	Stress Conditions	Duration	Wafer lots sampled	Wafers sampled	Total devices sampled
PV	n/a	n/a	3	9	30
EV	n/a	n/a	3	15	683
HTGB	VGS = 20 V, VDS = 0, Ta=150 ℃	1000 hrs	3	16	231
HTGS	VGS = 20 V, 20 kHz square wave 50% duty cycle, VDS = 0, Ta = 150 ℃	1000 hrs	6	15	200
H3TRB	85 ℃, 85% RH, VDS = 100 V, VGS=0	1000 hrs	6	16	200
HTRB	VDS = 960 V, VGS = 0, Ta = 135 ℃	1000 hrs	3	16	231
TC	-55 ℃ / +150 ℃, JESD22-A104 condition H, soak mode 1	1000 cycles	6	16	200
IOL	5 min on / 5 mins off, ΔTj ≥ 100 ℃, Tmax ≥ 150 ℃	6000 cycles	6	16	137
ESD-HBM	Classification at 25 ℃	n/a	1	1	5
ESD-MM	Classification at 25 ℃	n/a	1	1	5
ESD-CDM	Classification at 25 ℃	n/a	1	1	5

- MOSFETs were qualified per JEDEC automotive guidelines
- 80 mOhm and 160 mOhm qualified

1 Million Hours MTTF for SiC MOSFETs



- **Accelerated life tests performed at high voltages**
- **Extrapolated MTTF is > 1E6 hours at 800V**

Additional SiC MOSFET Reliability Testing

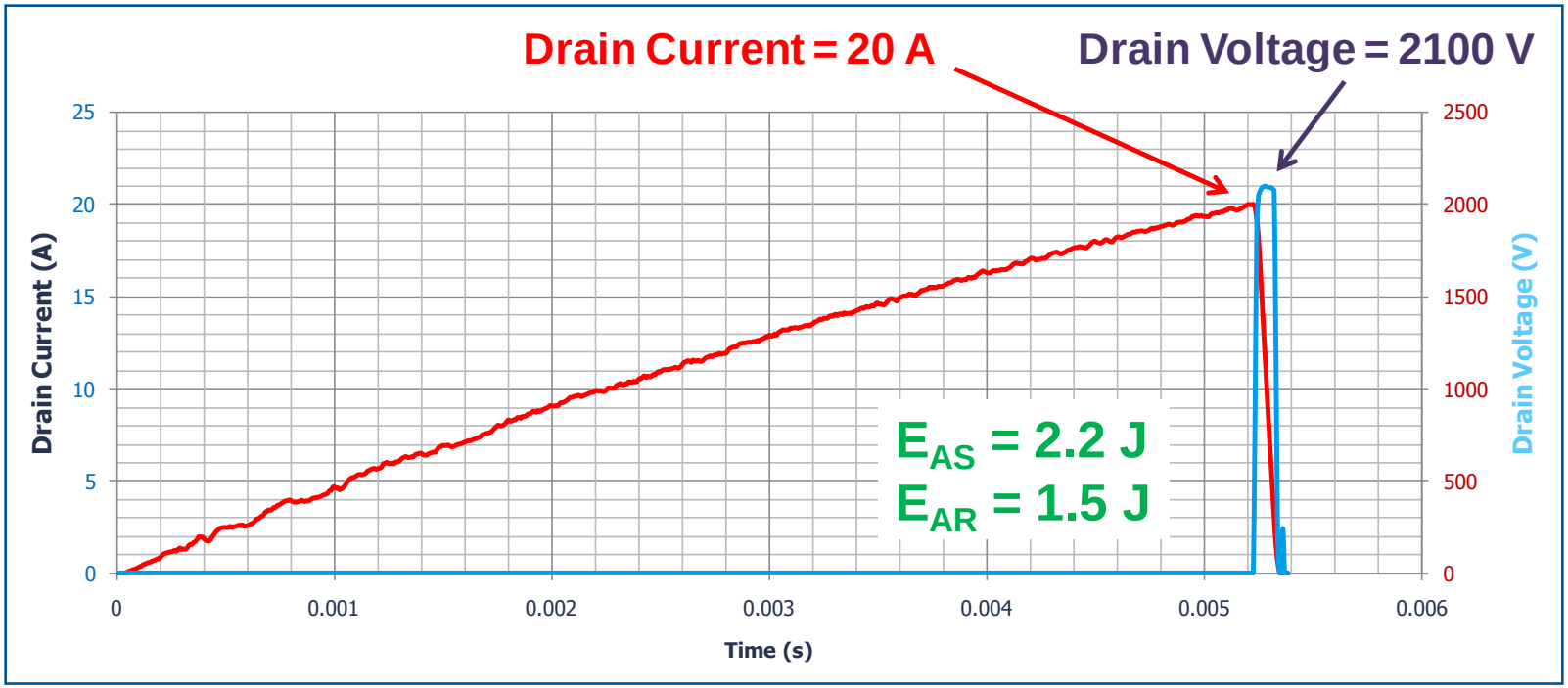
- **Field-Accelerated lifetime data predicts a MTTF of 1 million hours (> 100 years) at 800V continuous blocking**

- **Passed temperature-Humidity-Bias (THB) testing at 85-85-85**
  - **85°C**
  - **85% RH**
  - **85% of rated voltage (960V instead of JEDEC standard 100V)**

- **Power cycling of 20 Million cycles with zero fails**

- **Zero field failures with tens of thousands shipped**

SiC MOSFETs Show High Avalanche Ruggedness



Si SJ MOSFETs

E_{AS} = 0.5 to 1 J

E_{AR} = 1 to 10 mJ

Si IGBTs

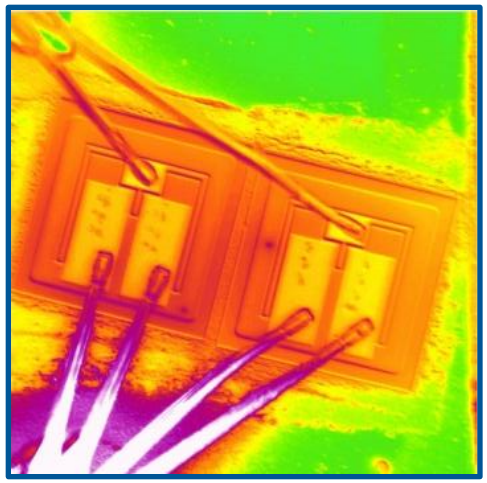
E_{AS} = 10 - 100 mJ

E_{AR} = N/A

SiC MOSFETs have highest avalanche energy of any 1200V switch

SiC MOSFETs Share Current for Easy Paralleling

Infrared Image of MOSFETs at 20 A Drain Current



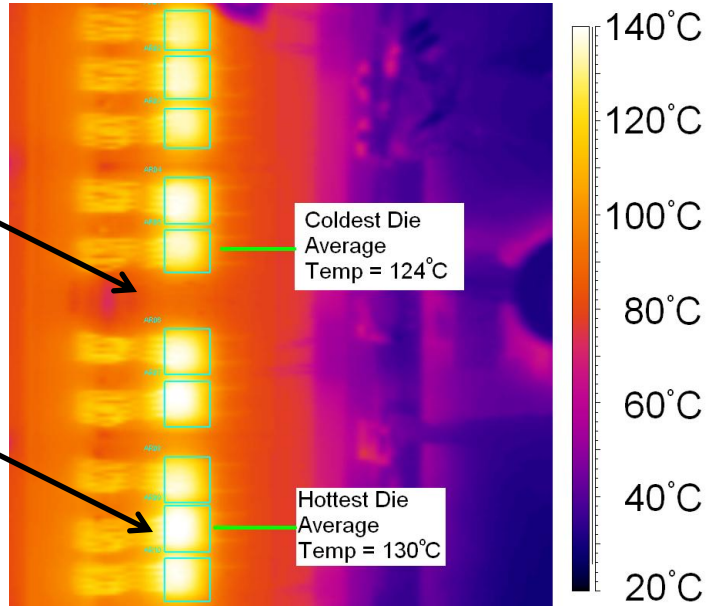
Static Drain Current (A)	Left MOSFET $R_{DS(on)}$ = 66 mΩ	Right MOSFET $R_{DS(on)}$ = 90 mΩ	MOSFET ΔT
40	93.0°C	91.7°C	1.3°C

- Positive temperature coefficient means self-regulation
- Cree has qualified modules with 5 chips in parallel

IR Image of Multiple Parallel SiC MOSFETs

Gap in layout creates cool areas for adjacent MOSFETs

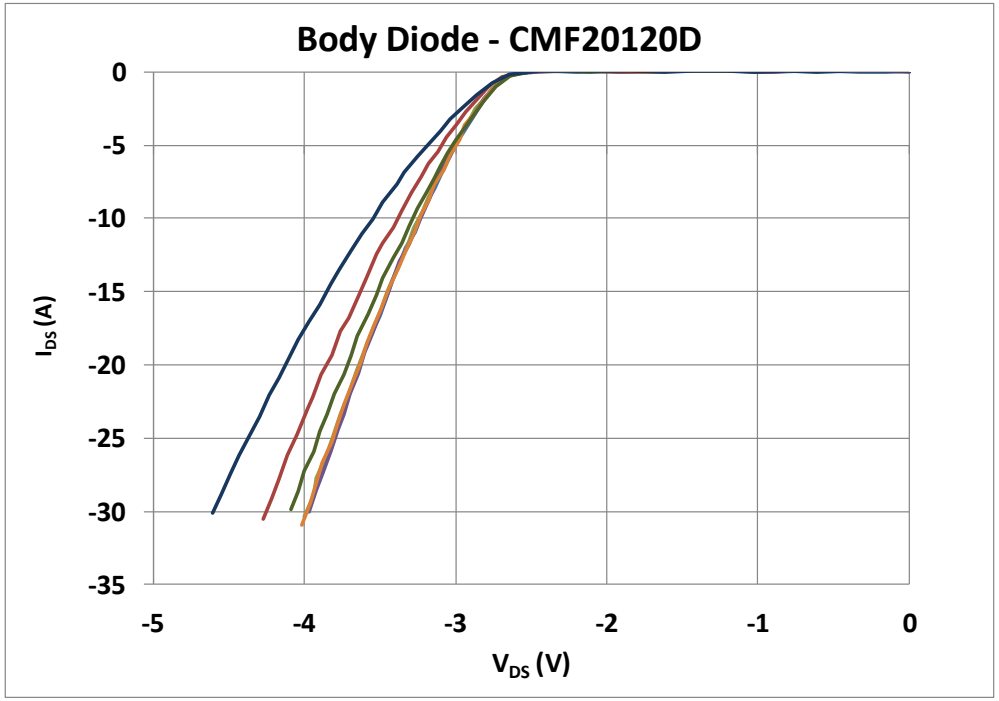
Three adjacent MOSFETs creates hotter area for center MOSFET



DC Drain Current	Coolest MOSFET	Hottest MOSFET	MOSFET ΔT
700 A	124°C	130°C	6°C

Despite sub-optimal layout, MOSFETs are stable and share DC current well with very small imbalance

Stable Body Diode Characteristics



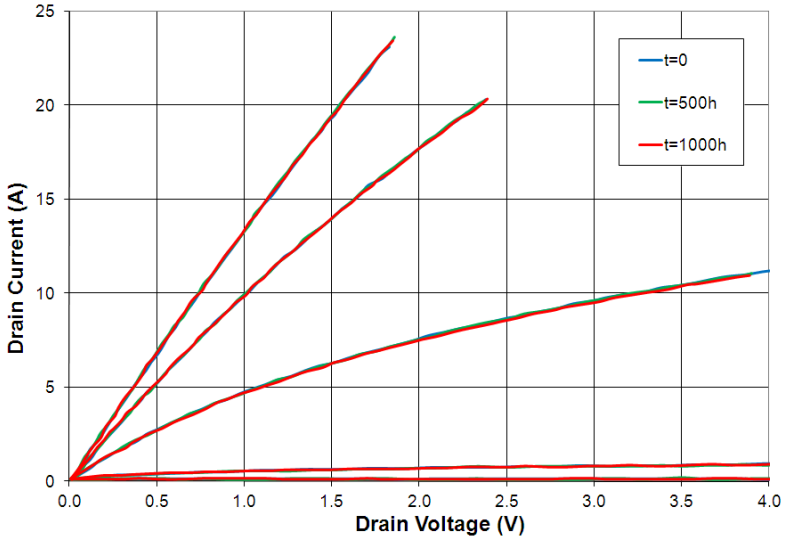
(Measured on 5 randomly selected parts)

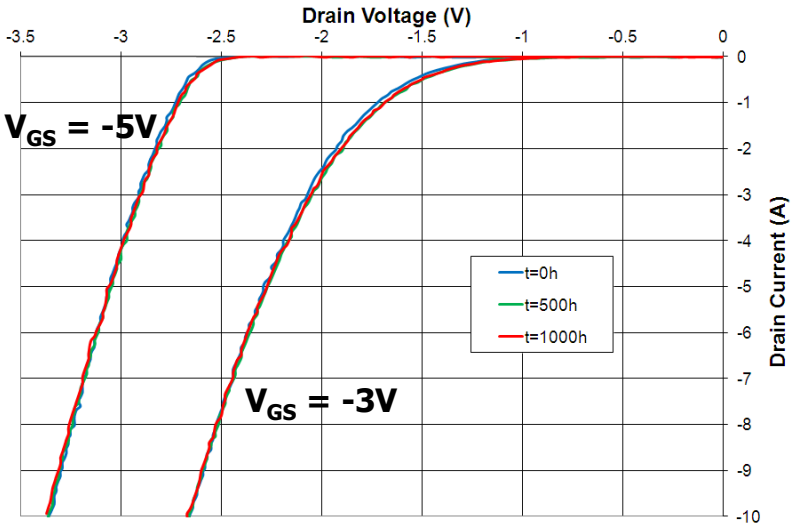
- **The body diode of the SiC MOSFET can be used**
- **Because it is usually only conducting during the "dead time" the high Vf does not impact efficiency**
- **Cree's proprietary design makes it highly reliable**

Body Diode Reliability in CMF20120D

HTOL Stress of Body Diode (V_{GS}= -5V) at I_{SD} = 10A

MOSFET V_{DSON} unchanged after 1000 hr stress of body diode



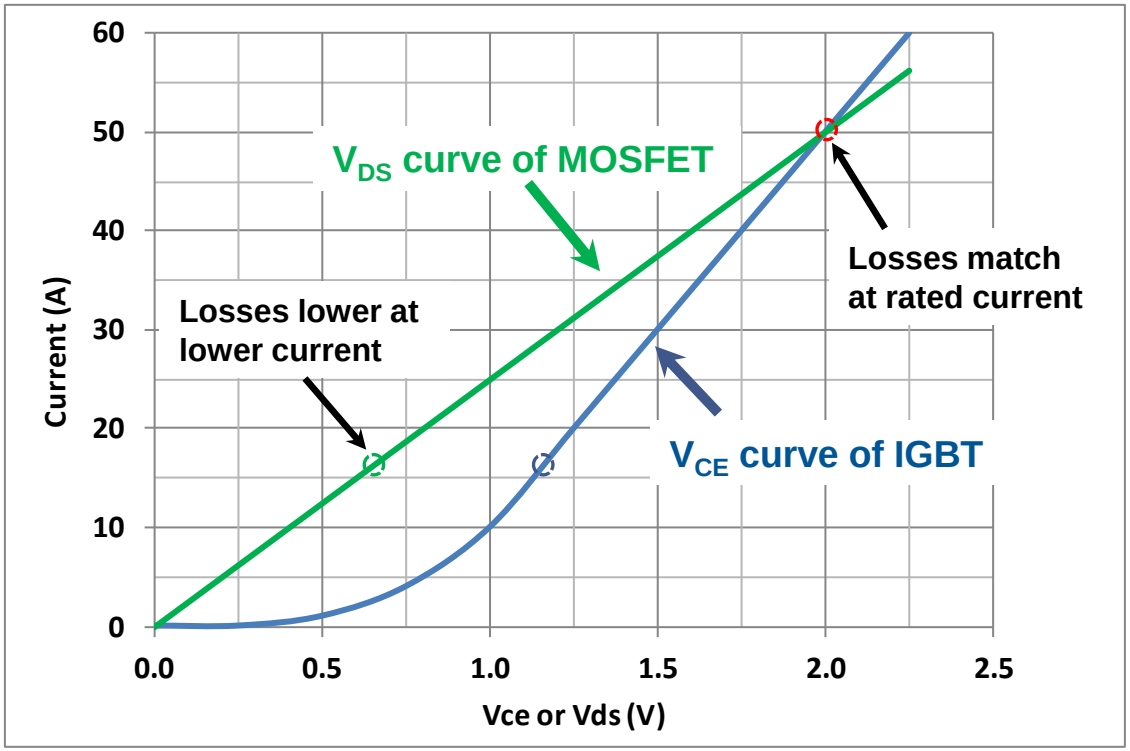


Body diode V_F unchanged after 1000 hr stress of body diode

Outline

- Overview of Cree's MOSFET Portfolio
- Reliability Studies of Cree's SiC MOSFETs
- **Beneficial Properties of SiC MOSFETs**
- Applications
- Cree Modules

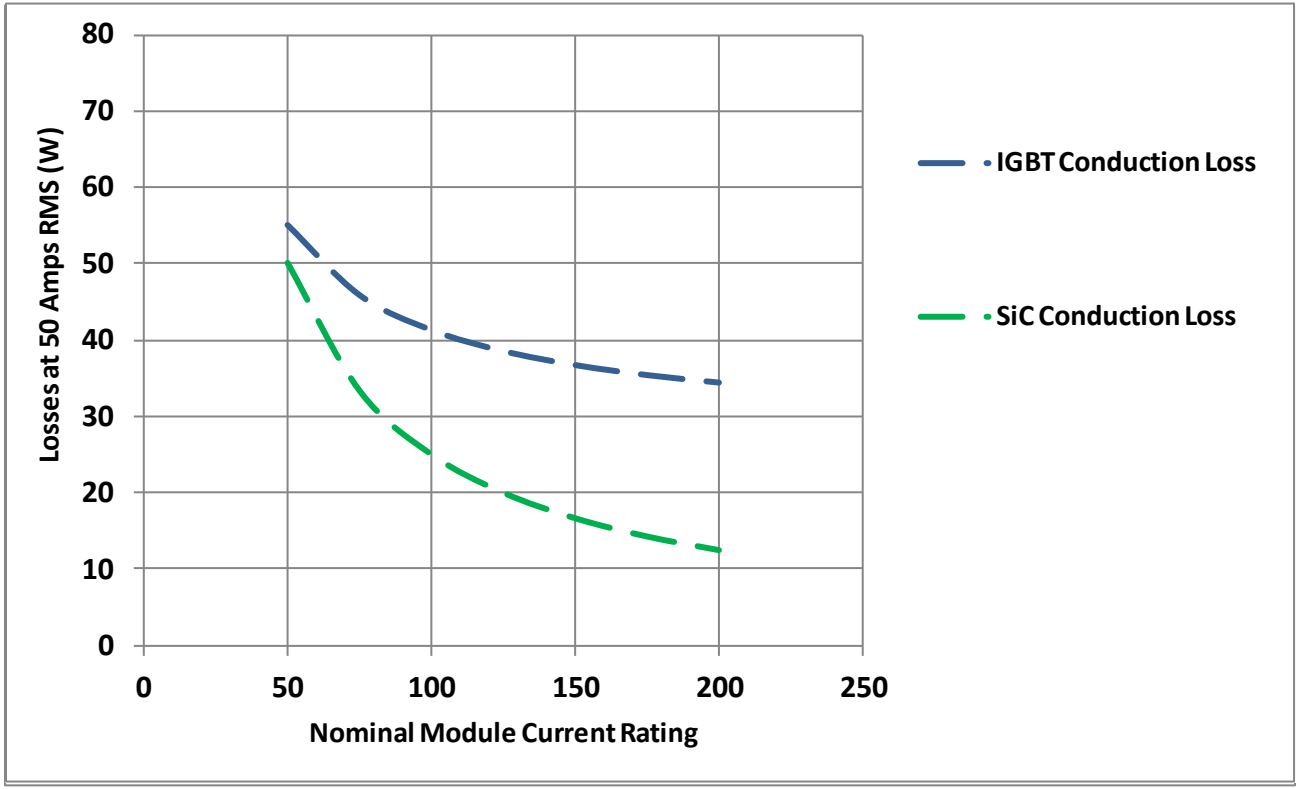
Conduction Losses of SiC MOSFETs Lower than in IGBTs



Comparison of 50 Amp IGBT4 to 50 Amp SiC MOSFET in module at T_J = 150° C

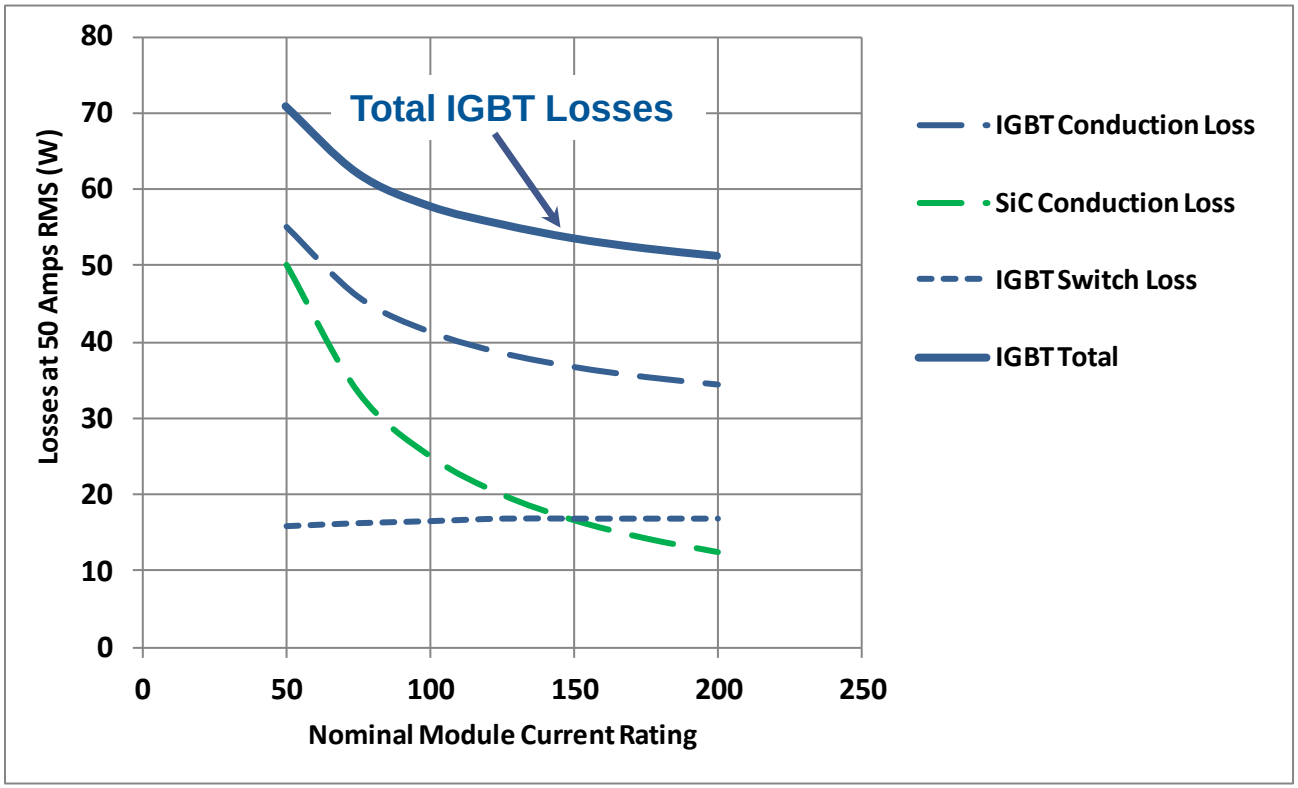
- **MOSFET conduction losses are half of the IGBT when backed off to 1/3 of rated current**

Efficiency Benefits of Larger SiC MOSFET Modules



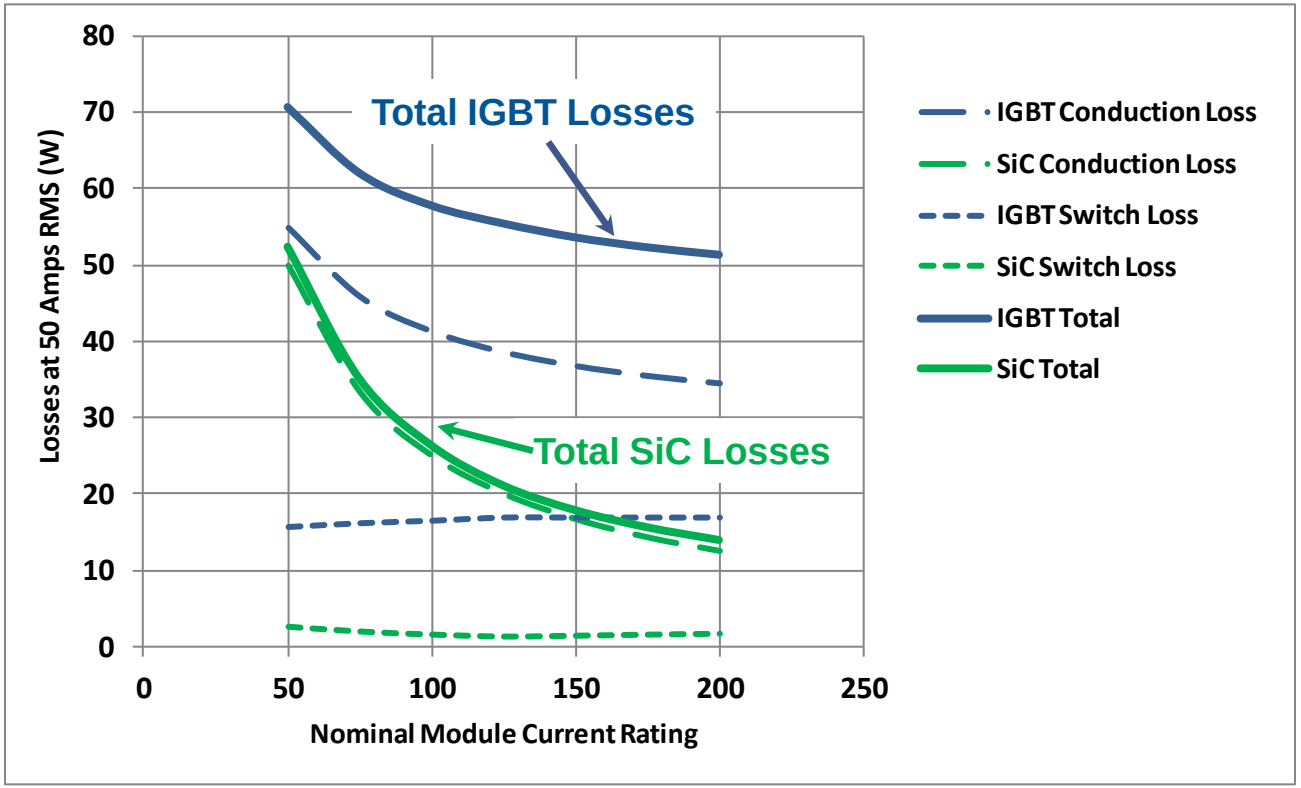
- **SiC losses decrease faster than IGBTs with increasing die count**

Switching Losses in IGBTs are High



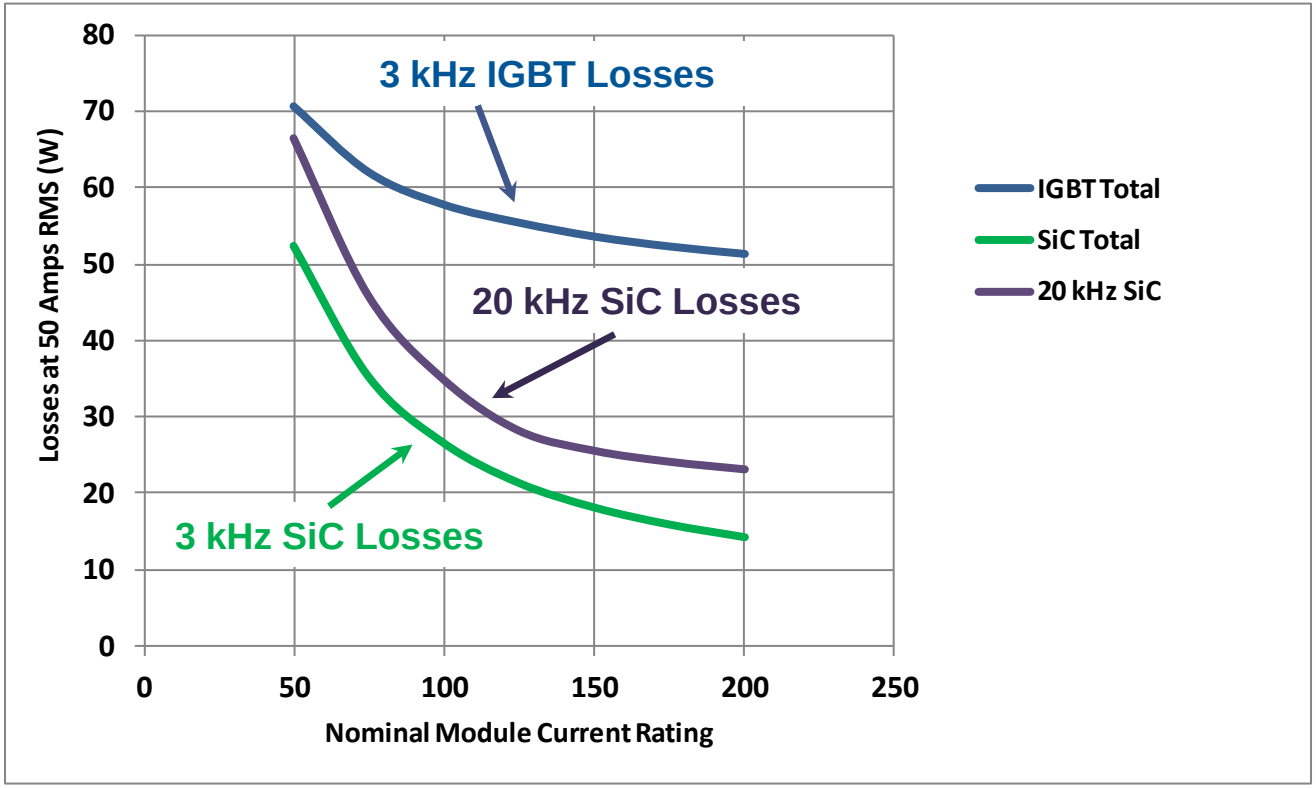
- Switching losses in IGBTs are significant even at 3 kHz
- 30% of the total loss with a 200A IGBT module would be from switching

Low Losses in SiC MOSFETs Provide System Advantages



- **50 Amp SiC module is more efficient than 150 Amp IGBT module**

Higher Frequency Enabled with SiC MOSFETs



- 50 Amp SiC module is more efficient than 150 Amp IGBT module
- SiC module at 20 kHz is more efficient than an IGBT module at 3 kHz

Full Analysis of Losses in a 250 kW Inverter

	IGBT Bricks				SiC MOSFET Bricks				
Module Rated Current (A)	600	900	1200		250	300	400	300	300
Switching Frequency (kHz)	3	3	3		3	3	3	10	25
Switch Conduction Loss (W)	129	110	100		179	144	106	147	154
Switch Switching Loss (W)	127	123	206		21	17	13	55	138
Diode Total Loss (W)	55	59	72		4	2	1	2	3
Junc. Temp. (@Tc = 90 °C)	110	103	102		114	106	99	110	119
Total Inverer Loss (W)	1866	1754	2267		1217	979	718	1228	1765
Power Stage Efficiency (%)	99.1%	99.2%	98.9%		99.4%	99.5%	99.7%	99.4%	99.1%

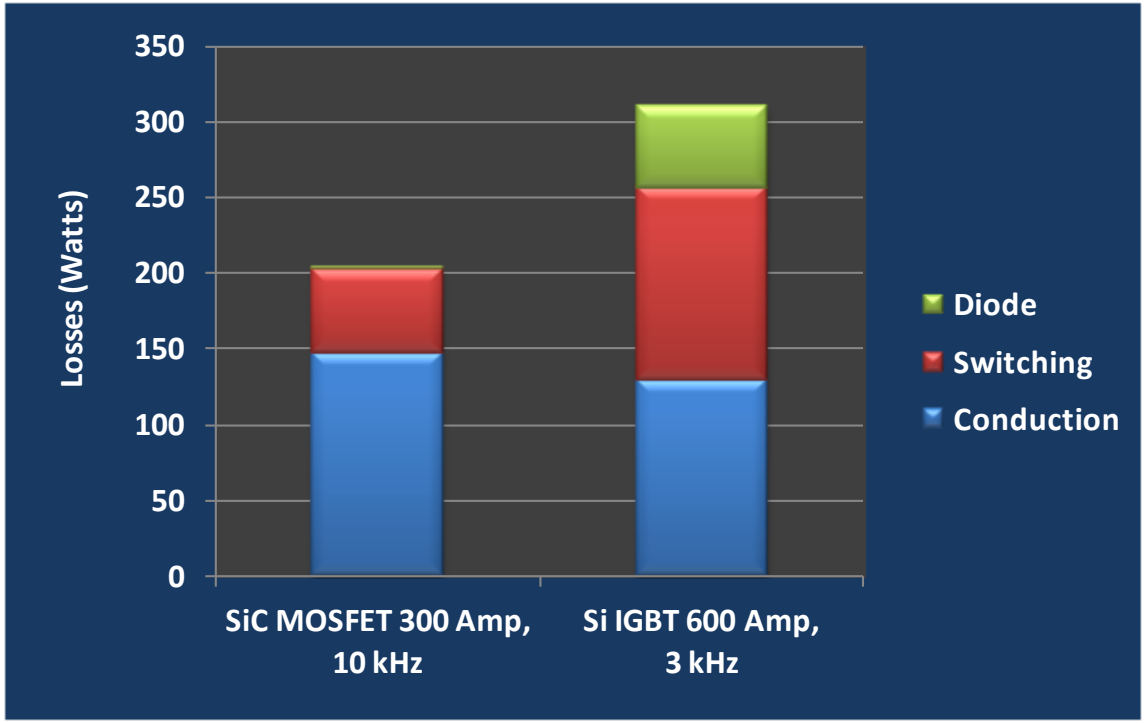
System Inputs

- Half Bridge, 3 Phase
- Control Algorithm: Sine-Triangle
- DC Link Voltage: +/- 500V
- Output Current: 240 A RMS
- Output Freq: 50 Hz
- Switching Freq: 3 kHz

- **300 Amp SiC Module at 10 kHz has lower losses than 900 Amp IGBT at 3 kHz**

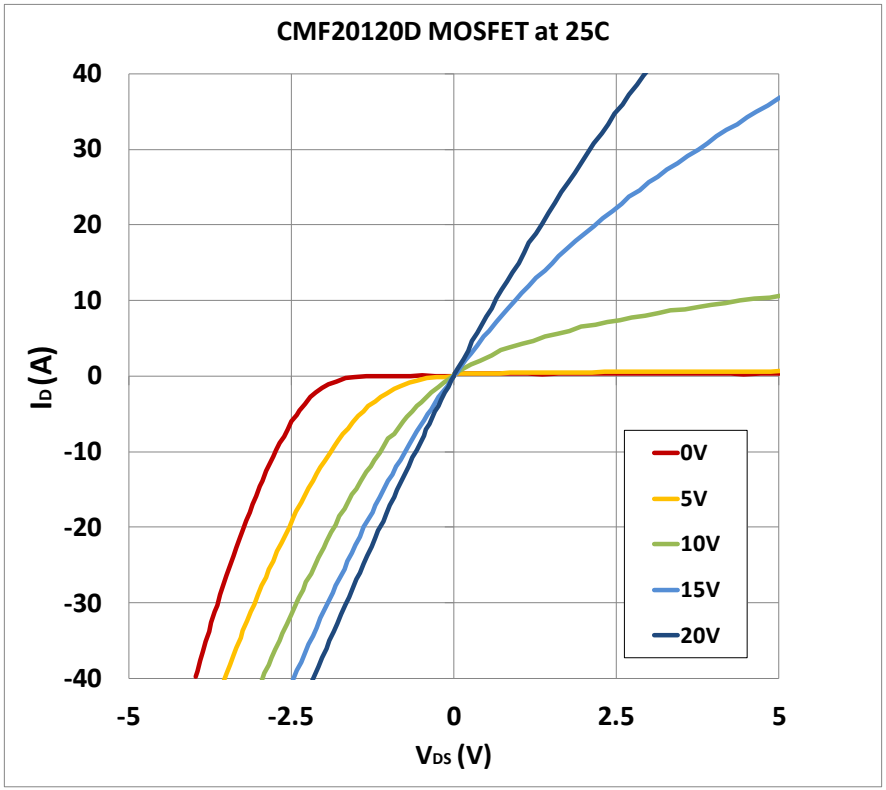
SiC MOSFETs Further Lower System Cost

300 Amp SiC More Capable than 600 Amp



- **System cost reduction of 20%**
  - **Increased frequency reduces size and weight of magnetics**
  - **Lower losses reduce system cooling requirements**
  - **Amperage rating for SiC less than half required for Si IGBTs**

Third Quadrant Operation for Maximum Efficiency

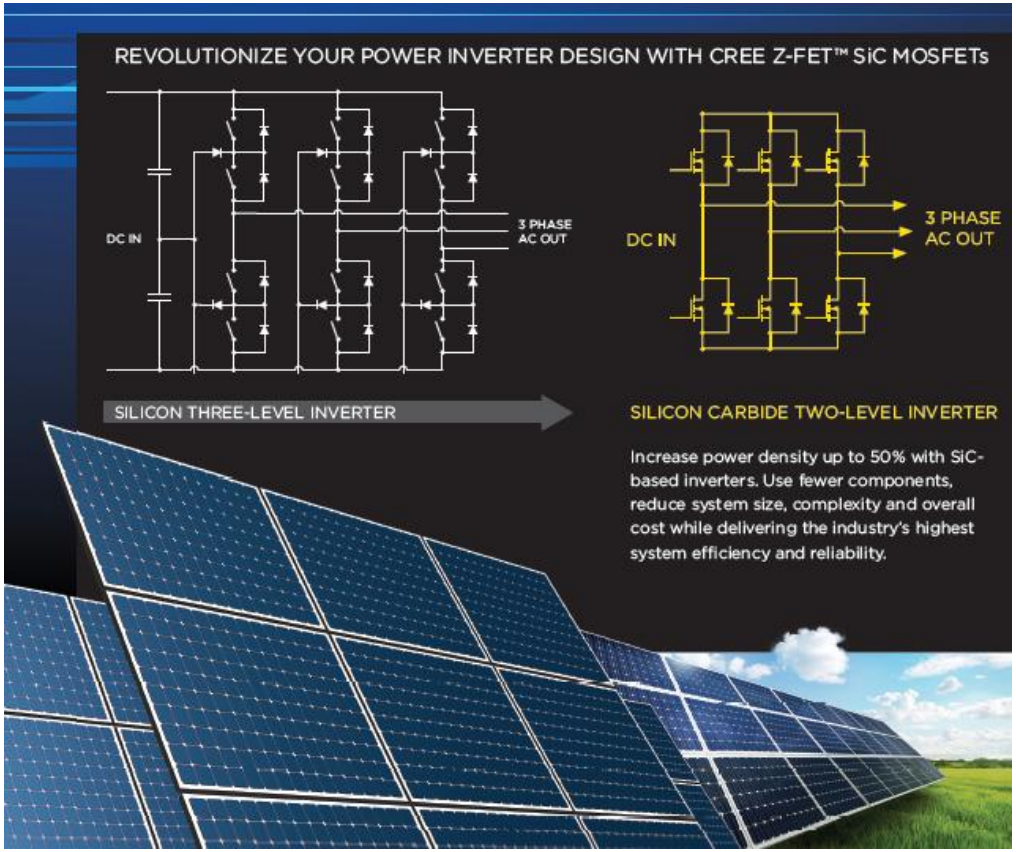


- MOSFET conduction is symmetric for positive and negative VDS
- Reverse characteristics are a parallel combination of the MOSFET and PN diode
- Applying positive gate bias turns the MOSFET fully on

Outline

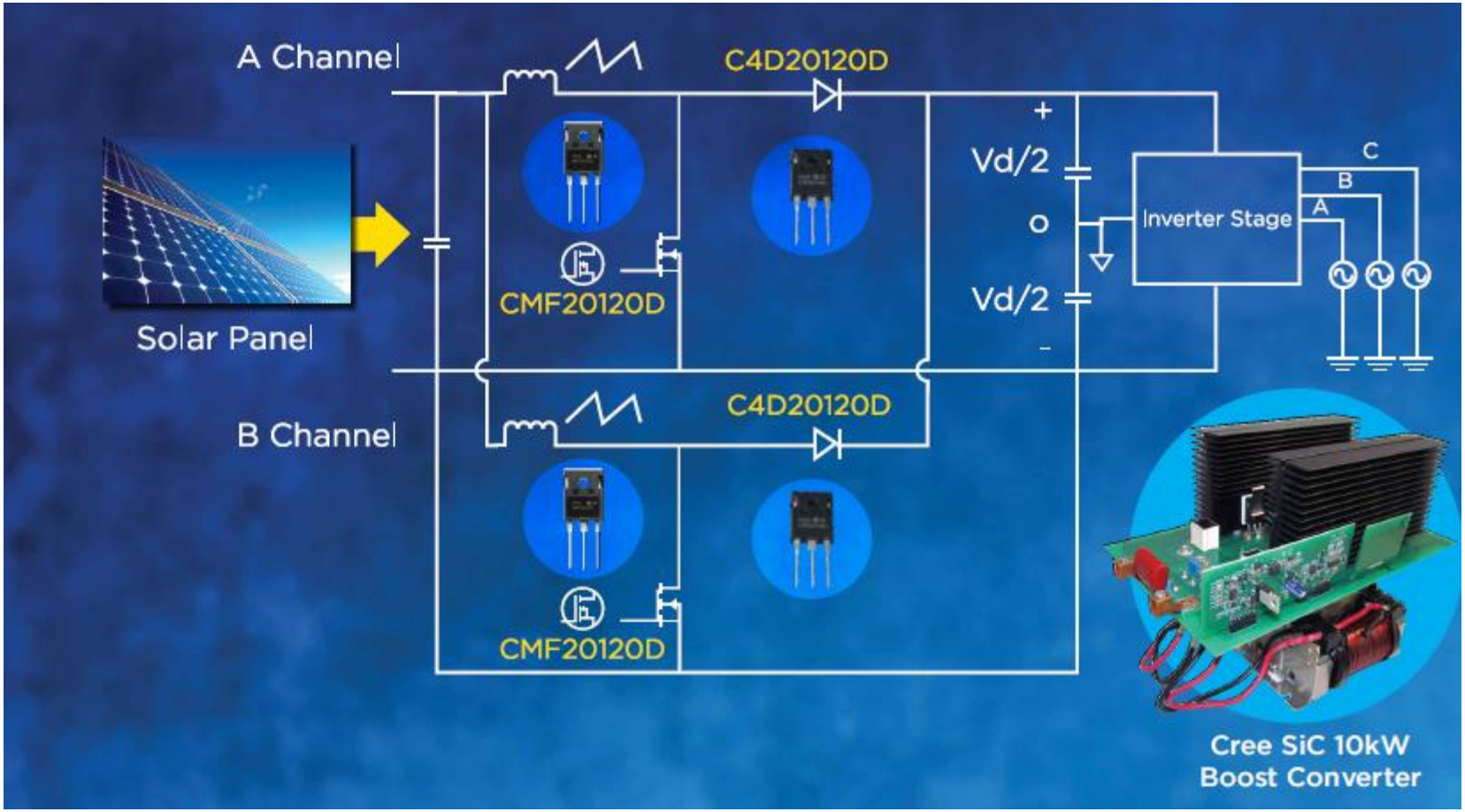
- Overview of Cree's MOSFET Portfolio
- Reliability Studies of Cree's SiC MOSFETs
- Beneficial Properties of SiC MOSFETs
- **Applications**
- Cree Modules

SiC MOSFETs Enable Higher Frequency and Lower Cost



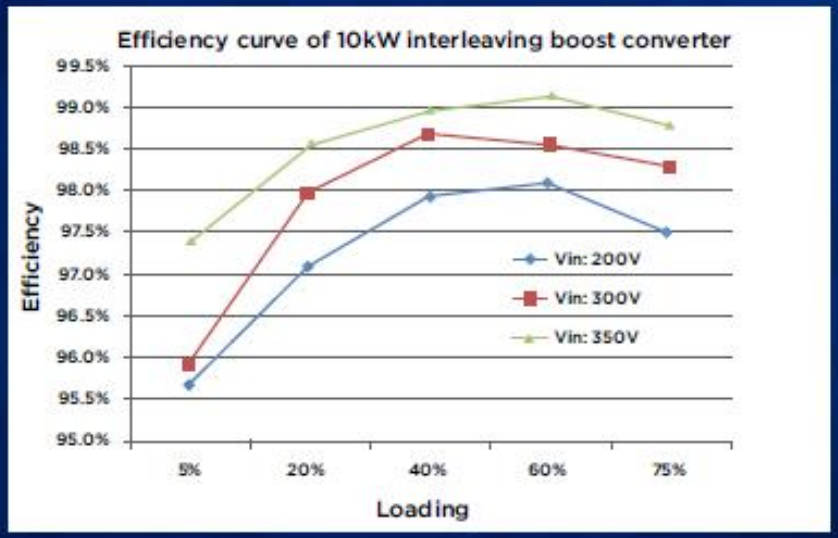
- **SiC MOSFETs enable hard-switched, simpler architectures**
- **Higher frequency reduces BOM cost from magnetics**

SiC MOSFETs Lower Cost of 10 kW Boot Inverter



Architecture of all-SiC Boost Inverter

SiC Inverter has Higher Efficiency and Lower Cost



DESIGN SPECIFICATION	
Input voltage:	200V to 400Vdc
Input power:	Max 10kW
Output voltage:	520Vdc
Output tolerance:	+/-2%
Output ripple:	<1%
Switching freq.:	60kHz-100kHz

- >99.1% peak efficiency achieved
- Interleaved design utilizes Cree SiC MOSFETs and Diodes
- 60kHz-100kHz switching enabled by SiC MOSFETs
- Utilizes Cree gate driver design and off-the-shelf interleaved controller
- High frequency and high density

Summary of SiC Boost Converter Advantages

Increase in system frequency dramatically reduces size and weight

Cost Comparison	Silicon Solution	SiC Solution
Frequency	**20 kHz**	**100 kHz**
Inductors	$75	$20
Capacitors	$65	$65
Heat sink	$45	$38
Si IGBT or SiC MOSFET	$4	$25
Si or SiC Diode	$2	$6
Total Cost	**$191**	**$154**

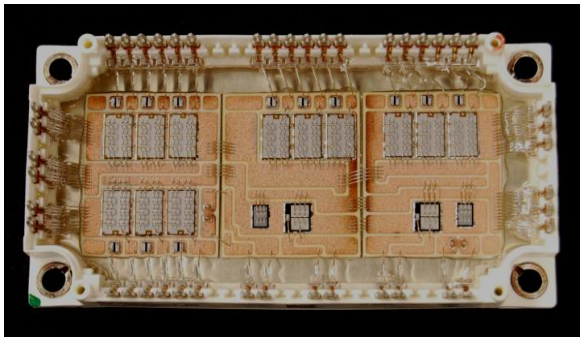
Transformer at 20 kHz

Transformer at 100 kHz

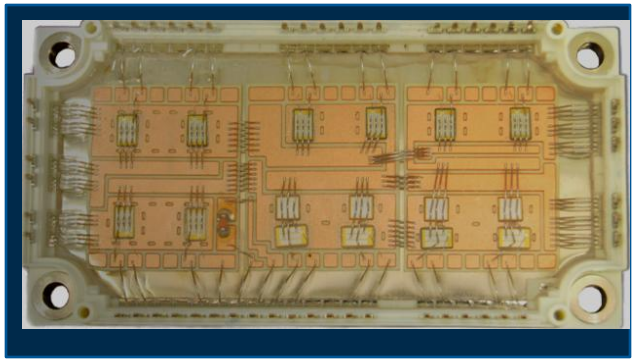
SiC solution (discrete) is 20% cheaper and 60% smaller

SiC MOSFET Reduction of Solar Inverter Cost

600V Si Module



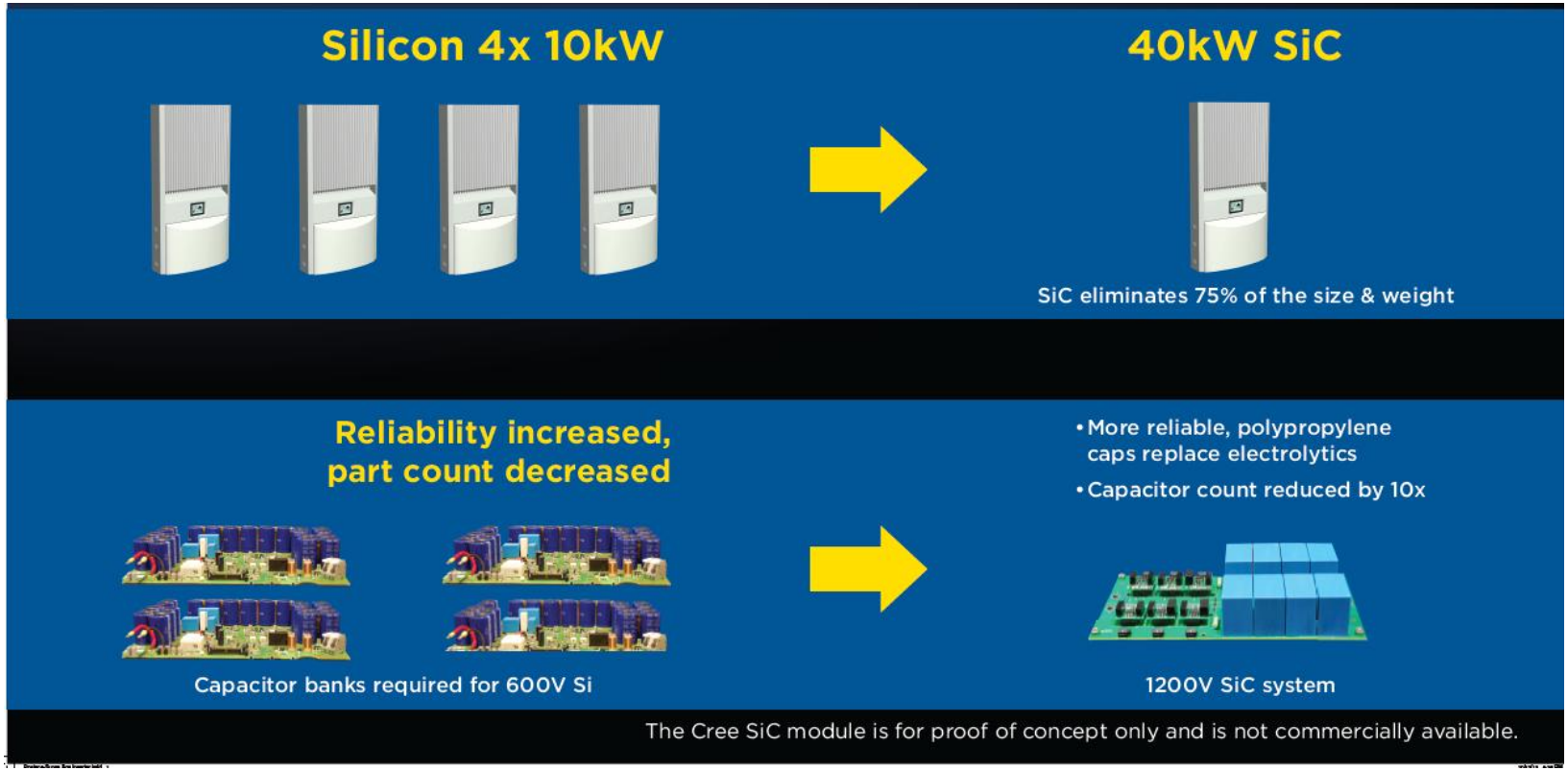
1200V SiC Module



- **600V Si module replaced with 1200V SiC module**
  - **Twice the voltage**
  - **Twice the current**
  - **Twice the frequency**
- **Power density increased by 4x**
  - **No increase in transistor losses**
  - **No increase in system size or weight**

Cost per kilowatt reduced by as much as 50%

Reliability Increased and Part Count Decreased

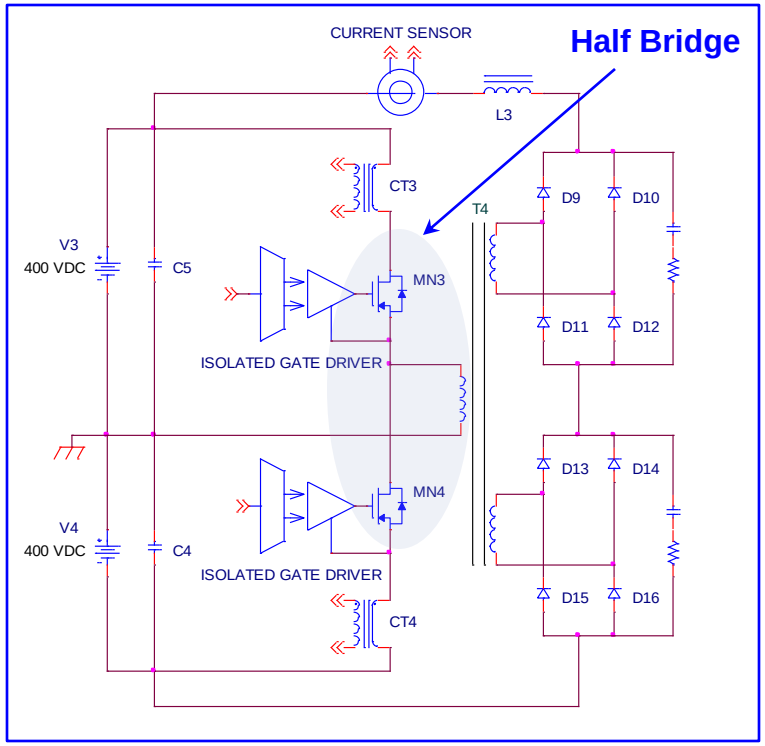


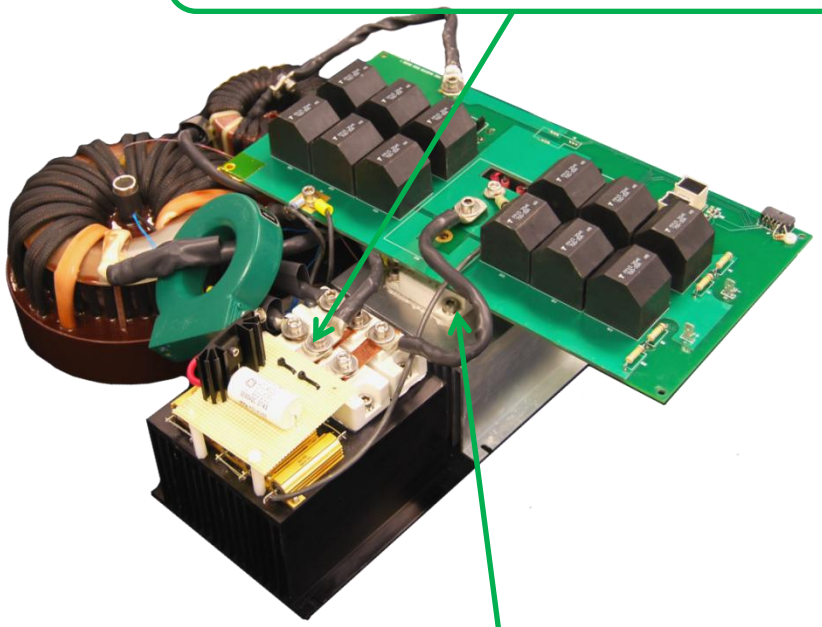
- **Capacitor count reduced by a factor of 10 due to higher voltage and frequency**
- **Electrolytic caps replaced with much more reliable polypropylene**
- **System weight reduced from 300 lbs. to 75 lbs.**

SiC 1700V MOSFET Module Demonstration

Half Bridge DC-DC Converter

- Power Level = 40kW
- Link Voltage = 1kV
- Output Current = 40A
- Switching Frequency = 32 kHz
- Efficiency = 97.5% (not fully optimized)

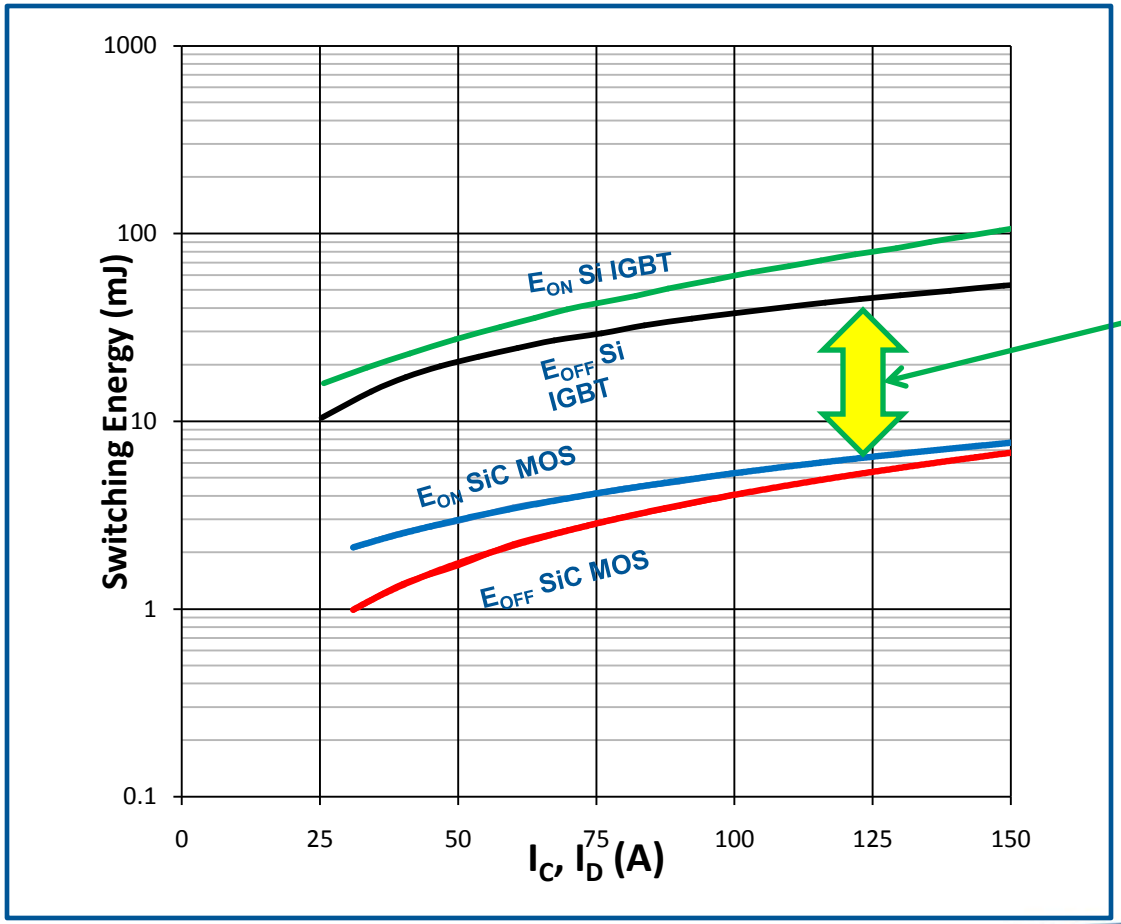




SiC MOSFETs Have 10 Times Lower Switching Losses

Switching Loss Comparison:

- **SiC MOS = Z-FET 1.7kV 100A Dual Module**
- **Si IGBT = Semikron SKM 145B176D 1.7kV 100A Dual Module**



Cree SiC MOSFET Advantage

- **10x lower switching loss = 10x higher switching frequency using simple hard-switched topology**
- **System size, weight and cost can be reduced by increasing the frequency**

Outline

- Overview of Cree's MOSFET Portfolio
- Reliability Studies of Cree's SiC MOSFETs
- Beneficial Properties of SiC MOSFETs
- Applications
- **Cree Modules**

New 100 Amp Cree-Branded Half-Bridge Module

Take full advantage of the superior switching performance of silicon carbide technology with Cree's all-SiC high-reliability power module. Incorporating Cree's SiC MOSFETs and SiC Schottky diodes, these power modules improve switching performance more than 5x compared to conventional silicon IGBT PIN modules.

FEATURES

- High frequency operation
- Zero reverse recovery current
- Ultra-fast switching (SiC MOSFET)
- Positive temperature coefficient on $R_{DS(ON)}$

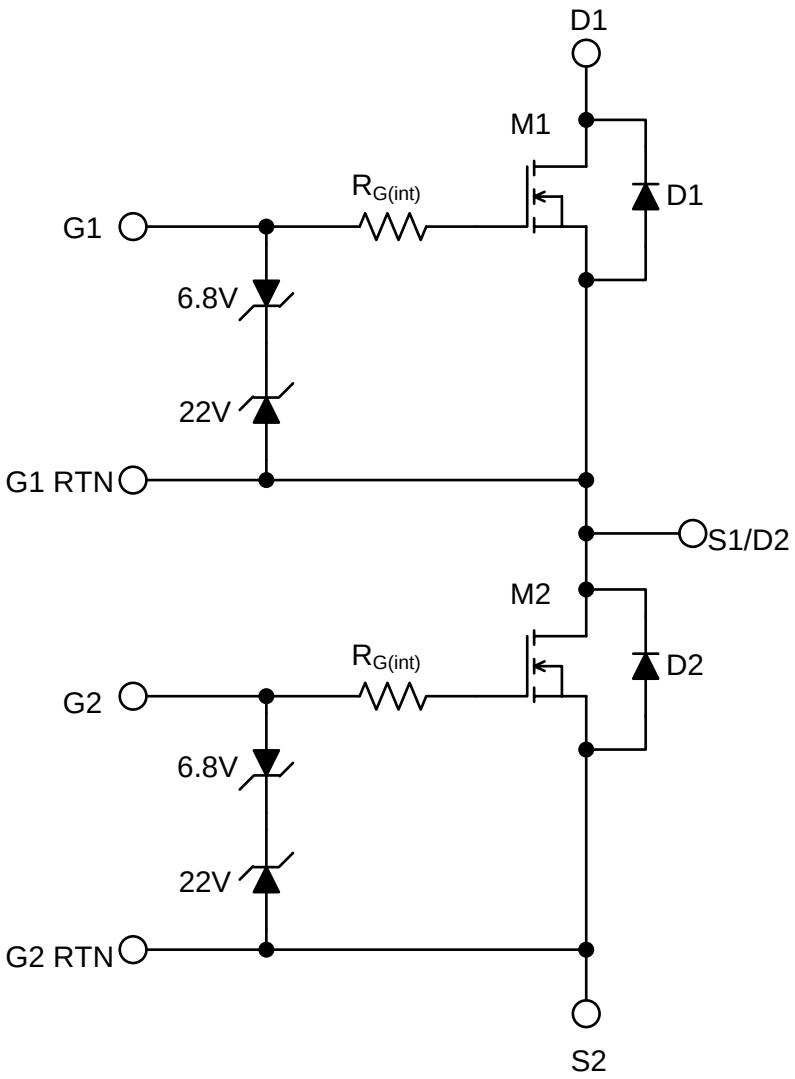
APPLICATIONS

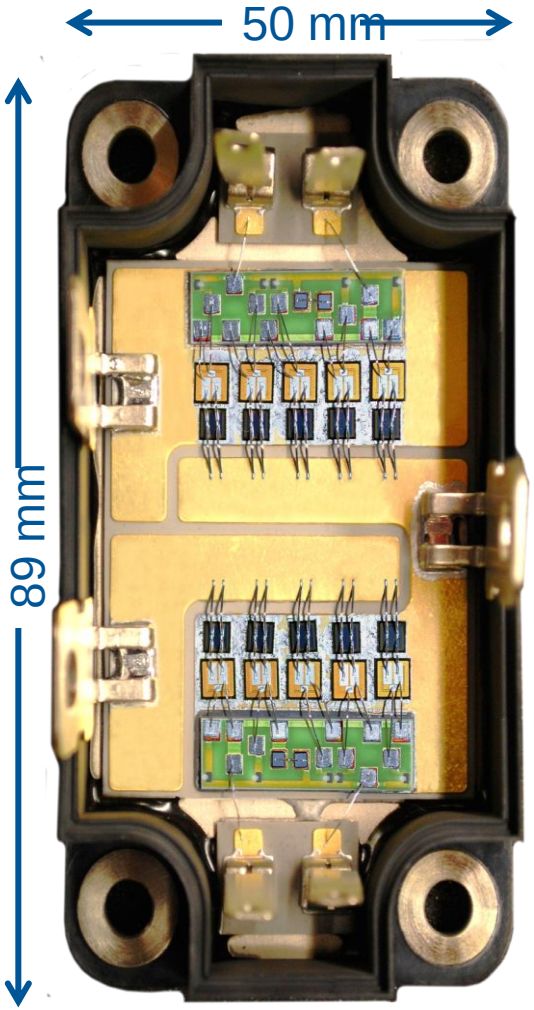
- Solar inverters
- Welding converters
- Uninterruptible power supplies
- High current motor control
- Auxiliary power supplies

CAS100H12AM1

V_{DSS}	1200V
$R_{DS(ON)}$	18 mΩ (T_C=25 °C)
I_D	100 A (T_C=100 °C)

CAS100H12AM1 Product Details: 1200V, 100A All-SiC Dual Module





Data sheet Comparison with IGBT4 Module

Parameter	Cree CAS100H12AM1	Infineon FF100R12RT4	Comparison to Infineon Si Module
Blocking Voltage (V)	1200	1200	Same
Max Continuous Current (A) T_C=100°C	105	100	Similar
On-state Voltage (V) T_J=150°C	2.0	2.1	Similar
E_{SW} @ 150°C (mJ)	3.5	20.5	Lower (5.9x)
Q_{RR} @ 150°C (µC)	1.6	19	Lower (11.9x)
V_{ISOL} (kV)	6.0	4.0	Higher (1.5x)
Baseplate	AlSiC	Cu	Lighter
Insulator	AMB Si_3N_4	DBC Al_2O_3	More Robust

Summary

- **Cree has established all necessary reliability metrics with our SiC MOSFETs**
  - **Gate oxide lifetime > 1E8 hours**
  - **MOSFET lifetime > 1E6 hours**
  - **Low Vth drift**

- **New humidity capability extends Cree's leadership in meeting harsh reliability requirements**

- **50 Amp die at 1200V and 1700V extends SiC benefits to high-power modules**

- **New Gen 2 product hits cost-performance point to wide scale adoption**

Cree is the leader in Silicon Carbide power semiconductors.

Cree is one of world's fastest-growing power semiconductor manufacturers.

Cree has excellent capitalization.

Cree is vertically integrated—for an efficient supply chain and product traceability.

Cree has the technology roadmap for improved SiC production and cost reduction.