CPES
Center for Power Electronics Systems
The Bradley Department of Electrical and Computer Engineering
College of Engineering
Virginia Tech, Blacksburg, Virginia, USA

Tutorial:

Is SiC a Game Changer?

Dushan Boroyevich, Christina DiMarino

Congresso Brasileito de Electrônica de Potência
Southern Power Electronics Conference
Fortaleza, Brazil
November 29, 2015

Outline

1. Introduction
2. High Frequency and High Efficiency
   – Comparison with Si
   – Characterization of 1.2 kV SiC discrete transistors
3. High Temperature
   – For power density in normal temperature ambient
   – For operation in high-temperature ambient
4. Medium Voltage
5. High Voltage
6. Conclusions
7. References

The requirements for power electronics are becoming more demanding.

Efficiency

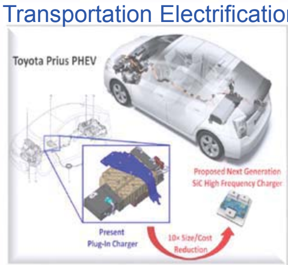
Renewable Energy

http://www.renewableenergyinstaller.co.uk/2013/01/uk-on-track-to-hit-2020-targets/

- Lower losses
- Higher voltage ratings

Power Density

Transportation Electrification

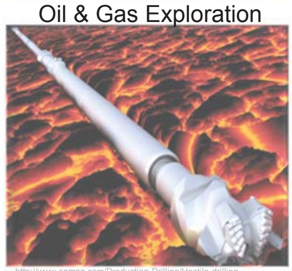


http://mscad.eleg.uark.edu/projects/projects.html

- Higher frequency
- Smaller cooling systems

Durability

Oil & Gas Exploration

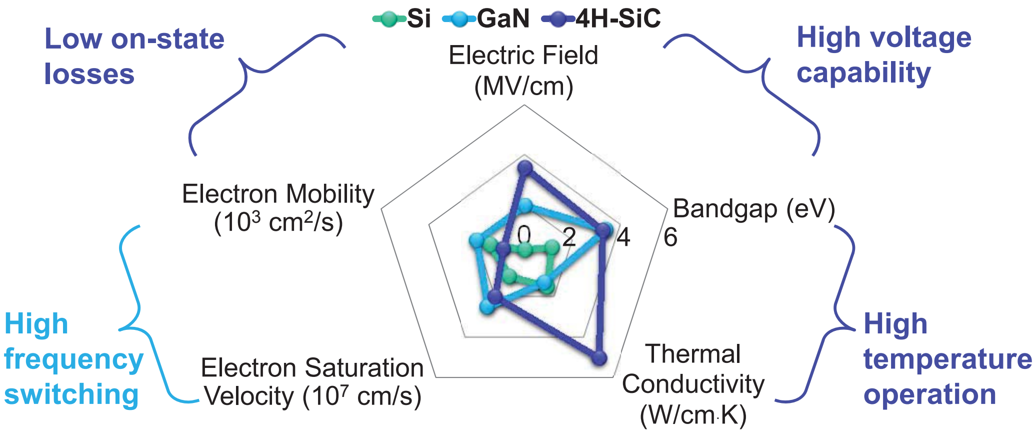


http://www.epmag.com/Production-Drilling/Hostile-drilling-environments-require-approach_42842

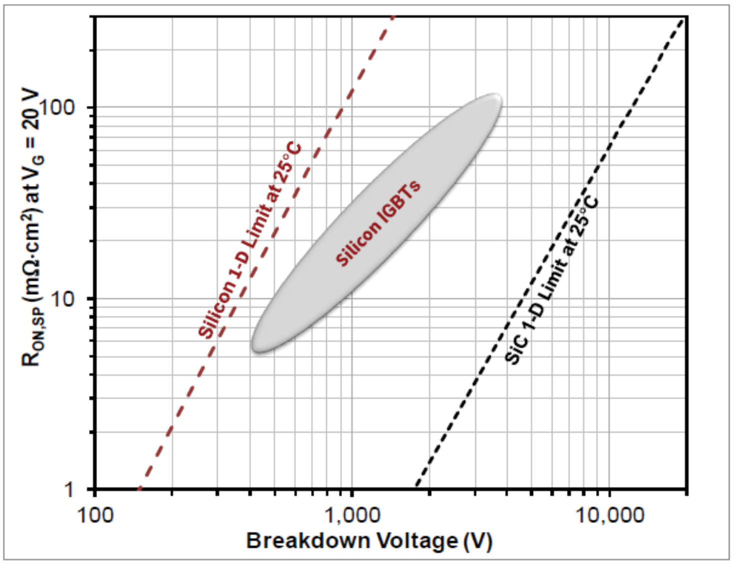
- High temperature capability
- Radiation hard

WBG devices and new packaging technologies are key to meeting these growing needs.

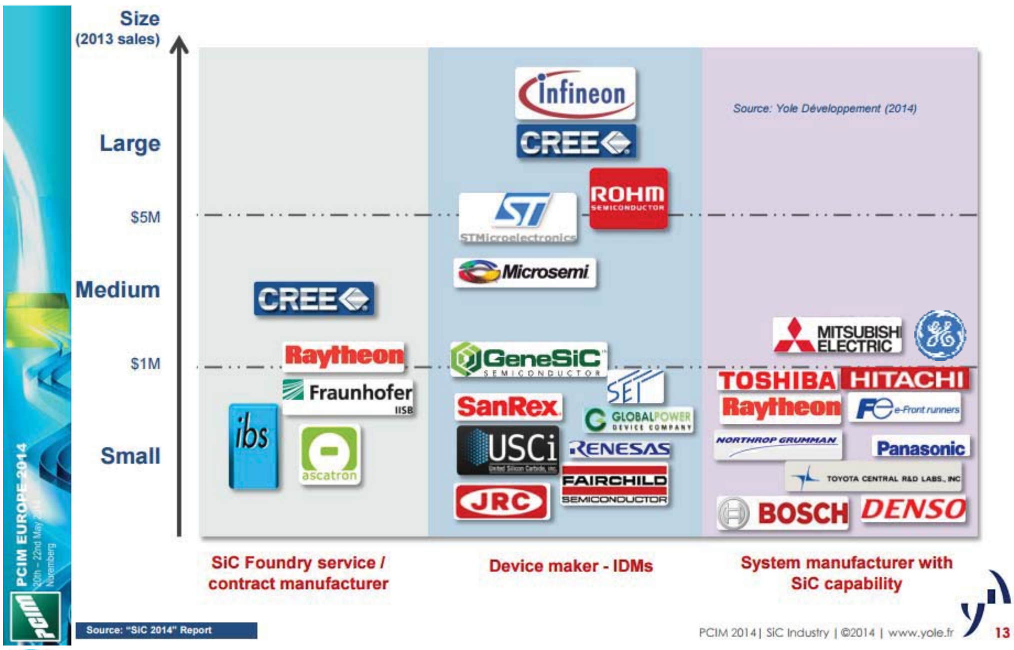
Wide bandgap (WBG) semiconductors are capable of achieving these goals.



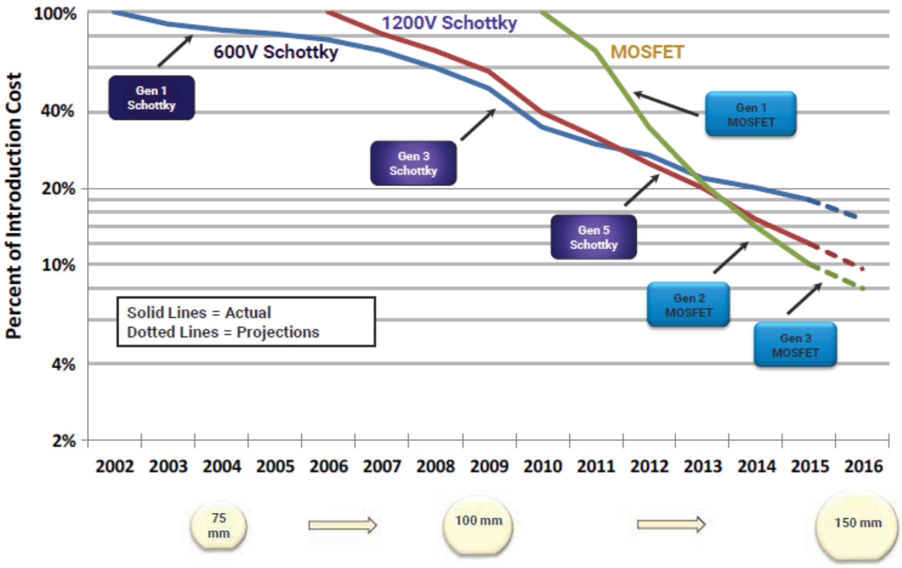
High electric breakdown field allows low on-resistance in SiC.



Power Electronics SiC Device Manufacturing



Cost Reduction of Wolfspeed's SiC Power Devices



Wafer diameter increases.

SiC Devices

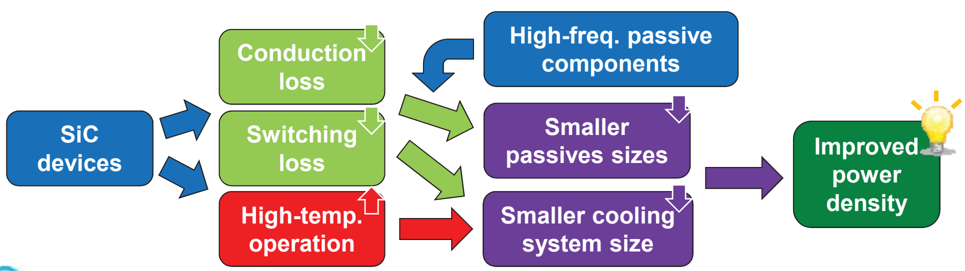
	Device	Advantages	Disadvantages	Voltage Rating
Unipolar	DMOSFET	Scalable	MOS Interface	0.4 kV – 15 kV
Unipolar	Trench MOSFET	High V_{TH}, Low R_{ON}	High Electric Field	0.6 kV – 1.2 kV
Unipolar	Normally-On JFET	High Temp.	Normally-On	1.2 kV – 6.5 kV
Unipolar	Normally-Off JFET	Normally-Off	High R_{ON}	1.2 kV – 6.5 kV
Bipolar	BJT	No Gate Oxide	Current Driven	1.2 kV – 10 kV
Bipolar	IGBT	High Voltage	Reliability	15 kV – 27 kV
Bipolar	GTO	Low Conduction Loss	Difficult Control	> 8 kV
	Schottky Diode	No Reverse Recovery	High Leakage	0.1 kV – 8 kV
	JBS Diode	Low Leakage	High Forward Voltage	0.65 kV – 10 kV
	PiN Diode	Forward Voltage	Degradation	10 kV

Outline

1. Introduction
2. High Frequency and High Efficiency
   – Comparison with Si
   – Characterization of 1.2 kV SiC discrete transistors
3. High Temperature
   – For power density in normal temperature ambient
   – For operation in high-temperature ambient
4. Medium Voltage
5. High Voltage
6. Conclusions
7. References

Wide-Bandgap Silicon Carbide (SiC) Power Semiconductors Devices

	Si	VS	SiC	
Band gap	1.1 eV		3.3 eV	High-voltage (≥ 1.2 kV);
Critical E-field	0.3 MV/cm		2.0 MV/cm	High-temperature (≥ 200 °C);
Doping	Low		High	
Thermal conductivity	1.5 W/cm·K		4.9 W/cm·K	Unipolar switches
State-of-the-art devices	Si IGBT ≤ 20 kHz, 150-175 °C		SiC FETs ≥ 20 kHz, 200-250 °C	for 0.5 kV < V_{dc} < 1 kV

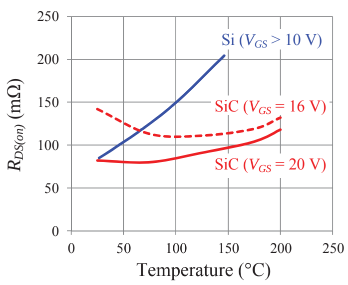


SiC Devices

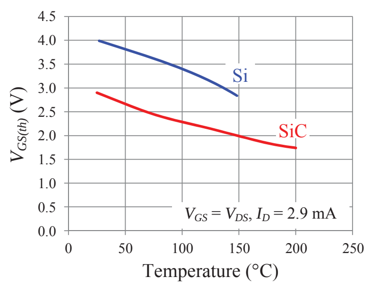
	Device	Advantages	Disadvantages	Voltage Rating
Unipolar	**DMOSFET**	**Scalable**	**MOS Interface**	**0.4 kV – 15 kV**
Unipolar	Trench MOSFET	High V_{TH}, Low R_{ON}	High Electric Field	0.6 kV – 1.2 kV
Unipolar	Normally-On JFET	High Temp.	Normally-On	1.2 kV – 6.5 kV
Unipolar	Normally-Off JFET	Normally-Off	High R_{ON}	1.2 kV – 6.5 kV
Bipolar	BJT	No Gate Oxide	Current Driven	1.2 kV – 10 kV
Bipolar	IGBT	High Voltage	Reliability	15 kV – 27 kV
Bipolar	GTO	Low Conduction Loss	Difficult Control	> 8 kV
	Schottky Diode	No Reverse Recovery	High Leakage	0.1 kV – 8 kV
	JBS Diode	Low Leakage	High Forward Voltage	0.65 kV – 10 kV
	PiN Diode	Forward Voltage	Degradation	10 kV

600 V Si CoolMOS vs. 1200 V SiC MOSFET: Static Characteristics

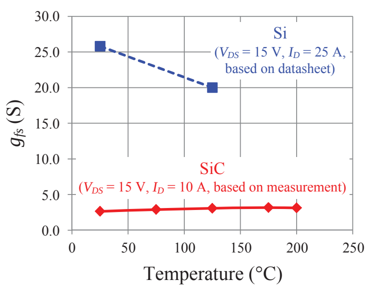
On-state resistance



Gate threshold voltage



Transconductance



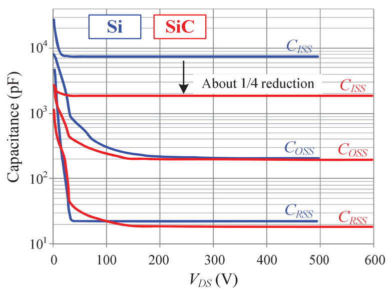
SiC MOSFETs:

- 20 V turn-on to achieve smaller & less temp.-sensitive $R_{DS(on)}$
- Neg. turn-off to ensure safe threshold margin
- Much lower g_{fs}, opposite temp.-dependence

(Z. Chen, 2010)

600 V Si CoolMOS vs. 1200 V SiC MOSFET: Dynamic Characteristics

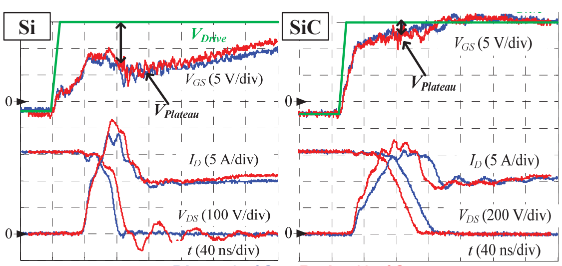
Junction capacitances



SiC MOSFET:

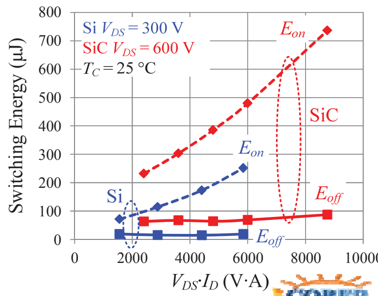
- 1/4 total gate charge
- Shorter on/off switching delays → Smaller dead time
- Driving speed significantly impeded by low g_{fs}
- Higher E_{SW} when switching the same apparent power and V_{GS}= +15 V/-2.5 V

Turn-on waveforms



Blue = 25 °C ***Red = 125 °C***

Switching energies



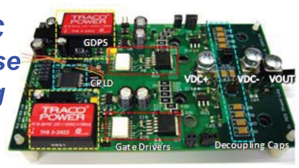
(Z. Chen, 2010)

600 V Si CoolMOS vs. 1200 V SiC MOSFET : Phase-Legs in a High-Frequency Converter

Module features

- 1200 V, 20 A SiC MOSFET phase-leg module
- Integrated peripheral functions
- High-speed gate drive (up to 500 kHz)
- Improved power stage layout (40% ↓ in stray L than conventional design)
- Compatible with Si MOSFET as well
  - 600 V, 46 A Si CoolMOS version

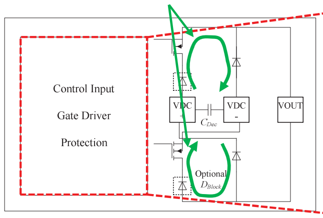
SiC Phase Leg



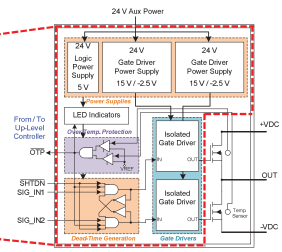
Si Phase Leg

Module layout

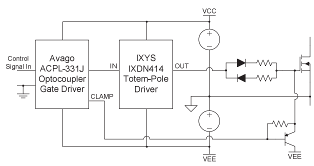
Switching loop inductance minimized



Integrated functions



Gate drive w/ Miller clamp

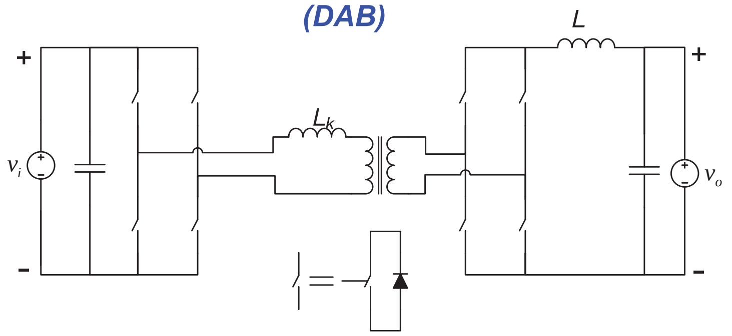


Suppressing cross-talk effect

(Z. Chen, 2010)

600 V Si CoolMOS vs. 1200 V SiC MOSFET:
High-Frequency Converter Comparison

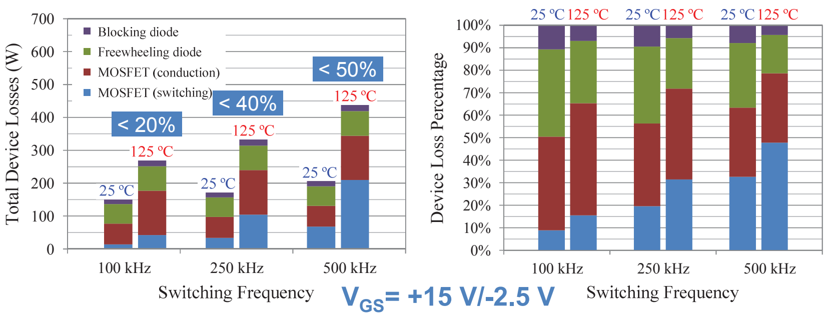
High-frequency dual-active-bridge (DAB)



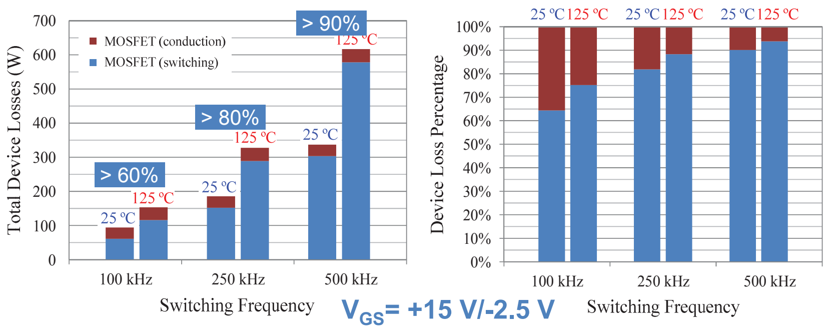
- **Isolated DC-DC converter, bidirectional power flow**
  - **Input & output DC bus:**
    300 V for Si CoolMOS, 600 V for SiC MOSFETs
  - **Same output power: 5 kW full-load**
  - **Switching frequency: 100 kHz, 250 kHz, 500 kHz**
  - **Device loss distribution calculated based on loss-less DAB model**

600 V Si CoolMOS vs. 1200 V SiC MOSFET:
Device Loss Distribution

600 V Si CoolMOS PEBB (300 V bus)



1200 V SiC MOSFET PEBB (600 V bus)



Brief Summary:
SiC MOSFET Under High-Frequency Operation

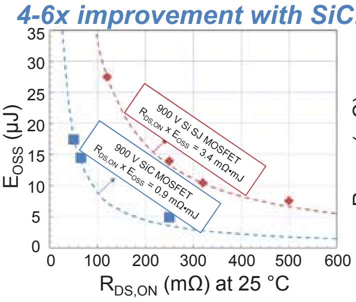
- **Si CoolMOS vs. SiC MOSFETs**

	Si CoolMOS (600 V, 46 A)	SiC MOSFET (1200 V, 20 A)
V_{GS}	0 –10 V	-5 – 20 V
$R_{DS(on)}$	Larger; Increases by > 200% at 125 °C	Smaller; Increases by < 200% at 200 °C
Junction caps	4x higher C_{ISS}; Slightly higher C_{RSS}, C_{OSS}	1/4x lower C_{ISS}; Slightly lower C_{RSS}, C_{OSS}
g_{fs}	Much higher	Much lower
E_{SW}	Lower	Higher (when driving with +15 V/-2.5 V)

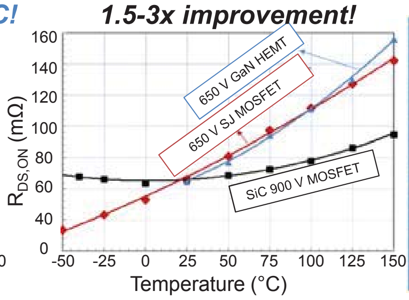
What about *newer-generation* SiC MOSFETs?

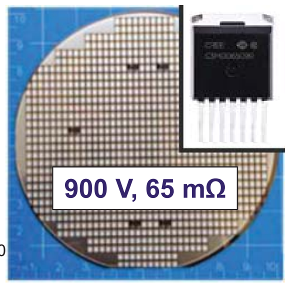
Industry's first 900 V SiC MOSFET vs. 900 V Si CoolMOS.

4-6x improvement with SiC!



1.5-3x improvement!





Key Parameters	Cree 900V C3M0065090J	CoolMOS™ 900V
RDS(ON) @ 25C	65 mΩ	280 mΩ
RDS(ON) @ 150C	90 mΩ	760 mΩ
Peak Current	90 A	34 A
Qg	30 nC	94 nC
Ciss	660 pF	2400 pF
Qrr	131 nC	11,000 nC
Trr	16 ns	510 ns

http://apps.richardsonrfpd.com/Mktg/Cree_900V_SiC-MOSFET.html

Industry's first 900 V SiC MOSFET vs. 650 V Si CoolMOS.

220 W LED driver using ***Si SJ MOSFETs***

220 W LED driver using Wolfspeed C3M ***SiC MOSFETs***

	650 V CoolMOS (2-Stage)	900 V SiC MOSFET (Single Stage)	
Input voltage Range	120-277V AC	120-277V AC	
Output Voltage Range	150-210V DC	150-210V DC	
Max Output Current	1.45 A	1.45 A	
Peak Efficiency	93.5 %	94.4 %	→ 1 % higher efficiency
Input THD	< 20%	< 20%	
Output Current Ripple	>0.95	>0.95	
Output Current Ripple	±5 %	±10 %	
Size	220 x 52 x 30 mm	140 x 50 x 30 mm	→ 40 % size reduction
Weight	2.7 lbs / 1.3 kg	1.1 lbs / 0.5 kg	→ 60 % weight reduction
Relative cost	1	0.85	→ 15 % BOM cost reduction

Wolfspeed. V. Pala, et al., "900 V silicon carbide MOSFETs for breakthrough power supply design," IEEE ECCE, pp. 4145-4150, 2015.

Brief Summary: SiC MOSFET Under High-Frequency Operation

- **Si CoolMOS vs. SiC MOSFETs**

	Si CoolMOS (600 V, 46 A)	SiC MOSFET (1200 V, 20 A)
V_{GS}	0 –10 V	-5 – 20 V
$R_{DS(on)}$	Larger; Increases by > 200% at 125 °C	Smaller; Increases by < 200% at 200 °C
Junction caps	4x higher C_{ISS}; Slightly higher C_{RSS}, C_{OSS}	1/4x lower C_{ISS}; Slightly lower C_{RSS}, C_{OSS}
g_{fs}	Much higher	Much lower
E_{SW}	~~Lower~~	~~Higher (when driving with +15 V/-2.5 V)~~

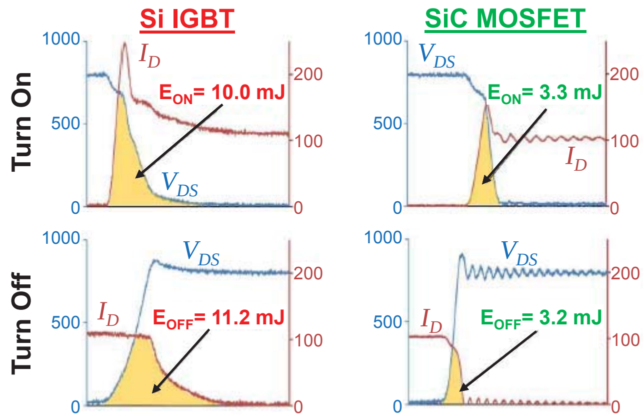
- **Suitable applications for SiC MOSFETs**
  - High DC bus voltage (> 400 V)
  - High power
  - High junction temperature
  - 10 kHz < frequency < 100 kHz

To replace state-of-the-art Si IGBTs
- Increase switching frequency
- Reduce conduction/switching losses

(Z. Chen, 2010)

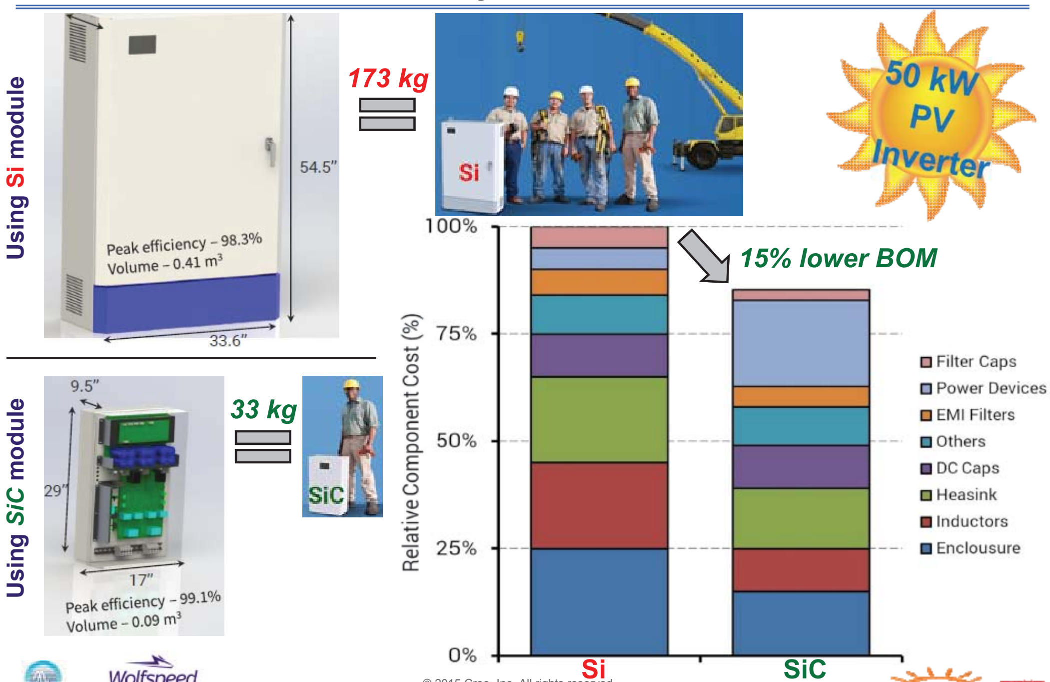
SiC MOSFET 6-Pack vs. Si IGBT (FS50R12KT4)

Switching test at 800 V, 100 A, and T_J= 150 °C.



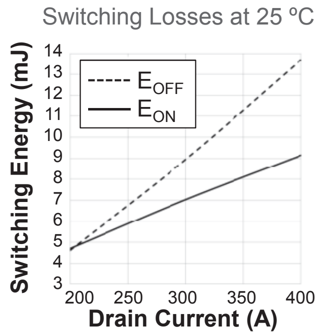
- Unlike Si IGBTs, SiC MOSFETs do not have a tail current. This results in significantly ***lower* turn-on switching losses**.
- SiC MOSFETs enable ***increased* switching frequency**, which ***reduces*** the **size**, **weight**, and BOM **cost** of power electronic systems.

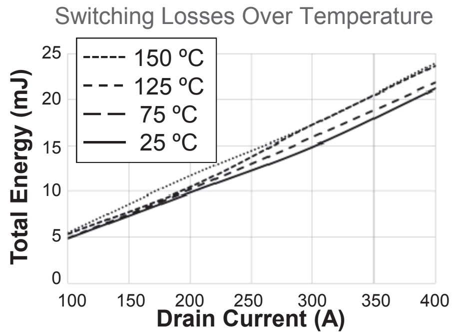
SiC MOSFETs reduce the converter size and weight, and lower system costs.



SiC MOSFET switching losses are < 1/10th that of Si IGBT.

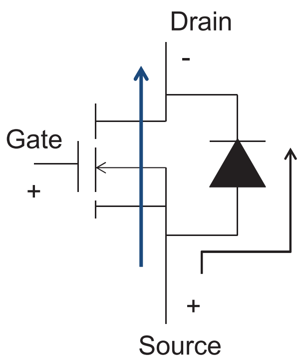
1.7 kV, 240 A SiC MOSFET Module Switching Test at V_{DS}= 900 V, R_G= 4.3 Ω

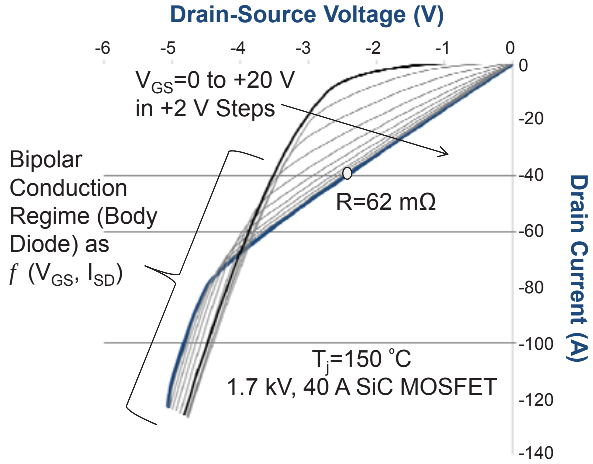




Module Type	Switching Test Conditions	E_{ON} (mJ)	E_{OFF} (mJ)	E_{REC} (mJ)	E_{SUM} (mJ)
1.7 kV SiC MOSFET	900 V, 400 A, 125 °C, R_{ON}=R_{OFF}=4.3 Ω	10	14	4	**28**
1.7 kV Si IGBT (FS450R17KE3)	900 V, 400 A, 125 °C, R_{ON}=R_{OFF}=3.3 Ω	130	130	100	**360**

SiC MOSFETs offer symmetric reverse conduction for synchronous rectification.



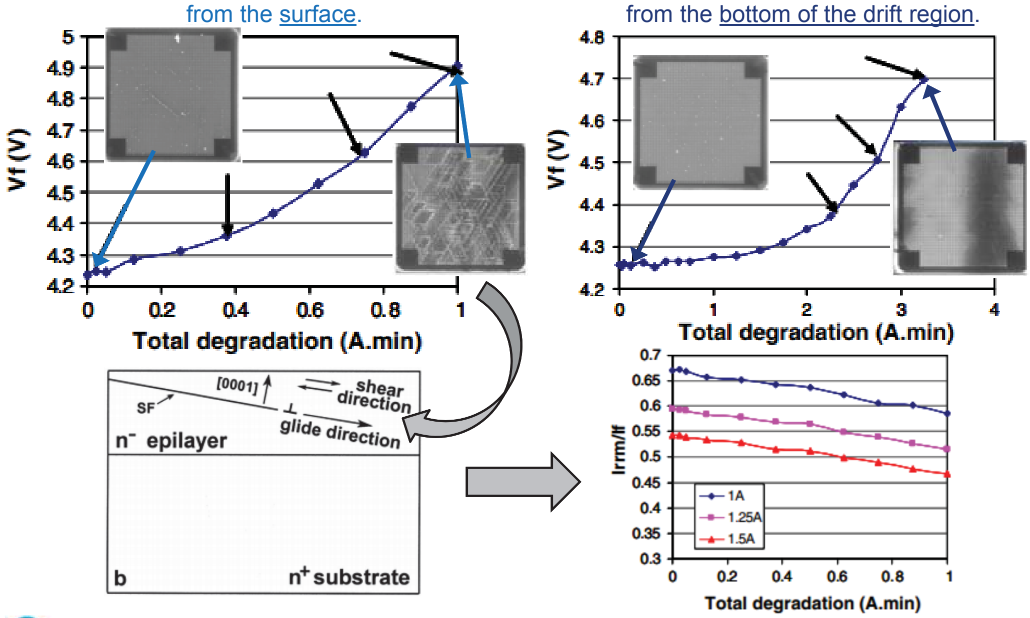


- The **body diode** of the SiC MOSFET is ideal for **synchronous rectification**.
- Using the body diode **eliminates** the need for an external **anti-parallel diode**, which increases the floor space thereby allowing for **higher-current modules.**

Previously, stacking faults resulted in degradation in SiC PN junctions.

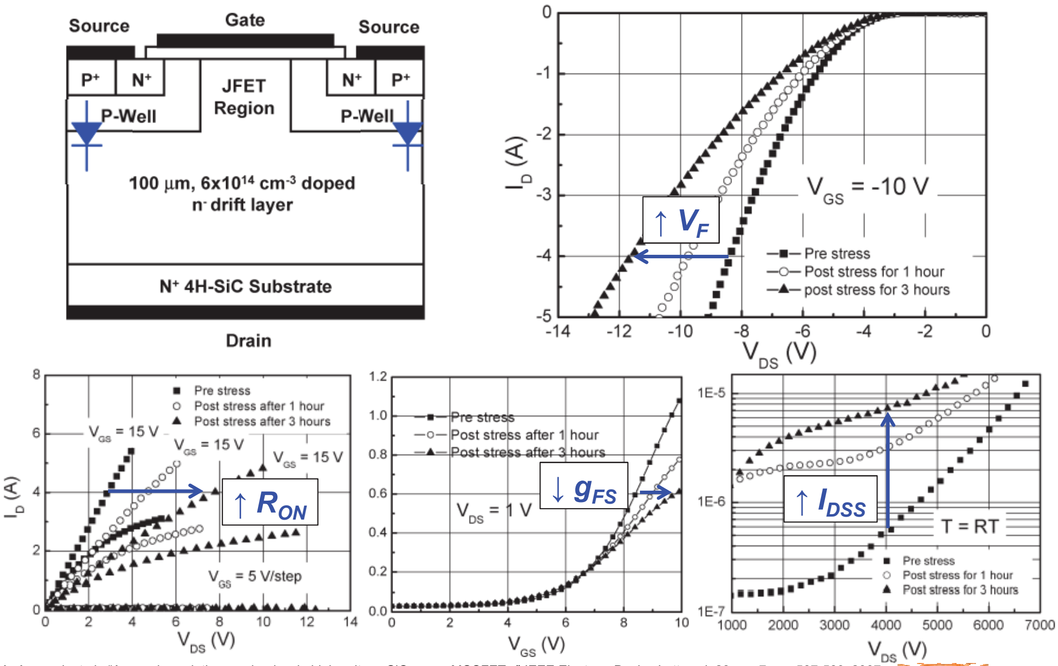
SiC PN diode with stacking fault originating from the surface.

SiC PN diode with stacking fault growing from the bottom of the drift region.



R. Singh, “Reliability and performance limitations in SiC power devices,” Microelectronics Rel., vol. 46, pp. 713-730, 2006.
J. Liu, et al., “Structure of recombination-induced stacking faults in high-voltage SiC p-n junctions,” Appl. Physics Lett., vol. 80, no. 5, pp. 749-751, 2002.

These faults were observed to degrade high-voltage SiC MOSFETs during body diode stressing.



A. Agarwal, et al., “A new degradation mechanism in high-voltage SiC power MOSFETs,” IEEE Electron. Device Lett., vol. 28, no. 7, pp. 587-589, 2007.

There were also concerns about the gate oxide reliability, especially under high temperature conditions.

SiC MOSFET

- Lower channel mobility
- Smaller effective barrier height
- Higher interface state densities…

→

- Time-dependent dielectric-breakdown
- Gate oxide defects
- Gate threshold voltage shift

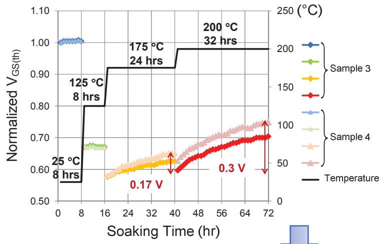
(A. Agarwal, 1997) (R. Singh, 2004, 2007) (A. Lelis, 2008, 2011) (M. Das, 2011)

Device terminal behaviors under both high V_{GS} and high T_J?

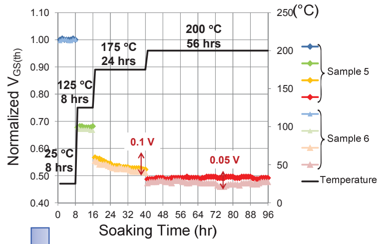
SiC MOS die in HT package

x2 for each test condition

HT gate biasing test
(T_J = 200 °C, V_{GS} = 20 VDC)



HT gate switching test
(T_J = 200 °C, V_{GS} = -4/20 V at 70 kHz)



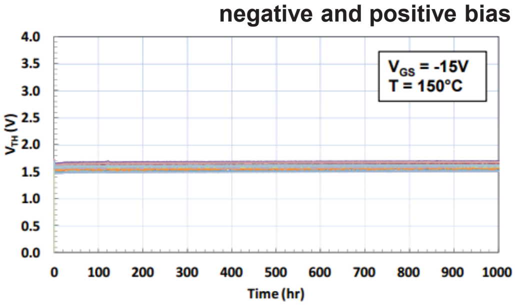
Other device parameters

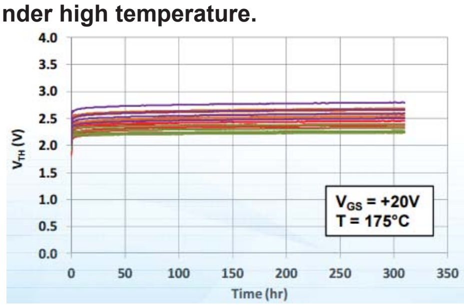
	HT gate biasing test	HT gate switching test
$V_{GS(th)}$	26% ↑	7% ↓
I_{DSS}	Negligible change	
$R_{DS(on)}$	Negligible change	
C_{ISS}	5% ↓	3% ↓

(Z. Chen, 2011)

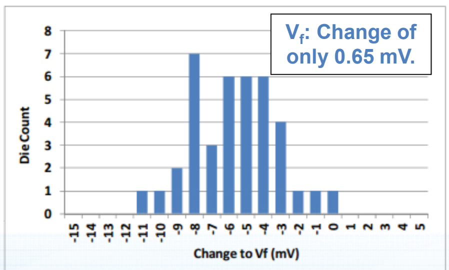
It has been shown that the gate oxide and body diode of newer-generation SiC MOSFETs are stable.

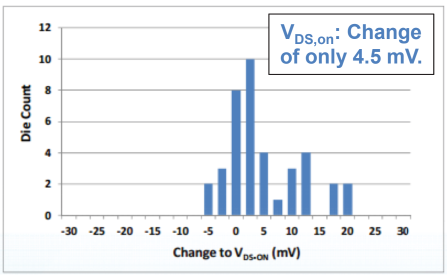
Threshold voltage stability of Wolfspeed's C2M0080120D SiC MOSFETs at negative and positive bias under high temperature.





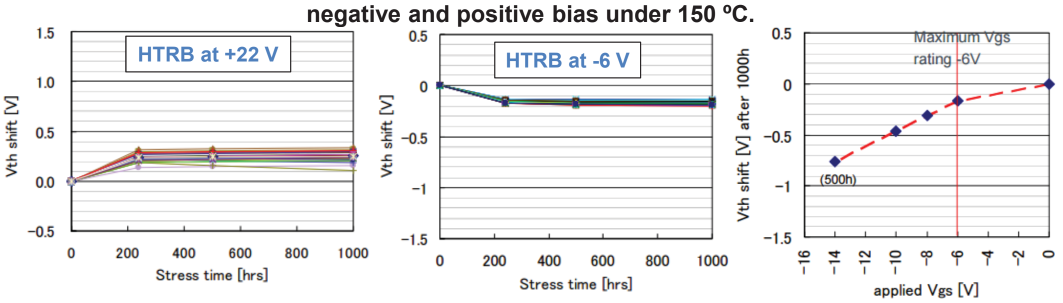
Body diode stability of Wolfspeed's C2M0080120D SiC MOSFETs at 10 A, 150 ºC.



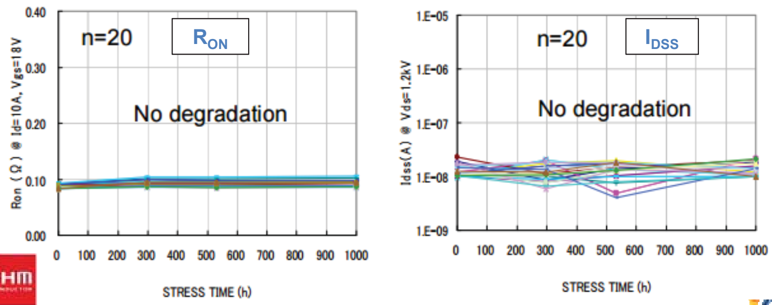


It has been shown that the gate oxide and body diode of newer-generation SiC MOSFETs are stable.

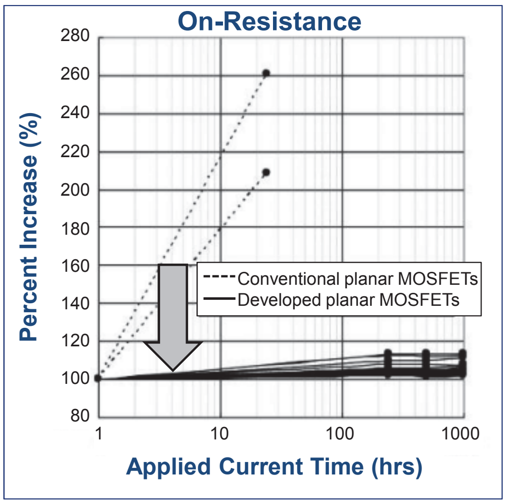
Threshold voltage stability of ROHM's Gen. 2 SiC MOSFETs at negative and positive bias under 150 ºC.

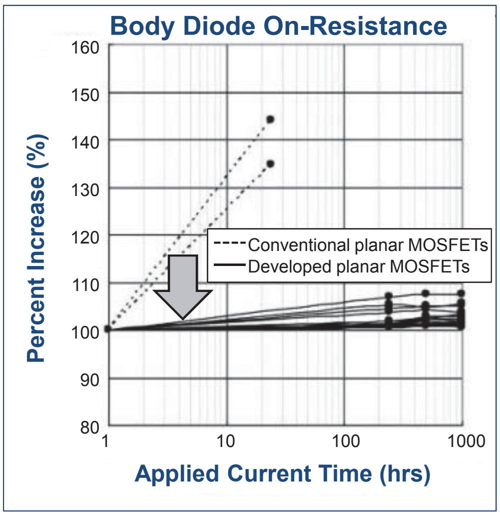


Body diode stability of ROHM's SCT2080KE SiC MOSFETs at 8 A, 25 ºC.



Body diode reliability can be achieved with improved substrate, epitaxy, and device fabrication processes.

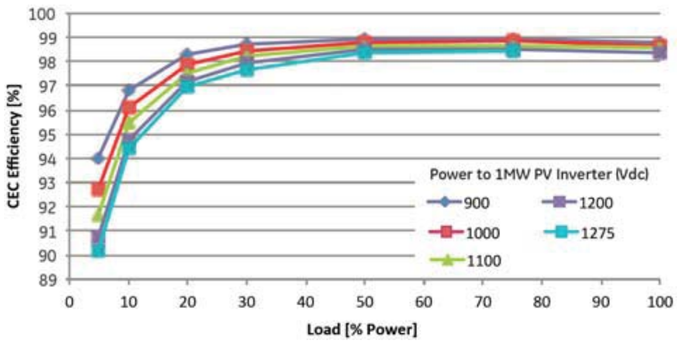


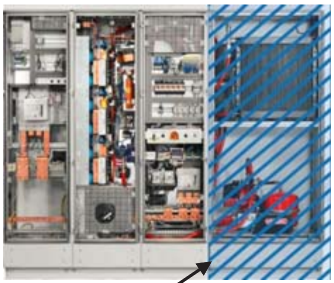


K Okumura, et al., "Ultra low on-resistance SiC trench devices," Power Semiconductors Mag., no. 4, pp. 22-25, 2012.

1 % higher CEC efficiency is achieved when using SiC MOSFETs (without JBS) instead of Si IGBTs.

1 MW, 2L PV inverter switching at 8 kHz with 1.7 kV SiC MOSFET modules.



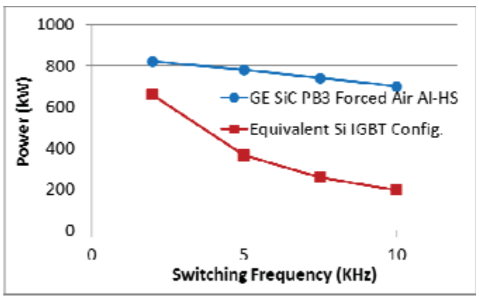


- 99.4 % module efficiency
- Outstanding CEC* efficiency, approaching 99.0 %
- 50 % lower losses → air cooling
- Simpler system for lower manufacturing cost

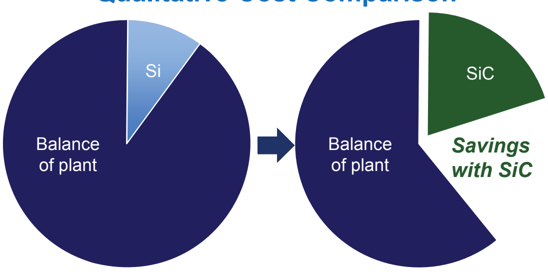
*CEC= California Energy Commission. The Commission sets standards for appliances and buildings in order to promote energy efficiency, among other responsibilities.

SiC MOSFETs reduce the converter size and weight, and lower system costs.

Less heat to manage	Operate at higher temp	Higher frequency
50% lower power losses vs. IGBT	50^{o}C higher junction temp. vs. IGBT	10X higher frequency vs. IGBT



Qualitative Cost Comparison

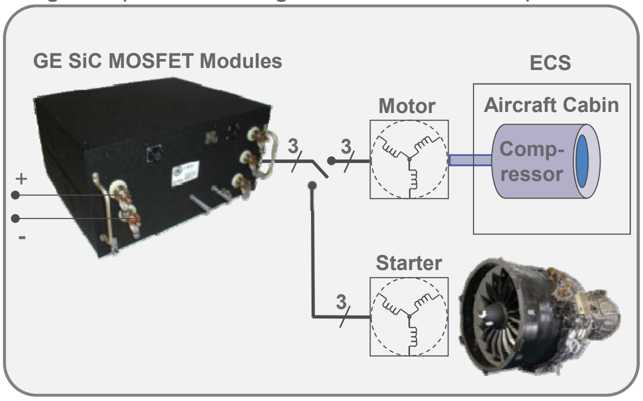


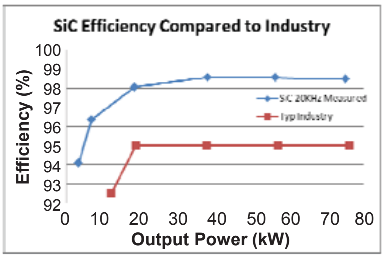
- Not necessary for SiC to be at Si cost
- Focus on high power, high volume apps where SiC offers attractive value proposition

A 75 kW aviation converter with 98.5 % efficiency at 20 kHz is realized using SiC MOSFETs.

$V_{IN} = \pm 270 V_{DC}, V_{OUT} = 220 V_{LN}, P_{OUT} = 75kW, F_{FUND\_MAX} = 1.8kHz$

High freq. drive for engine start + ECS compressor



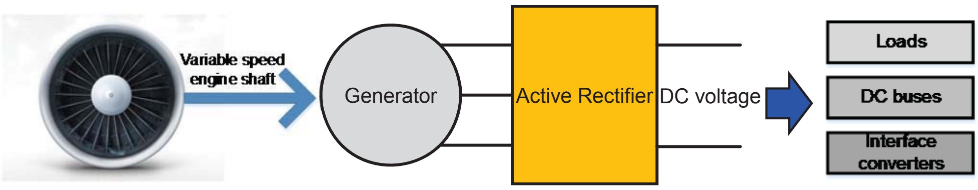


50 % *smaller* inverter size and weight

70 % *lower* losses liquid → air cooled

500 lb *less* per aircraft

99 % - *Efficient* Rectifiers for Aerospace Applications

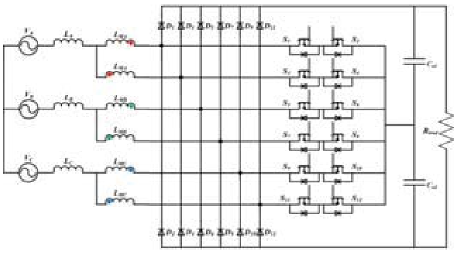


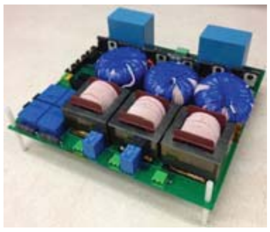
Target Specifications	
Input RMS Voltage	230 V (L-N)
Input Frequency	360 Hz ~ 800 Hz
Output DC Voltage	650 V
Nominal Power	3 kW
Cooling	Free Convection
Efficiency	99 % at Full Load

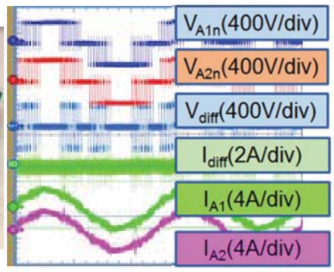
According to a loss estimation, the **highest efficiency** could be achieved **using SiC MOSFETs**.

99 % - Efficient 3 kW SiC Vienna Rectifier for Aerospace

Interleaved VR Circuit Diagram | **Converter Prototype** | **Experimental Waveforms**



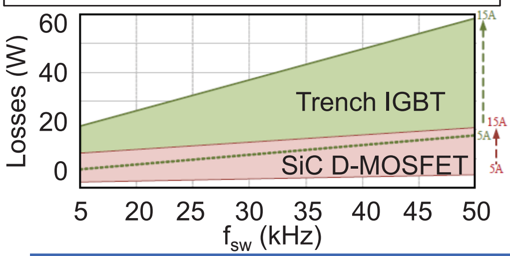




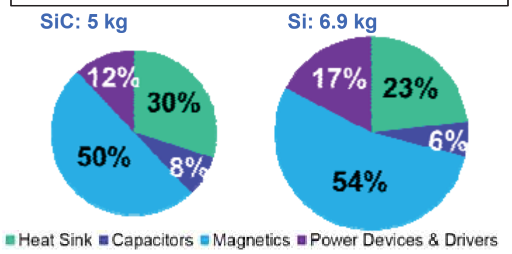
- All switches implemented with SiC devices
- Total measured loss is 22.4 W (**99.26% efficiency** at 3 kW output power ***without* active cooling**)
- Device case/surface temperatures without active cooling at room-temperature ambient (22 ºC):
  - ❖ SiC MOSFET: **53 ºC**
  - ❖ SiC Schottky Diode: **74 ºC**
  - ❖ Boost inductor: 35 ºC
  - ❖ Coupled inductor: 37 ºC

SiC has shown numerous benefits over Si.

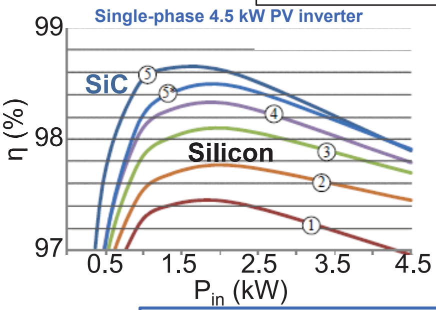
Double-pulse tests reveal reduced switching losses.



SiC offers increased power density.



Improved efficiency has been proven when using SiC.



Dual 52.8 kW interleaved bidirectional IGBT converter

Component	Type	SiC Losses	Si Losses
Power modules	Switching	673 W	1586 W
	Conduction	459 W	398 W
Drivers	Driver	73 W	10 W
Magnetic components	Inductor	134 W	230 W
	IPT	124 W	160 W
	Total	**1,463 W**	**2,384 W**

How do the SiC devices compare to one another?

SiC Devices

	Device	Advantages	Disadvantages	Voltage Rating
Unipolar	DMOSFET	Scalable	MOS Interface	0.4 kV – 15 kV
	Trench MOSFET	High V_{TH}, Low R_{ON}	High Electric Field	0.6 kV – 1.2 kV
	Normally-On JFET	High Temp.	Normally-On	1.2 kV – 6.5 kV
	Normally-Off JFET	Normally-Off	High R_{ON}	1.2 kV – 6.5 kV
Bipolar	BJT	No Gate Oxide	Current Driven	1.2 kV – 10 kV
	IGBT	High Voltage	Reliability	15 kV – 27 kV
	GTO	Low Conduction Loss	Difficult Control	> 8 kV
	Schottky Diode	No Reverse Recovery	High Leakage	0.1 kV – 8 kV
	JBS Diode	Low Leakage	High Forward Voltage	0.65 kV – 10 kV
	PiN Diode	Forward Voltage	Degradation	10 kV

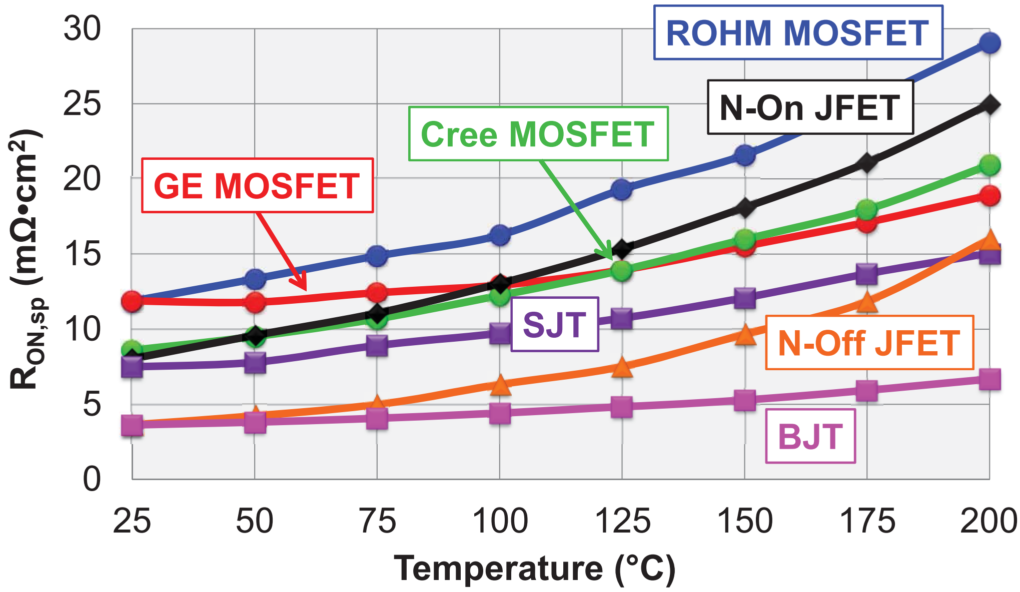
SiC Device Comparative Characterization

	Device	Continuous Current Rating*	T_{MAX}*	Normalized Die Area**
CREE	SiC MOSFET (C2M0080120D)	20 A (100 °C)	150 °C	1.00
ROHM	SiC MOSFET (SCH2080KE)	22 A (100 °C)	150 °C	1.21
GE	SiC MOSFET (GE12N20L)	22.5 A (100 °C)	***200 °C***	0.97
FAIRCHILD SEMICONDUCTOR	SiC BJT (FSICBH057A120)	15 A	175 °C	0.64
GeneSiC SEMICONDUCTOR	SiC SJT (GA10JT12)	6 A (25 °C)	175 °C	0.33
Infineon	N-On SiC JFET (IJW120R100T1)	10 A (≤ 150 °C)	175 °C	1.29
SemiSouth	N-Off SiC JFET (SJEP120R100)	17 A (100 °C)	150 °C	0.43

*Ratings from the device datasheet.
**Normalized to the die area of the Cree C2M0080120D SiC MOSFET.

(C. DiMarino, 2014)

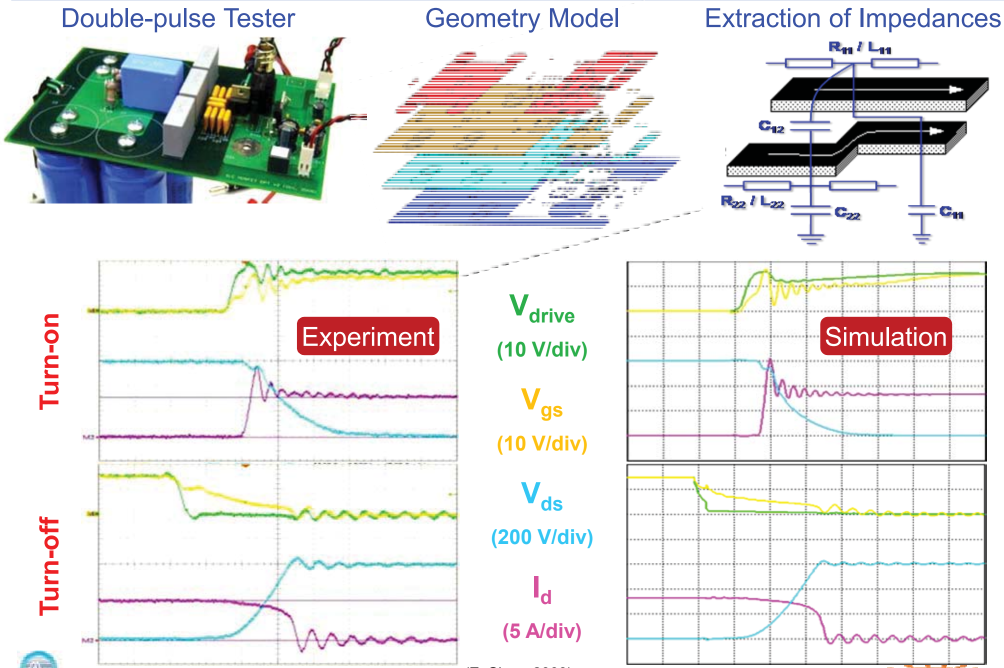
SiC Switch Comparative Characterization: Specific On-Resistance vs. Temperature



*$R_{ON,sp}$= R_{ON} x Die Area

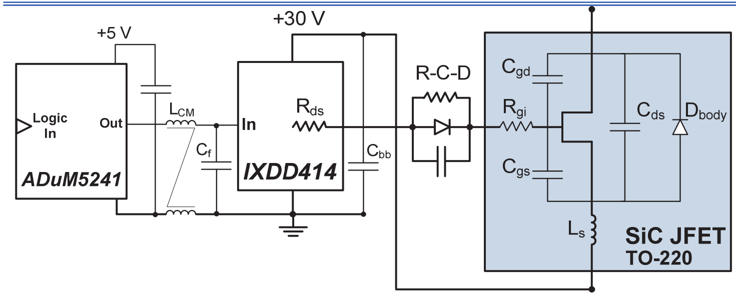
(C. DiMarino, 2014)

Modeling of Switching Behavior



(Z. Chen, 2009)

Design of a 0-Ω Gate Drive for 1.2 kV SiC Normally-On JFET

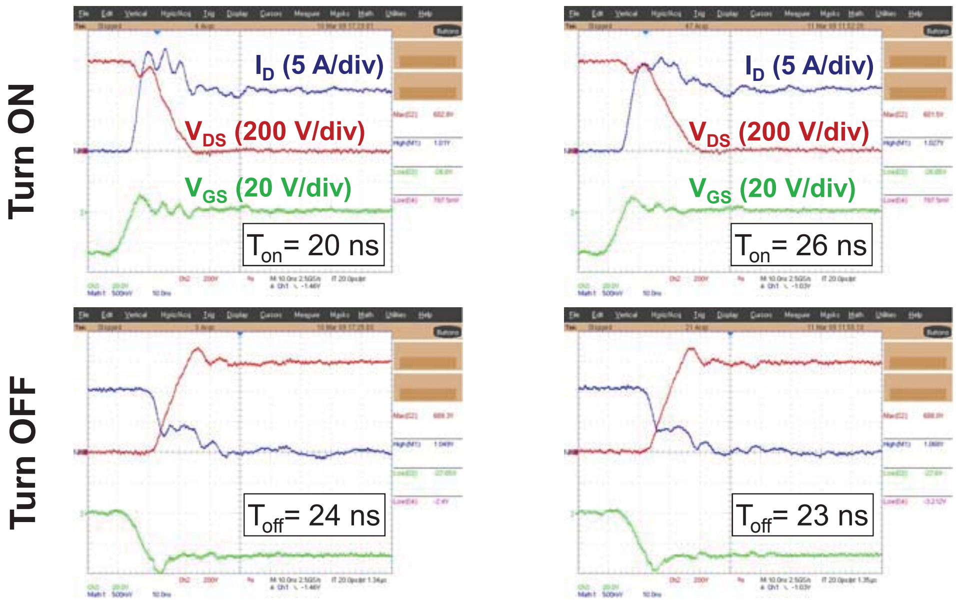


V_{DS}: 100 x Probe, 2500 V, P5100
V_{GS}: 10 x Probe, 300 V, P6139A
I_D: 0.1 Ω Coaxial Shunt SDN-10

(R. Burgos, 2009)

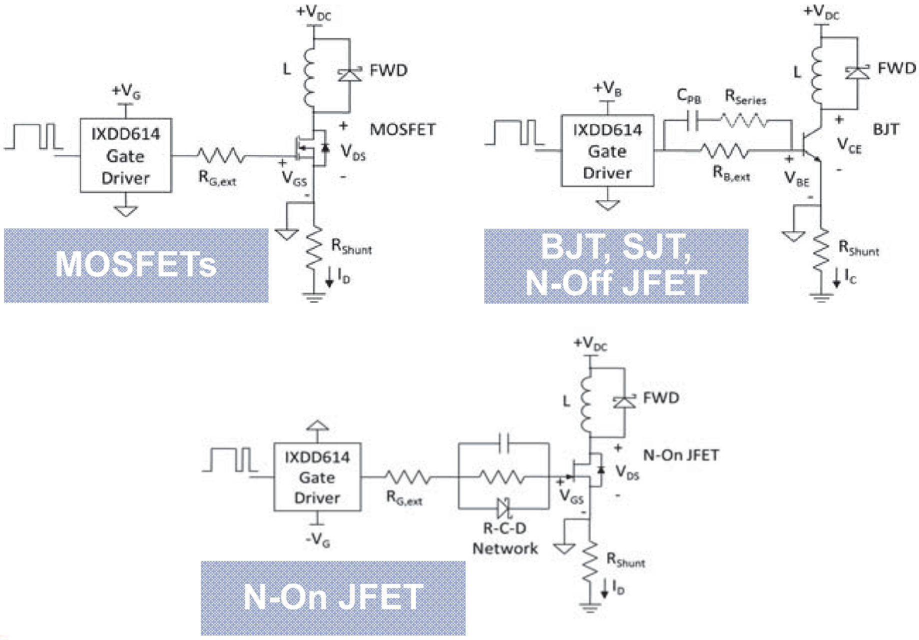
Switching of SiC Normally-On JFET at Different Temperatures

25° C — **0-Ω Gate Drive, 600 V, 10 A** — *200° C*

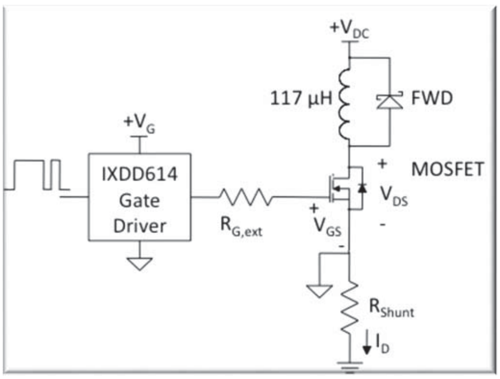


(R. Burgos, 2009)

Minimal modifications are made to the driving circuits to allow for fair comparisons.

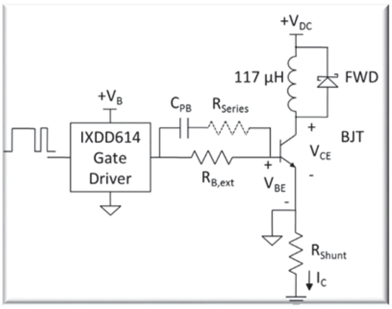


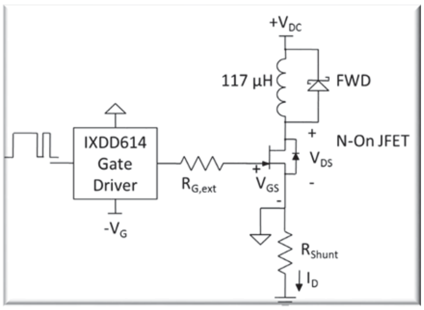
Driving Method for the SiC MOSFETs



Mfg.	Part #	$R_{G,ext}$	R_{total}
CREE	CMF20120D	2.5 Ω	7.5 Ω
	C2M0080120D	2.5 Ω	7.4 Ω
GE	GE12N20L	5 Ω	7.4 Ω
ROHM SEMICONDUCTOR	SCT2080KE	0 Ω	7.3 Ω

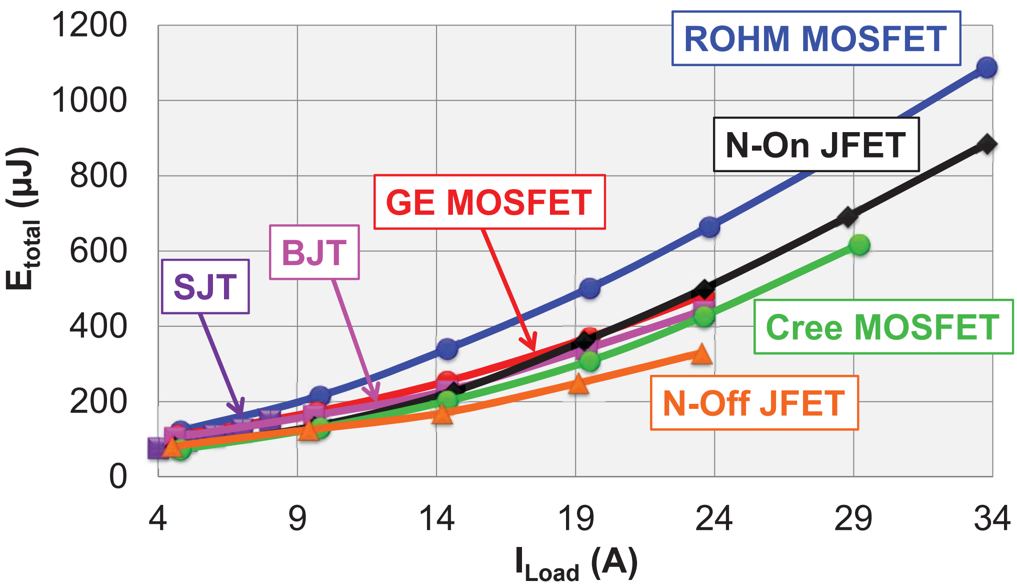
Driving Methods for the SiC BJT, SJT, and JFETs





Device	V_{drive}	C_{PB}	$R_{G,ext}$	R_{series}
BJT	0 V - 20 V	47 nF	30 Ω	3 Ω
SJT	0 V - 20 V	47 nF	30 Ω	0 Ω
N-Off JFET	0 V - 20 V	47 nF	30 Ω	3 Ω
N-On JFET	-19 V - 0 V	N/A	3.3 Ω	N/A

SiC Switch Comparative Characterization:
Switching Energy vs. Load Current

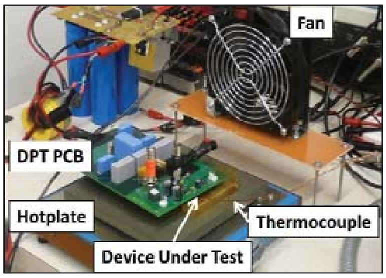


V_{DC}= 600 V. Driver losses not included.

The switching loss of SiC transistors is independent of temperature.

For ΔT of 175 ºC (from 25 ºC to 200 ºC)

Device	ΔE_{ON}	ΔE_{OFF}	ΔE_{TOT}
Cree MOSFET	↓	↑	↓ 6 %
ROHM MOSFET	↓	↑	↓ 8 %
GE MOSFET	↓	↑	constant
BJT	↓	↓	↓ 6 %
SJT	↓	↓	↓ 14 %
N-Off JFET	↑	constant	↑ 11 %
N-On JFET	constant	↓	↓ 11 %

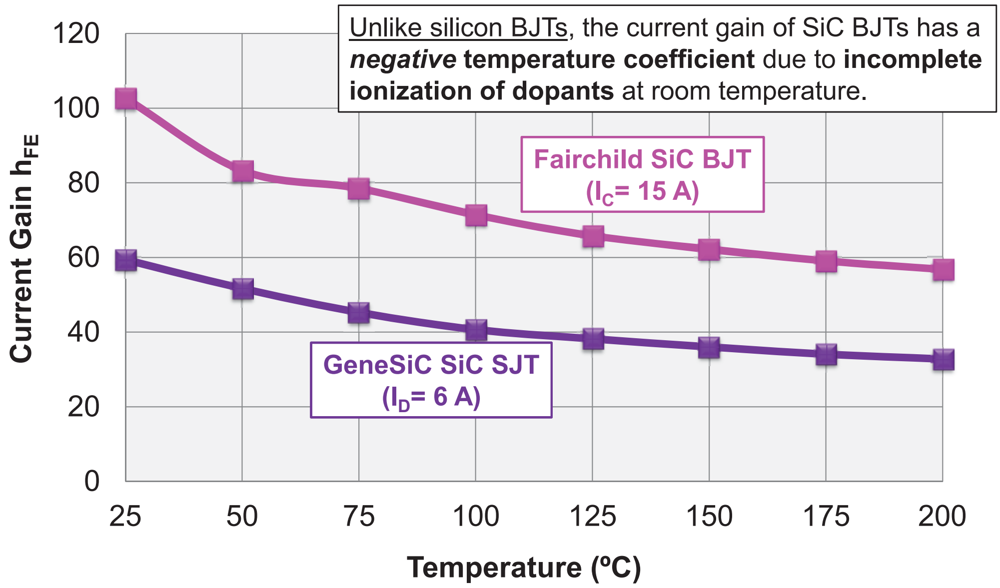


(C. DiMarino, 2014)

SiC Devices

	Device	Advantages	Disadvantages	Voltage Rating
Unipolar	DMOSFET	Scalable	MOS Interface	0.4 kV – 15 kV
Unipolar	Trench MOSFET	High V_{TH}, Low R_{ON}	High Electric Field	0.6 kV – 1.2 kV
Unipolar	Normally-On JFET	High Temp.	Normally-On	1.2 kV – 6.5 kV
Unipolar	Normally-Off JFET	Normally-Off	High R_{ON}	1.2 kV – 6.5 kV
Bipolar	**BJT**	**No Gate Oxide**	**Current Driven**	**1.2 kV – 10 kV**
Bipolar	IGBT	High Voltage	Reliability	15 kV – 22 kV
Bipolar	GTO	Low Conduction Loss	Difficult Control	> 8 kV
	Schottky Diode	No Reverse Recovery	High Leakage	0.1 kV – 8 kV
	JBS Diode	Low Leakage	High Forward Voltage	0.65 kV – 10 kV
	PiN Diode	Forward Voltage	Degradation	10 kV

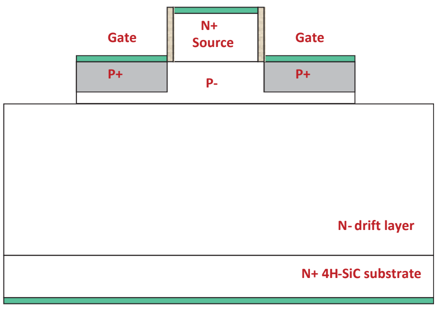
The SiC BJT and SJT have high current gains with a negative temperature coefficient.



*h_{FE} taken at V_{CE}= 5 V.

(C. DiMarino, 2014)

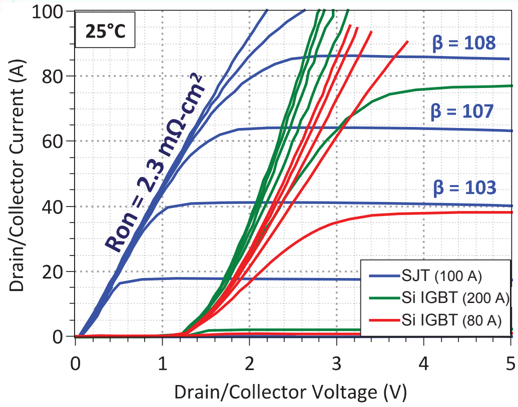
Silicon Carbide Junction Transistor (SJT)

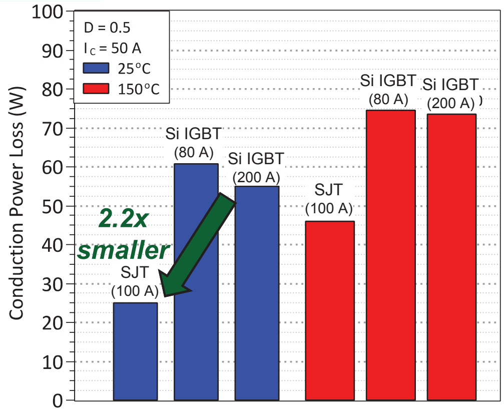


- Lowest $V_{DS(ON)}$ as compared to any other commercial SiC switch
- Best-in-class temperature independent switching
- Positive temperature coefficient for easy paralleling
- Gate oxide free SiC switch = high operating temperature
- Avalanche-capable, short-circuit rated
- Easy to drive using commercial drivers
- Suitable for connecting anti-parallel diode
- Low gate charge, low intrinsic capacitance
- High yielding, smaller size, lower cost

Information courtesy of GeneSiC™

1700 V SJT vs. Si IGBT: Conduction Loss

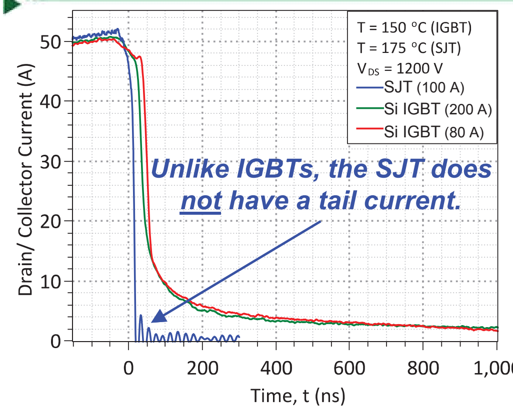


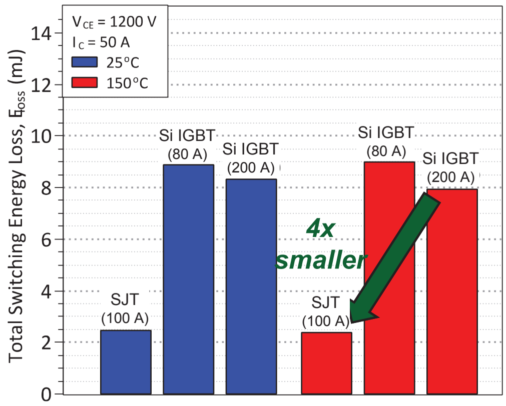


- Benchmarked with best-in-class 40-75 A 1700 V Si IGBTs
- The **SJT's V_F is 50% lower** than either IGBT at high operating temperatures
- The **conduction power loss** of the SiC SJT is ***2.2x smaller*** than the Si IGBT during 25 °C operation

Information courtesy of GeneSiC™

1700 V SJT vs. Si IGBT: Turn-Off Loss

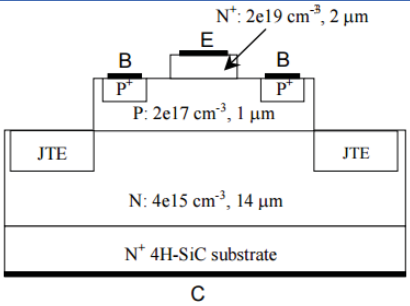




- SJT shows **MOSFET-like** fast turn-off waveforms, due to unipolar operation
- SiC SJT offers the **lowest switching energy loss** at all temperatures due to:
  - Small chip size
  - Lack of minority charge storage (also resulting in temperature invariant switching)

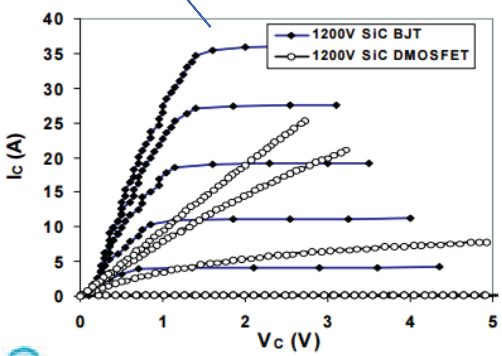
Information courtesy of GeneSiC™

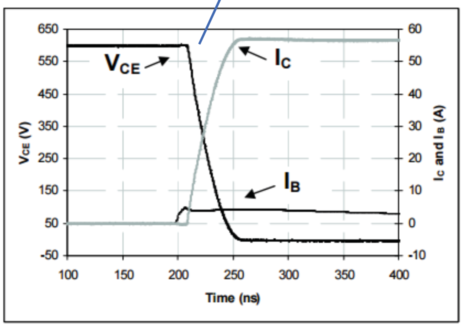
Why does the SiC BJT behave like a MOSFET?



SiC BJTs feature **low on-state losses** due to **cancellation of the junction voltages**.

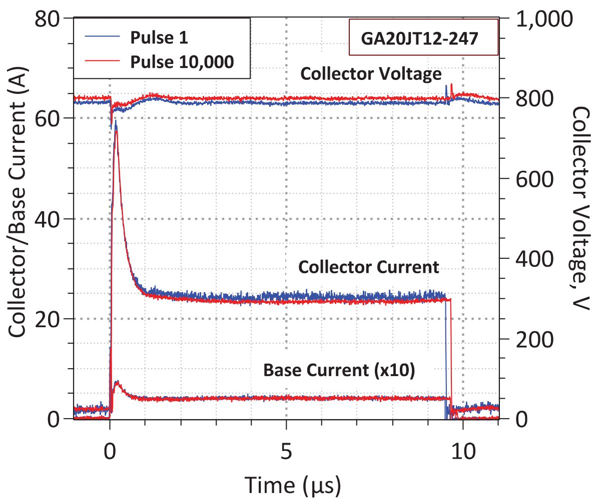
Higher doping causes the SiC BJT to behave like a **majority-carrier** device, resulting in **faster switching speeds** compared to silicon BJTs.





A. Agarwal, et al., "Prospects of bipolar power devices in silicon carbide," IEEE IECON, pp. 2879-2884, 2008.

SJT Repetitive Short-Circuit at 800 V



- 1200 V, 50 mΩ SJT subjected to 10000, **10 µs short-circuit** pulses with low (1 Hz) repetition frequency
- SJT switched on under typical base drive conditions at **800 V**
- Test is periodically interrupted and the device parameters are monitored

Information courtesy of GeneSiC^{TM}

SiC Devices

	Device	Advantages	Disadvantages	Voltage Rating
Unipolar	DMOSFET	Scalable	MOS Interface	1.2 kV – 15 kV
Unipolar	**Trench MOSFET**	**High V_{TH}, Low R_{ON}**	**High Electric Field**	**0.6 kV – 1.2 kV**
Unipolar	Normally-On JFET	High Temp.	Normally-On	1.2 kV – 6.5 kV
Unipolar	Normally-Off JFET	Normally-Off	High R_{ON}	1.2 kV – 6.5 kV
Bipolar	BJT	No Gate Oxide	Current Driven	1.2 kV – 10 kV
Bipolar	IGBT	High Voltage	Reliability	15 kV – 27 kV
Bipolar	GTO	Low Conduction Loss	Difficult Control	> 8 kV
	Schottky Diode	No Reverse Recovery	High Leakage	0.1 kV – 8 kV
	JBS Diode	Low Leakage	High Forward Voltage	0.65 kV – 10 kV
	PiN Diode	Forward Voltage	Degradation	10 kV

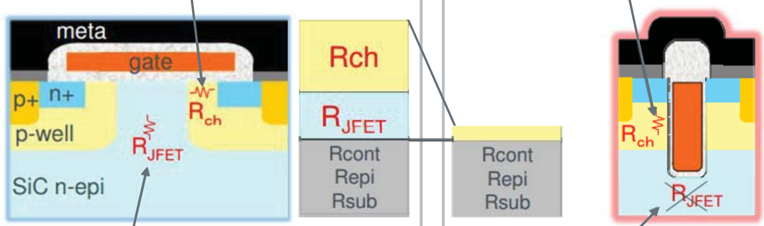
Advantages of SiC Trench MOSFETs

SiC DMOSFET (Planar)

Large R_{ON}
(**Low channel mobility**.)

SiC Trench MOSFET

Lower R_{ON} by high cell density
(**High channel mobility**.)



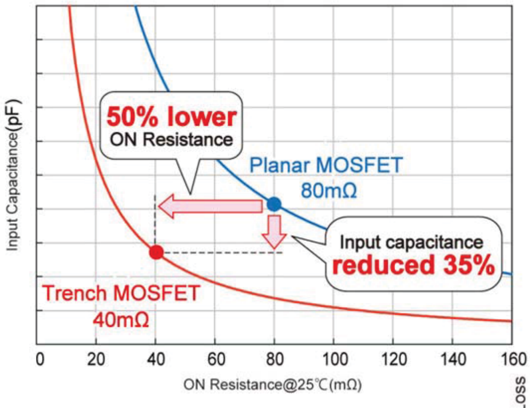
The **JFET resistance** cannot be eliminated from the planar structure.

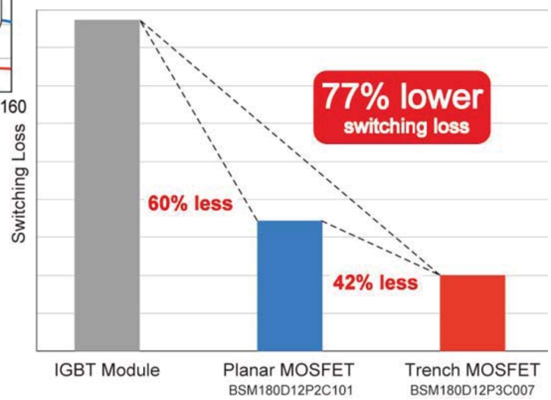
There is **no JFET region** in the trench gate structure.

It is expected that the on-resistance can be drastically reduced with the trench gate structure.

"SiC Products," ROHM Co., Ltd., 2011, http://www.tecnoimprese.it/user/0900_Doc/20121017152721ROHM%20SiC%20Power%20%20Sep%202012.pdf

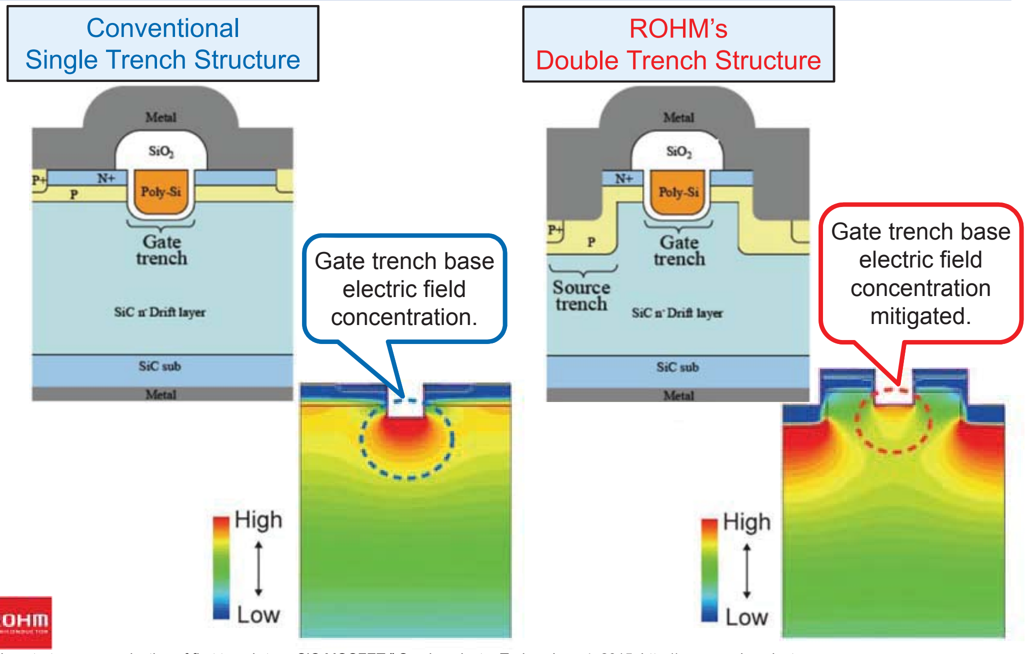
The 1.2 kV double-trench SiC MOSFET shows promising advantages over planar SiC MOSFETs.





"Rohm starts mass production of first trench-type SiC MOSFET," Semiconductor Today, June 4, 2015, http://www.semiconductor-today.com/news_items/2015/jun/rohm_040615.shtml

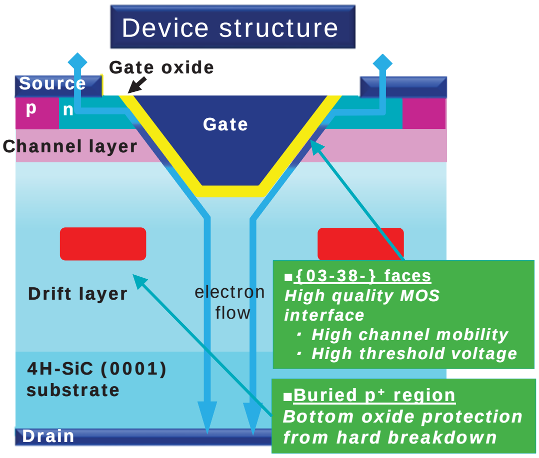
The double-trench structure reduces the electric field at the gate.

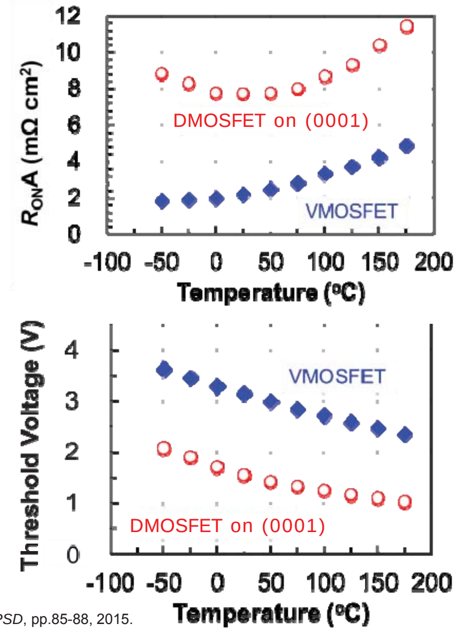


"Rohm starts mass production of first trench-type SiC MOSFET," Semiconductor Today, June 4, 2015, http://www.semiconductor-today.com/news_items/2015/jun/rohm_040615.shtml

1200 V “V-groove” 4H-SiC MOSFET

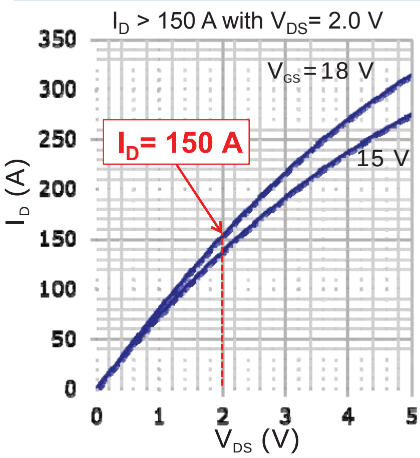
- Unique high-mobility channel
- Lower $R_{DS(on)}$ with high blocking voltage

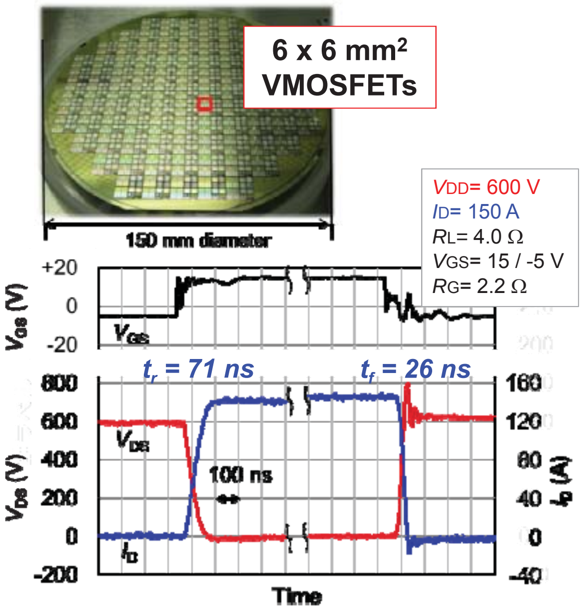




K. Uchida el al., *Proc. of the 27th ISPSD*, pp.85-88, 2015.

I-V Characteristics of 6 x 6 mm² VMOSFET

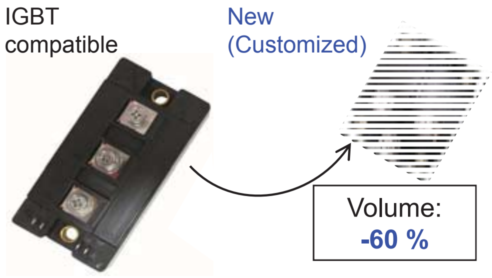


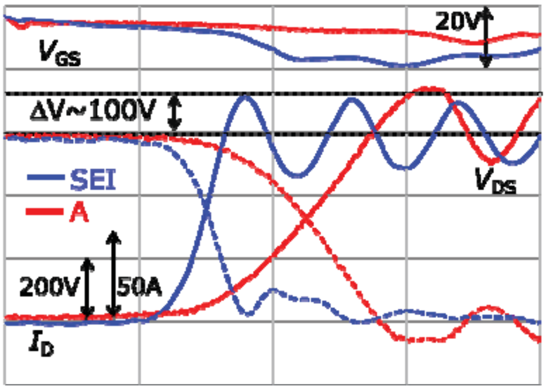


K. Uchida et al., Proc. 2nd Advanced power devices, pp. 36–37, 2015.

Low-Inductance, 2-in-1 Module for 1200 V VMOSFET

Items	SiC MOSFET		Si IGBT
	New	IGBT compatible	
I_D	100 A	100 A	100 A
$R_{DS(on)}$	**12 mΩ**	18 mΩ	(21 mΩ)
$E_{on} + E_{off}$	**1.1 mJ**	4.8 mJ	14.5 mJ





	SiC MOSFET		
	SEI	A	B
R_G	**1.0 Ω**	4.7 Ω	6.7 Ω
t_f	**20 ns**	58 ns	46 ns
$t_{d(off)}$	**59 ns**	79 ns	138 ns
ΔV	100 V	110 V	110 V

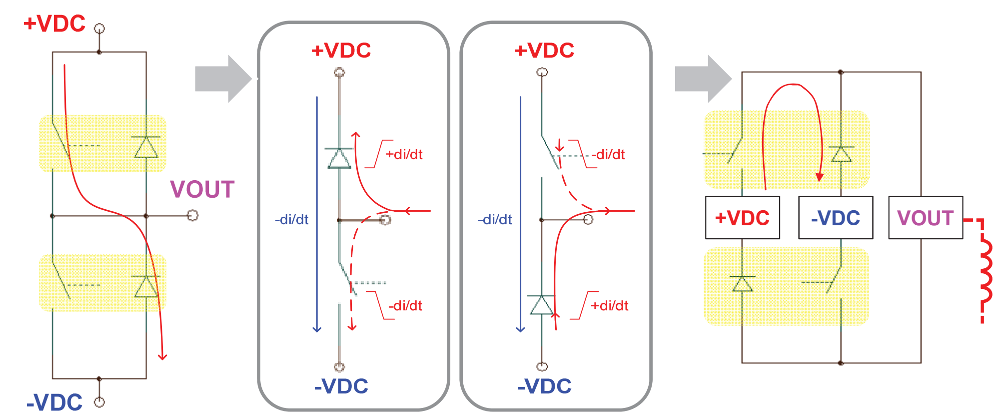
V_{DS}=600 V, I_D=100 A, R_G=1 Ω,
V_{GS}=-5 V/ +15 V, T_j=25 ºC, Resistive mode

S. Toyoshima et al., SEI Technical Review, No.80, pp. 80-84, 2015

SEI Proprietary

Layout Improvement Considerations

Conventional Layout | *Switch Pairs in a Phase-Leg* | *Improved Layout*



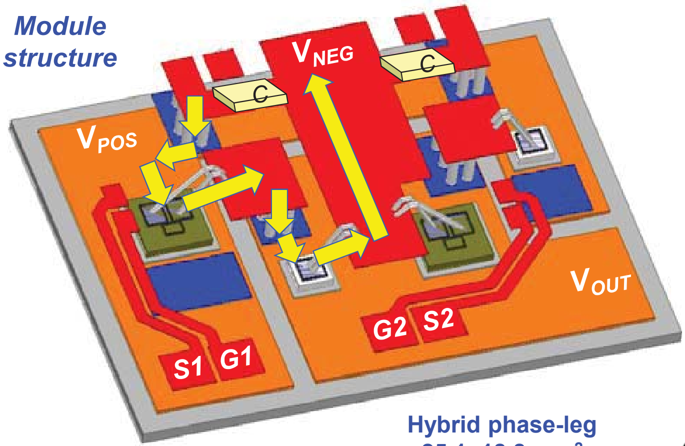
Switching loop handles
the most severe di/dt!

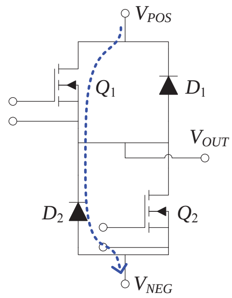
(Z. Chen, 2012)

High-Frequency Hybrid Phase-Leg Module Design

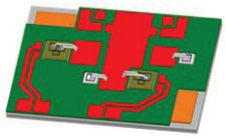
- **1200 V, 10 A SiC DMOSFETs + 1200 V, 5 A SiC SBDs**

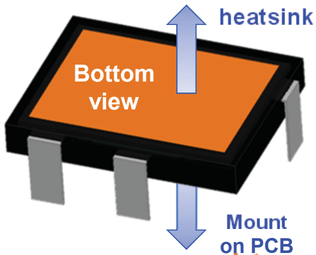
Module structure





Hybrid phase-leg 25.1×18.8 mm²

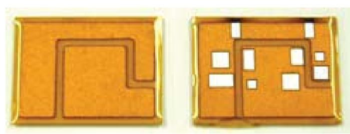




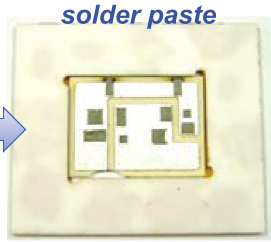
(Z. Chen, 2012)

Fabrication of Hybrid Phase-Leg Module

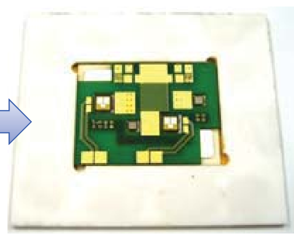
Substrate & stencil preparation



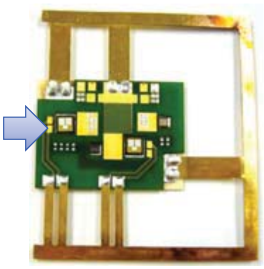
Stencil printing solder paste



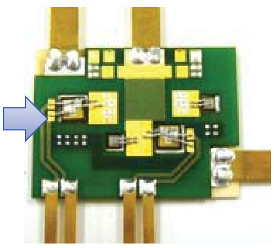
Placing PCB & dice

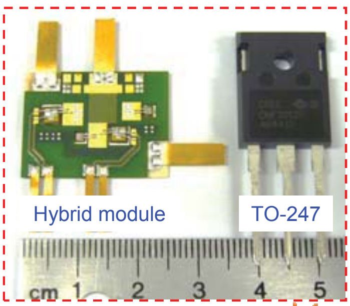


PCB, dice, & leadframe soldering



Wire-bonding

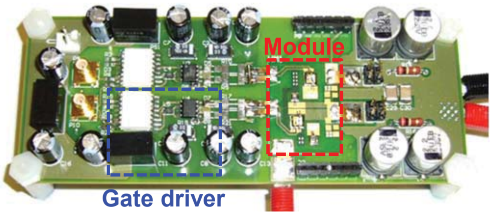




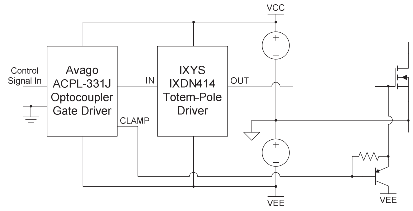
(Z. Chen, 2012)

Switching Performance with R_G = 0 Ω

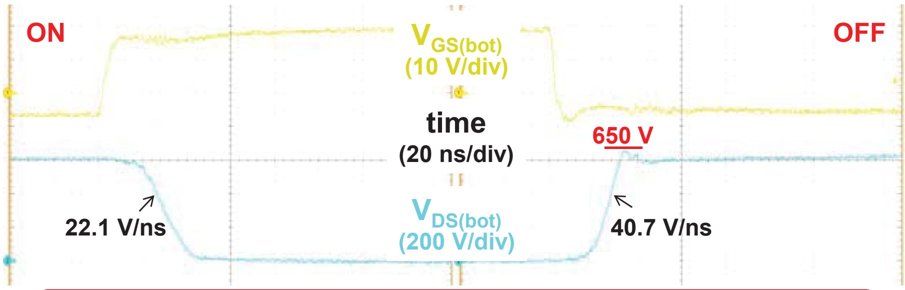
Phase-leg with drivers



MOSFET gate driver



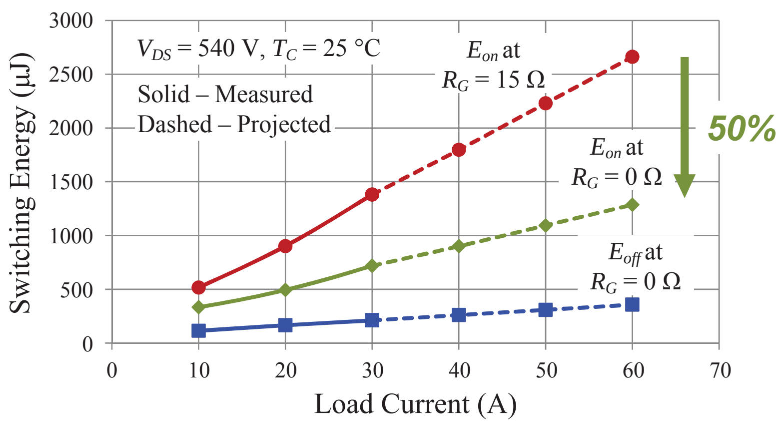
Phase-leg switching waveforms
(Clamped inductive switching at *600 V, 17.4 A*)



Device switching speed limit reached without excessive ringing!

Switching Energies vs. Load Current

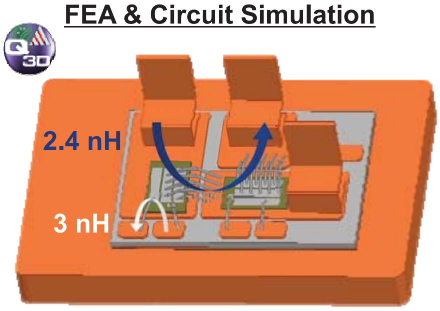
- **Measured at 25 °C**

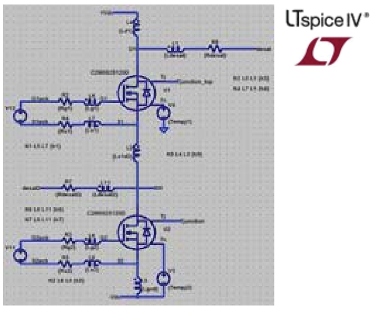


Smaller switching energy can be achieved without compromising to the parasitic ringing.

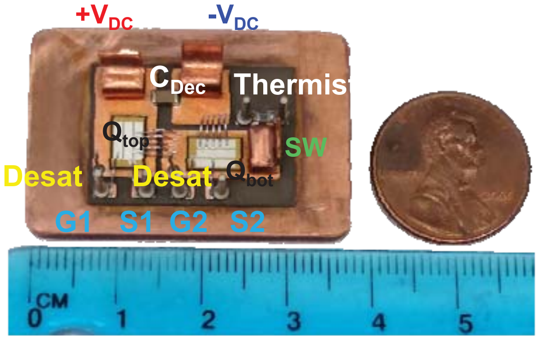
High-Speed, High-Efficiency SiC MOSFET Half-Bridge 1.2 kV, 90 A Power Module

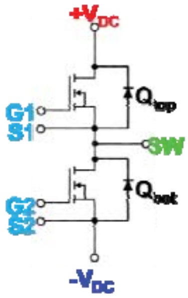
FEA & Circuit Simulation





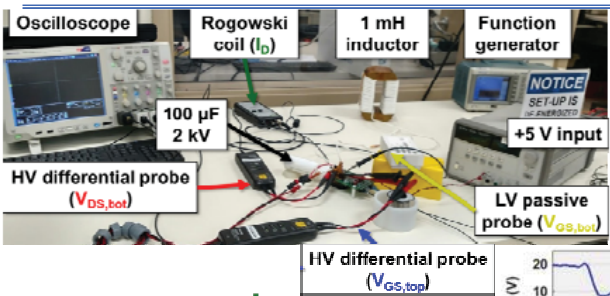
Module Fabrication

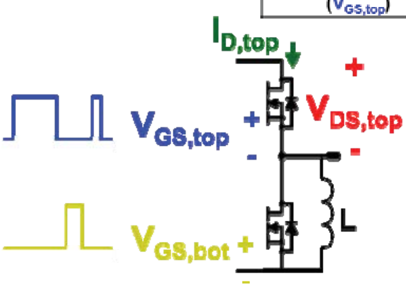




(C. DiMarino, 2015)

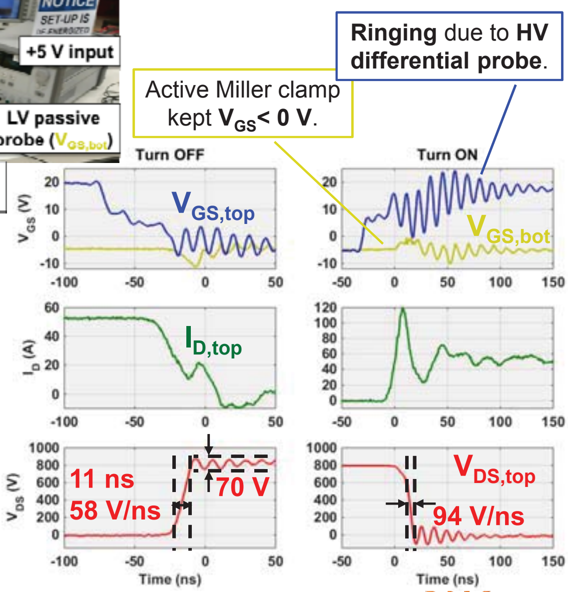
High-Speed, High-Efficiency SiC MOSFET Half-Bridge 1.2 kV, 90 A Power Module





***DPTs** were performed on the **top MOSFET** so that the **Miller effect** could be more accurately observed.*

Double-Pulse Tests at 800 V, 50 A, $R_{G,ext}$= 2.5 Ω



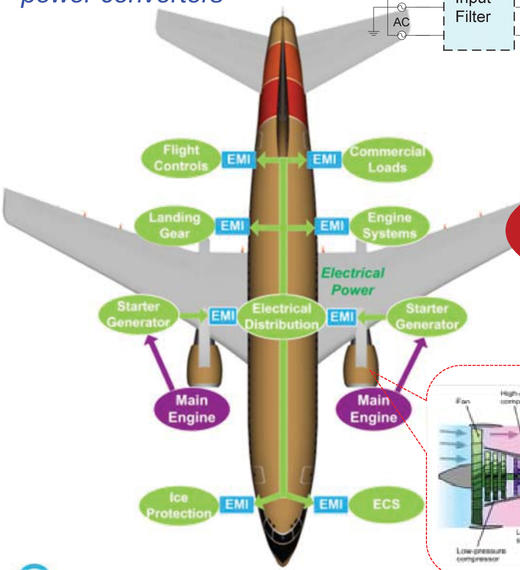
(C. DiMarino, 2015)

Outline

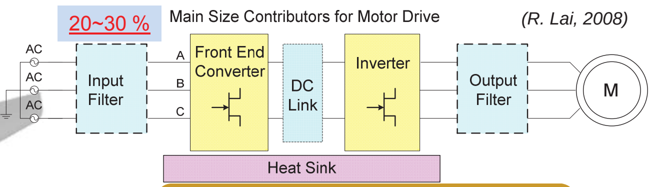
1. Introduction
2. High Frequency and High Efficiency
   – Comparison with Si
   – Characterization of 1.2 kV SiC discrete transistors
3. **High Temperature**
   – **For power density in normal temperature ambient**
   – **For operation in high-temperature ambient**
4. Medium Voltage
5. High Voltage
6. Conclusions
7. References

Demands for High-Power-Density Converters

More Electric Airplanes: Limited space and more power converters



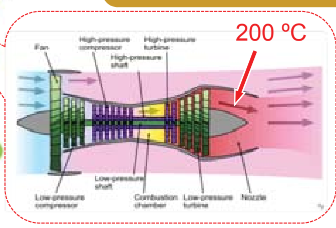
(R. Lai, 2008)

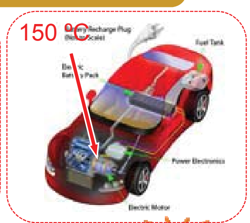


Size & weight restrictions

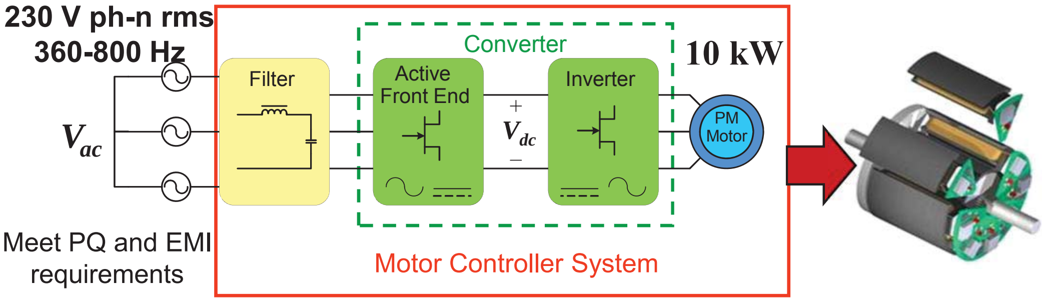
Semiconductor switches of high voltage, high frequency, and high temperature

Harsh environments





High-Power-Density, 10 kW Motor Drive with High-Temperature Modules



Passive cooling with air at 70 °C

Objective:

- **Reduce weight through integration and high-temperature operation**

Targets & Desired Features

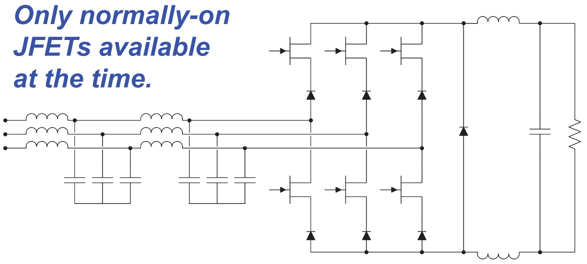
- **Specific power: > 2 kVA/lb**
- **Device junction temperature 200-300 °C with SiC devices**
- **Advanced topologies**
- **Reduced filter size**

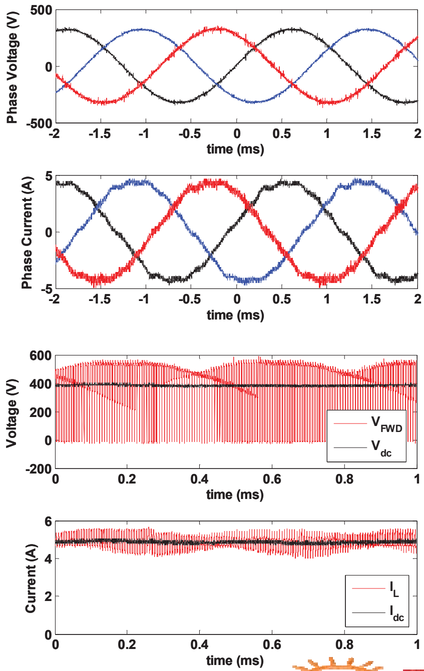
SiC Devices

	Device	Advantages	Disadvantages	Voltage Rating
Unipolar	DMOSFET	Scalable	MOS Interface	0.4 kV – 15 kV
Unipolar	Trench MOSFET	High V_{TH}, Low R_{ON}	High Electric Field	0.6 kV – 1.2 kV
Unipolar	**Normally-On JFET**	**High Temp.**	**Normally-On**	**1.2 kV – 6.5 kV**
Unipolar	Normally-Off JFET	Normally-Off	High R_{ON}	1.2 kV – 6.5 kV
Bipolar	BJT	No Gate Oxide	Current Driven	1.2 kV – 10 kV
Bipolar	IGBT	High Voltage	Reliability	15 kV – 27 kV
Bipolar	GTO	Low Conduction Loss	Difficult Control	> 8 kV
	Schottky Diode	No Reverse Recovery	High Leakage	0.1 kV – 8 kV
	JBS Diode	Low Leakage	High Forward Voltage	0.65 kV – 10 kV
	PiN Diode	Forward Voltage	Degradation	10 kV

Three-Phase SiC Buck Rectifier using Normally-On JFETs and Switching at 150 kHz

Only normally-on JFETs available at the time.



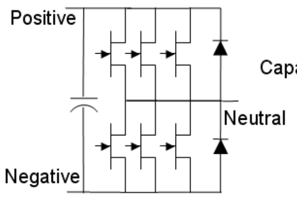


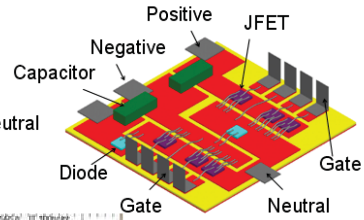
- Efficiency below 95 %
- DC link inductor very heavy

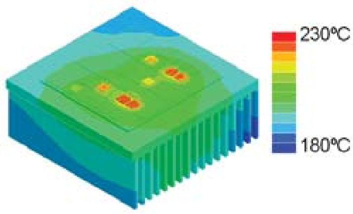
High-Temperature Wire-Bond Power Module Design

– Minimize structural impedances
– Maximize thermal performance
– Reduce footprint

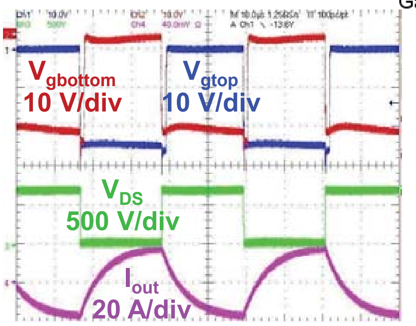
6x SiC JFETs
2x SiC diodes







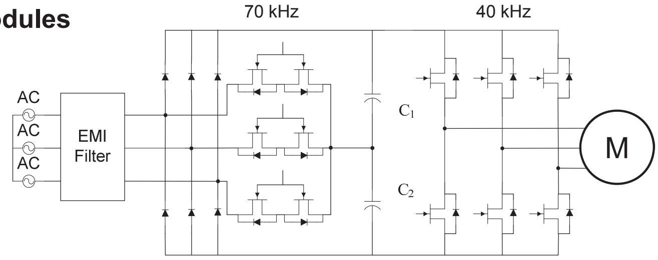
FEA thermal simulation



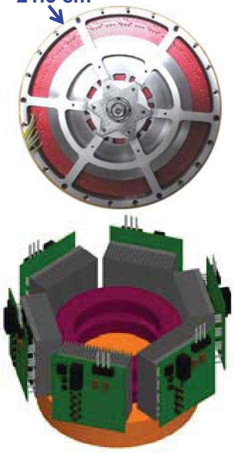
Continuous operation at 250 ºC

High-Power-Density, 10 kW Motor Drive with High-Temperature Modules

- High-temperature SiC modules
- Sensorless control
- Soft start
- Fan load application



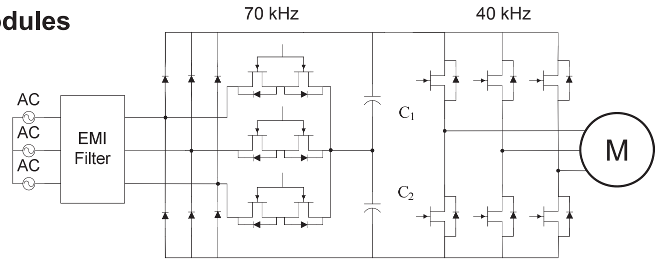
Ø = 21.5 cm



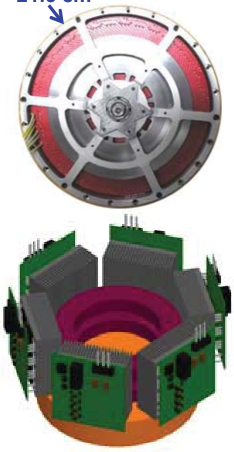
175 ºC Converter

High-Power-Density, 10 kW Motor Drive with High-Temperature Modules

- High-temperature SiC modules
- Sensorless control
- Soft start
- Fan load application



Ø = 21.5 cm

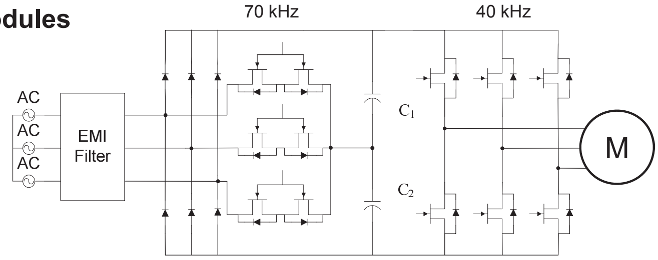


175 ºC Converter

250 ºC Converter

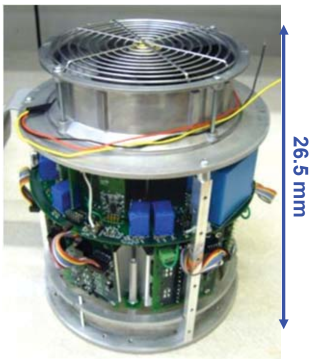
High-Power-Density, 10 kW Motor Drive with High-Temperature Modules

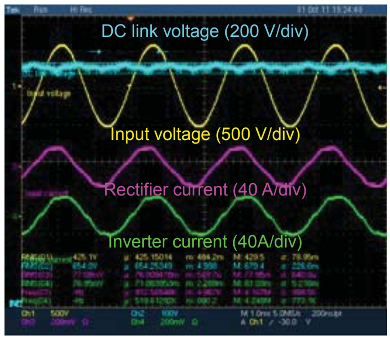
- High-temperature SiC modules
- Sensorless control
- Soft start
- Fan load application



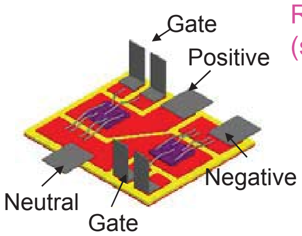
Ø = 21.5 cm

Power Density:
- Low-temperature 1.04 kW/lb
- High-temperature 1.27 kW/lb
- Thermal management is 50% smaller for HT

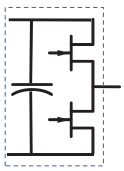


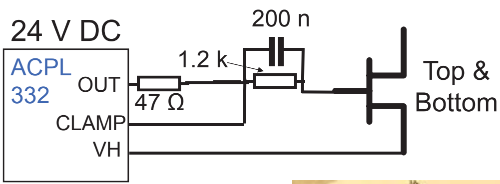


Improved SiC JFET Power Module



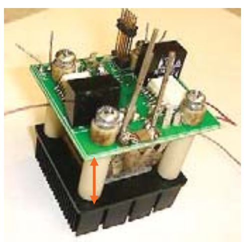
Reverse conduction (synchronous rectification)



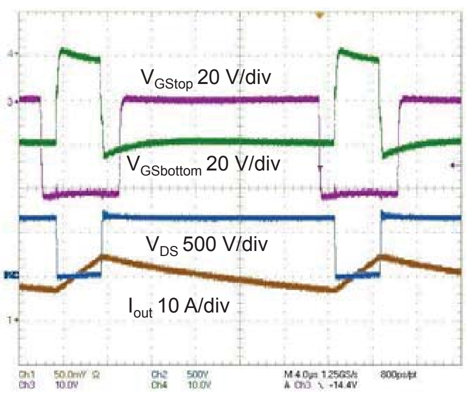


Gate Drive

Temperature isolation



Test condition
Input voltage: 700 V
Duty cycle: 15.7%
Output current: 11 A (rms)
Switching frequency: 40 kHz
Junction temperature 250 ºC

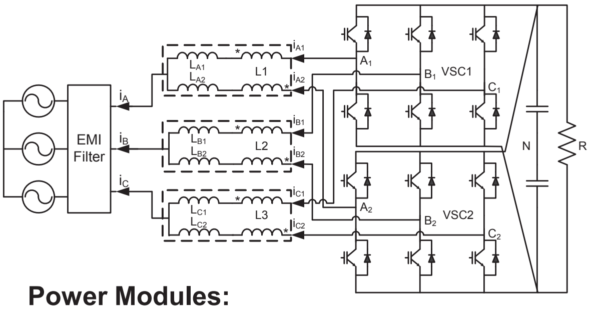


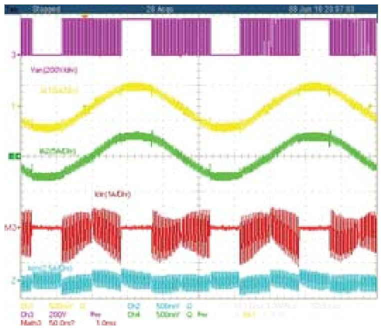
Time 4 μs/div

Turn on/off time: 60 ns

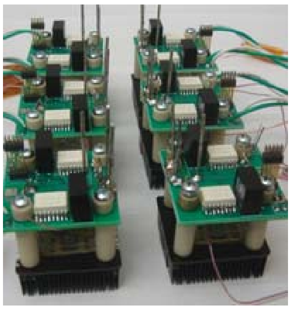
Interleaved High Power Density AFE Converter

(15 kW, SiC, 2 Parallel Interleaved 3-phase Boost Rectifiers)





Power Modules:

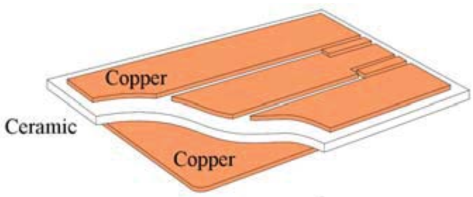


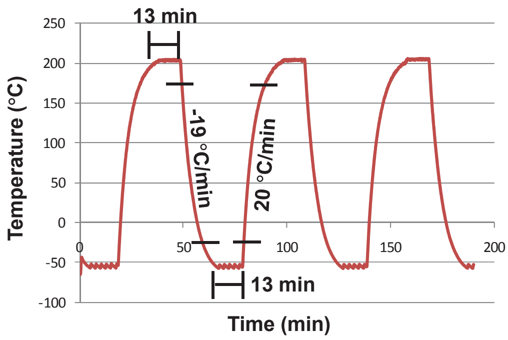
EMI Filter

15 kW @ 6.3 kW/l with θ_{jmax} = 250 ºC

Reliability of Direct-Bond-Copper (DBC) Substrate

Reliability of DBC substrate in thermal cycling between -55ºC and 200ºC

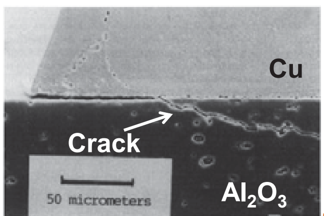




- **DBC substrate fails in < 20 cycles**

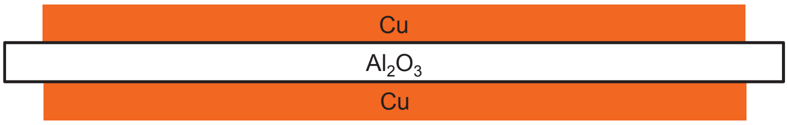
Before temperature cycling

After temperature cycling



Reliability of Direct-Bond-Copper (DBC) Substrate

Reliability of DBC substrate in thermal cycling between -55ºC and 200ºC



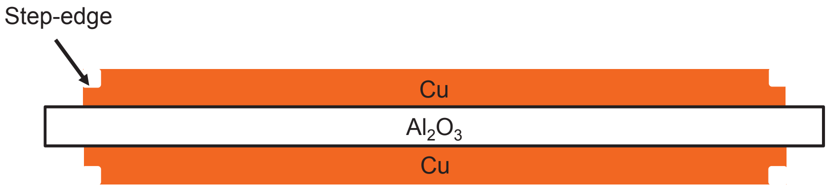
Direct-Bond-Copper Substrate

- **DBC substrate fails in** **< 20 cycles**

Reliability of Direct-Bond-Copper (DBC) Substrate

Reliability of DBC substrate in thermal cycling between -55ºC and 200ºC

❖ Creating stepped edges



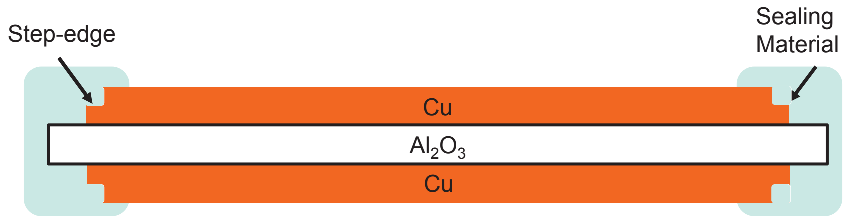
Direct-Bond-Copper Substrate

- **DBC substrate fails in** **< 20 cycles**
- **With stepped-edge fails in** **~ 100 cycles**

Reliability of Direct-Bond-Copper (DBC) Substrate

Reliability of DBC substrate in thermal cycling between -55ºC and 200ºC

❖ Creating stepped edges ❖ Applying sealing material



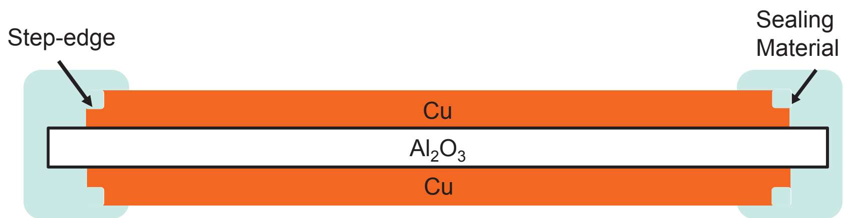
Direct-Bond-Copper Substrate

• **DBC substrate fails in**	**< 20 cycles**
• **With stepped-edge fails in**	**~ 100 cycles**
• **With stepped-edge and Parylene HT sealant fails in**	**~ 300 cycles**
• **With stepped-edge and Nysil sealant fails in**	**~ 1200 cycles**

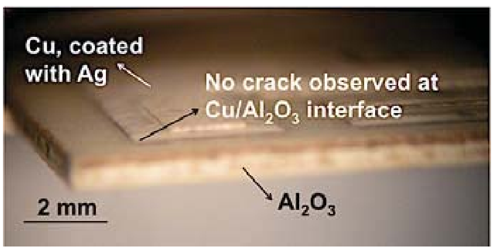
Reliability of Direct-Bond-Copper (DBC) Substrate

Reliability of DBC substrate in thermal cycling between -55ºC and 200ºC

❖ Creating stepped edges ❖ Applying sealing material

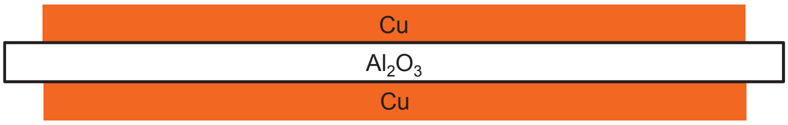


Direct-Bond-Copper Substrate



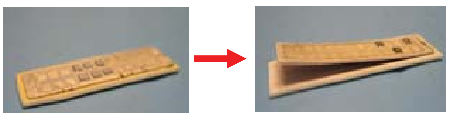
Reliability of Direct-Bond-Copper (DBC) Substrate

Reliability of DBC substrate in thermal cycling between -55ºC and 200ºC

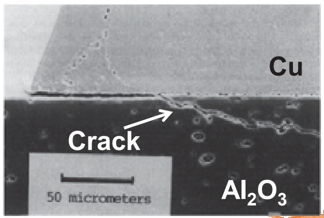


Direct-Bond-Copper Substrate

- **DBC substrate fails in < 20 cycles**



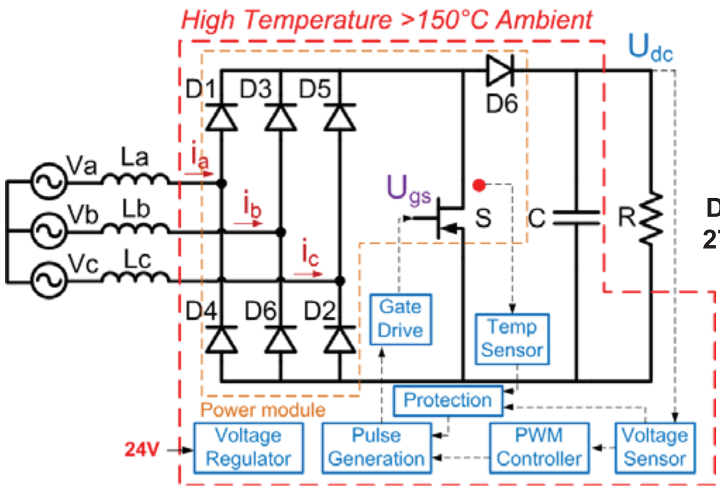
Before temperature cycling **After temperature cycling**



High-Temperature Single-Switch Three-Phase Rectifier

Targets:
- **Junction temperature up to 250 °C.**
- **Ambient temperature over 15 0°C.**

AC input: 100 V, 400 Hz



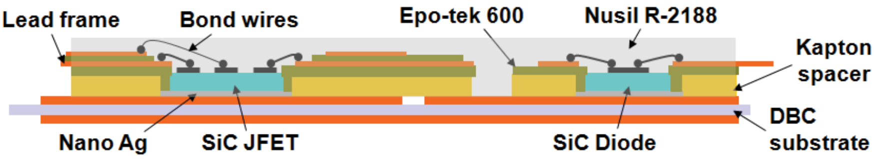
DC output: 270 V, 1 kW

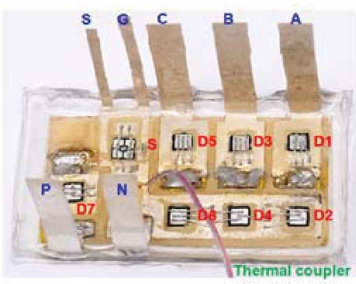
30 kHz Switching Frequency

Component Selection

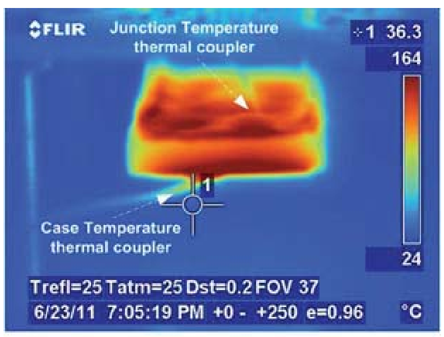
- Power devices
  - 1200 V, 10 A SiC JFET from SiCed
  - 600 V, 10 A SiC Schottky diode from Cree
- Controller devices
  - SOI discrete devices from Honeywell, Cissoid
- Passive components
  - Nanocrystalline core and High temperature wire
  - Film resistor from Caddock, Vishey,…
  - Ceramic capacitor from Novacap, Kemet, Eurofarad,…
- PCB
  - Polyimide pcb from 4PCB, Standard Printed Circuits Inc, …

Modified Hybrid Packaging Structure





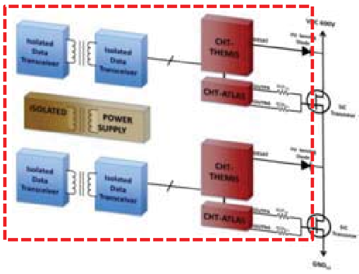
Multiple chip Hybrid Power Module



Power module thermal test

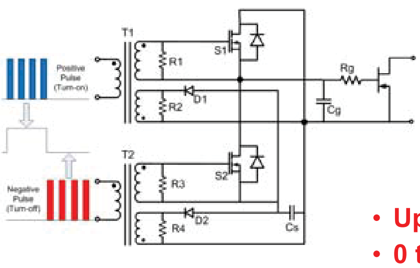
High-Temperature Gate Drivers

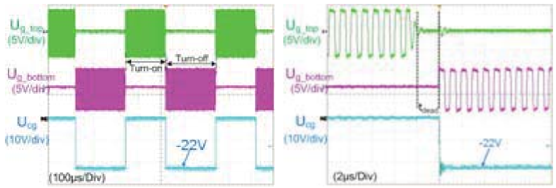
SOI-based half-bridge gate driver for SiC MOSFETs by Cissoid



- Up to 225 °C
- Drive 1.2 kV MOSFETs / JFETs
- 4 A max. I_G
- UVLO & de-sat protections
- Active Miller clamp

High-freq. modulation SiC JFET driver by Univ. Buffalo



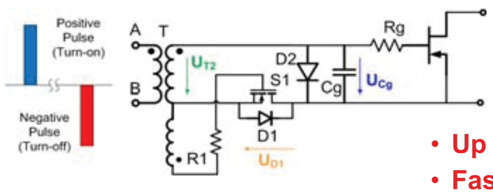


- Up to 250 °C
- 0 to 100% duty cycle
- High driving speed

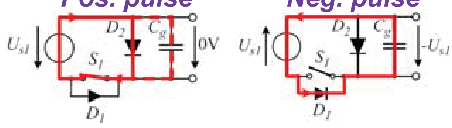
- Complex topology
- Limited duty cycle resolution

High-Temperature Gate Drivers (Cont'd)

Edge-triggered SiC JFET driver by ETH



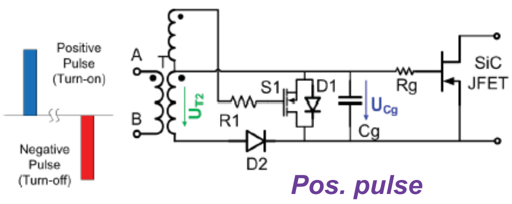
Pos. pulse *Neg. pulse*



- Up to 200 °C
- Fast switching
- Small part count

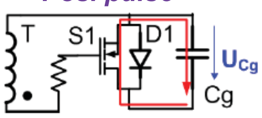
- Need refreshing
- Same on/off driving speed

Modified edge-triggered SiC JFET driver by CPES

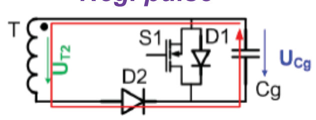


- Same features as above
- Independent on/off driving speed

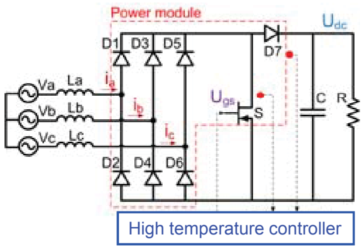
Pos. pulse



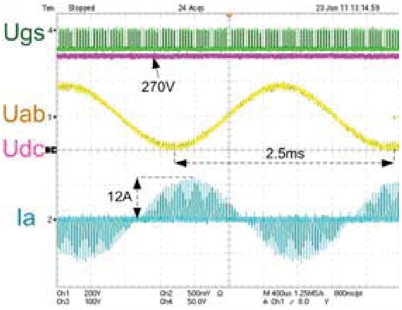
Neg. pulse



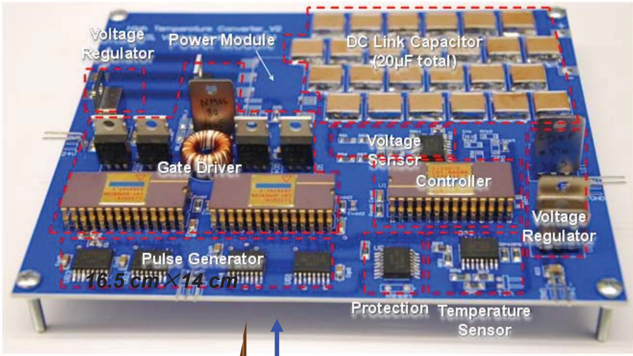
Integration of High-Temperature Three-Phase Rectifier

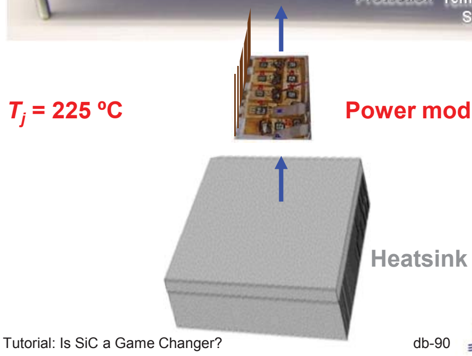


Electrical test

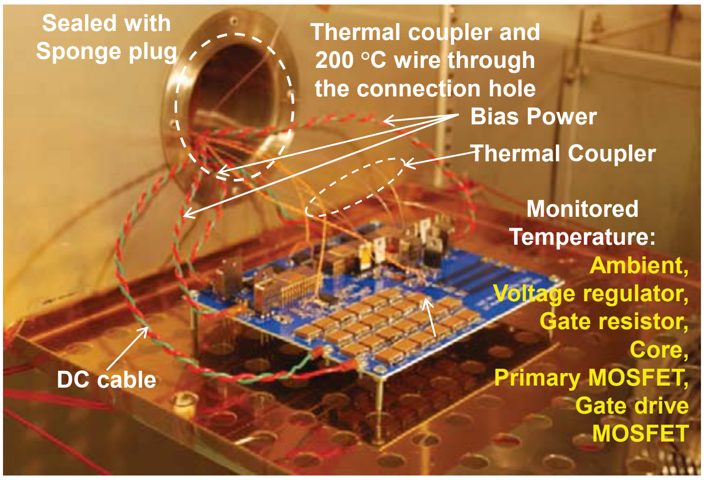


Mother board (driver, sensor, etc.)

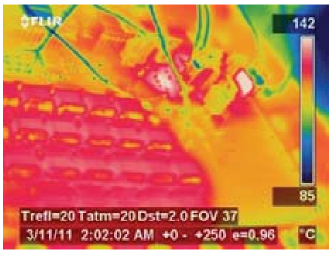


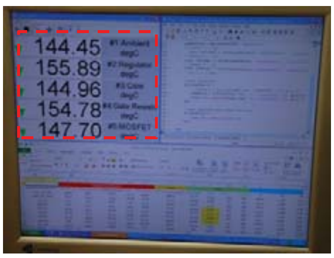


Converter Thermal Testing



Ambient temperature test point:
-50 °C, -25 °C, 0 °C, 25 °C, 50 °C, 75 °C, 100 °C, 125 °C, 150 °C





Test Picture for 150 °C Ambient Temperature

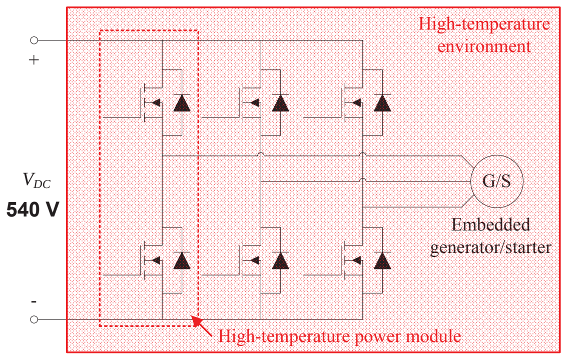
Electrical and thermal performance met design targets.
Ceramic capacitors and their attach to PCB exhibited early failures.

SiC Devices

	Device	Advantages	Disadvantages	Voltage Rating
Unipolar	**DMOSFET**	**Scalable**	**MOS Interface**	**0.4 kV – 15 kV**
Unipolar	Trench MOSFET	High V_{TH}, Low R_{ON}	High Electric Field	0.6 kV – 1.2 kV
Unipolar	Normally-On JFET	High Temp.	Normally-On	1.2 kV – 6.5 kV
Unipolar	Normally-Off JFET	Normally-Off	High R_{ON}	1.2 kV – 6.5 kV
Bipolar	BJT	No Gate Oxide	Current Driven	1.2 kV – 10 kV
Bipolar	IGBT	High Voltage	Reliability	15 kV – 27 kV
Bipolar	GTO	Low Conduction Loss	Difficult Control	> 8 kV
	Schottky Diode	No Reverse Recovery	High Leakage	0.1 kV – 8 kV
	JBS Diode	Low Leakage	High Forward Voltage	0.65 kV – 10 kV
	PiN Diode	Forward Voltage	Degradation	10 kV

High-Temperature 3-Phase AC-DC Converter for Embedded Generators in MEA

Target:
- *50 kW inverter/rectifier for starter/generator*
- *High-temperature and high-power-density*
- *Ambient temperature: 200 – 250 °C*
- *Switching frequency: 70 kHz*



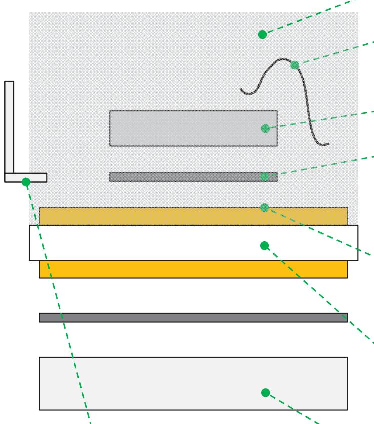
Commercial products (1200 V, 100 A)

Powerex SiC MOSFET module (2012) 150 °C

Cree SiC MOSFET module (2013) 125 °C

Need a power module capable of both high-temperature & high-frequency operations!

High-Temperature Packaging Materials Used

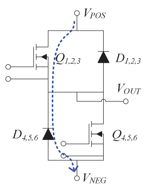


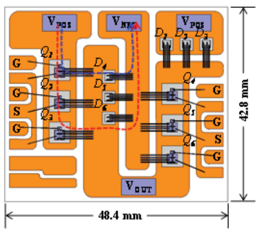
- Encapsulant (*NuSil R-2188 silicone*)
- Bonding wire (*Al*)
  - ~15 A for a 10 mil wire
- SiC MOSFET/diode
- Solder (*Pb95-Sn5*)
  - Liquidus point 312 °C
  - Better solderability on Ni surface
- Surface plating (*Electro-less Ni*)
  - Works best with Al wire-bonding
  - Up to 300 °C
- Substrate (*AlN DBC*)
  - High thermal conductivity
  - Best overall performance
- Baseplate (*AlSiC*)
- Terminals (*Ni-plated Cu*)

High-temperature capability of the material;
Suitable combinations of materials to achieve higher reliability

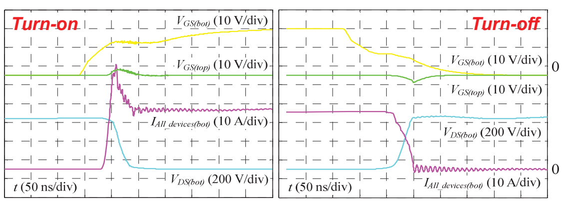
1200 V, 60 A SiC Phase-Leg Module Design

Improved substrate layout to minimize loop inductances





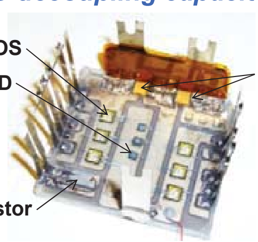
Fast & clean switching



Hard switching w/ $R_G = 0\ \Omega$
Fast di/dt & dv/dt with small V_{DS} overshoot

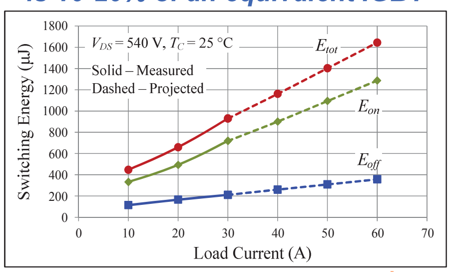
Fabricated module with DC decoupling capacitors

SiC MOS
SiC SBD
HT ceramic caps



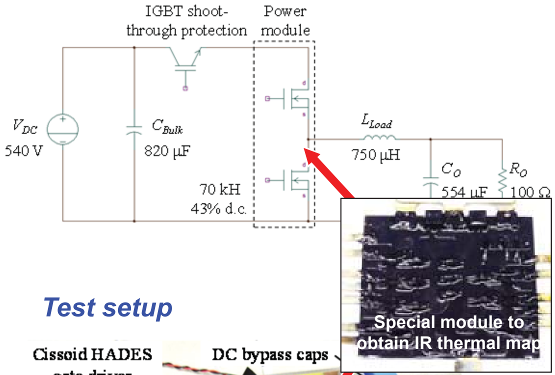
Thermistor

Switching Loss is 10-20% of an equivalent IGBT

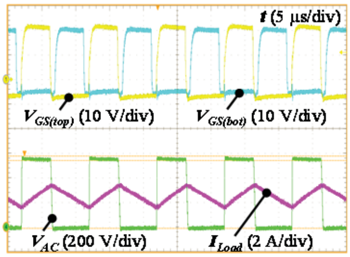


200 °C, 1200 V, 60 A SiC Phase-Leg Module: Continuous Operation at 200 °C

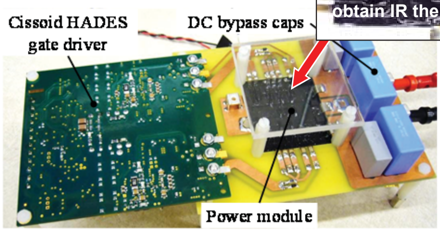
Buck-mode operation

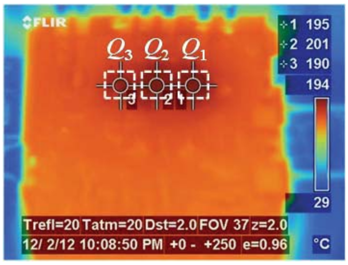


Test results at 560 V & 100 kHz



Test setup

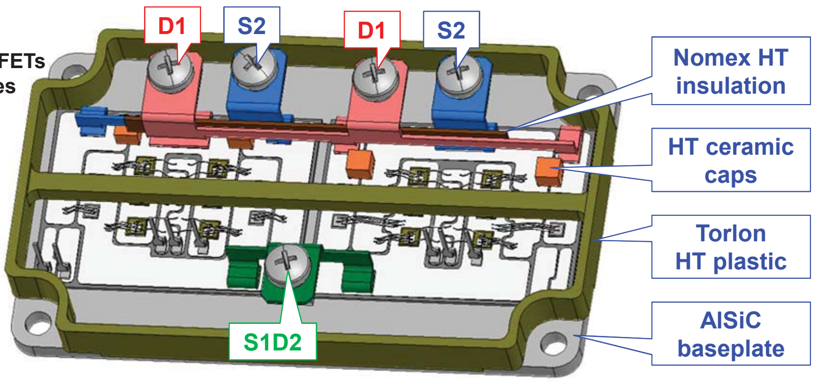




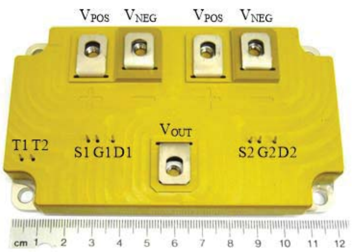
200 °C, 1200 V, 120 A SiC Phase-Leg Module: Module Design

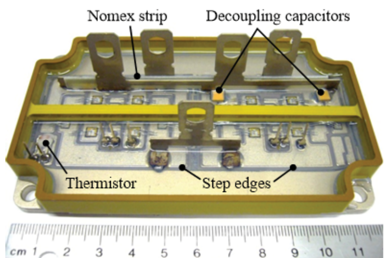
Each switch:
6x 20 A MOSFETs
4x 20 A diodes

L: 119 mm
W: 69 mm
H: 19 mm

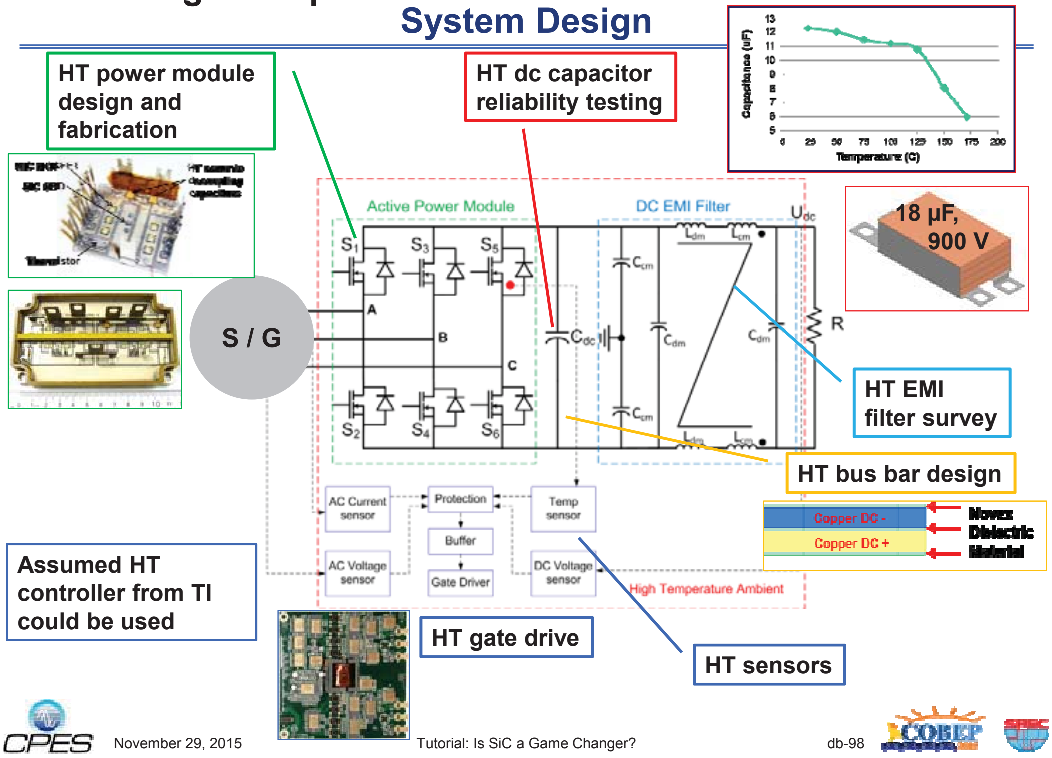


Fabricated module

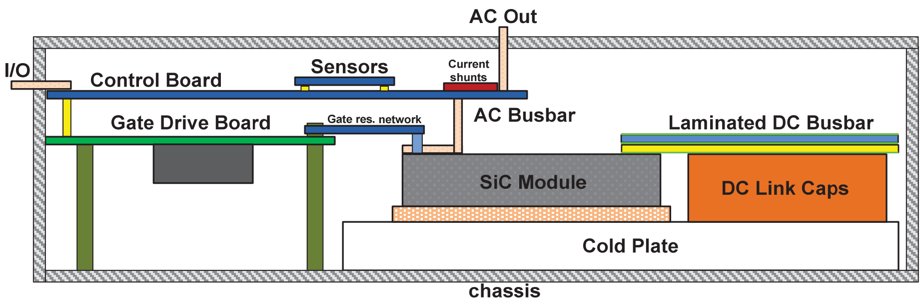


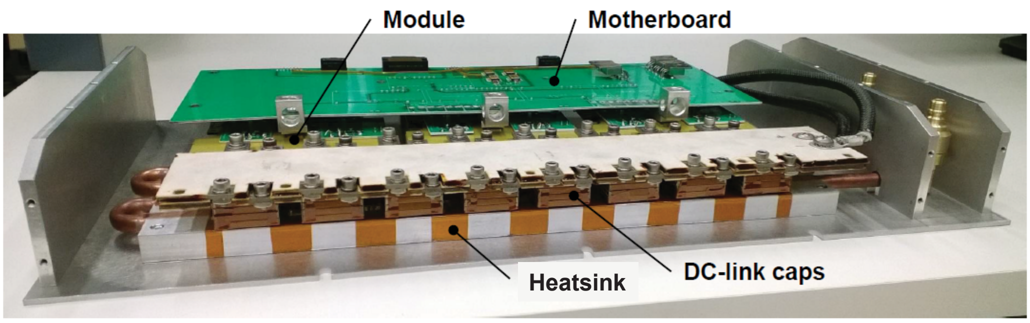


High-Temperature 3-Phase AC-DC Converter: System Design

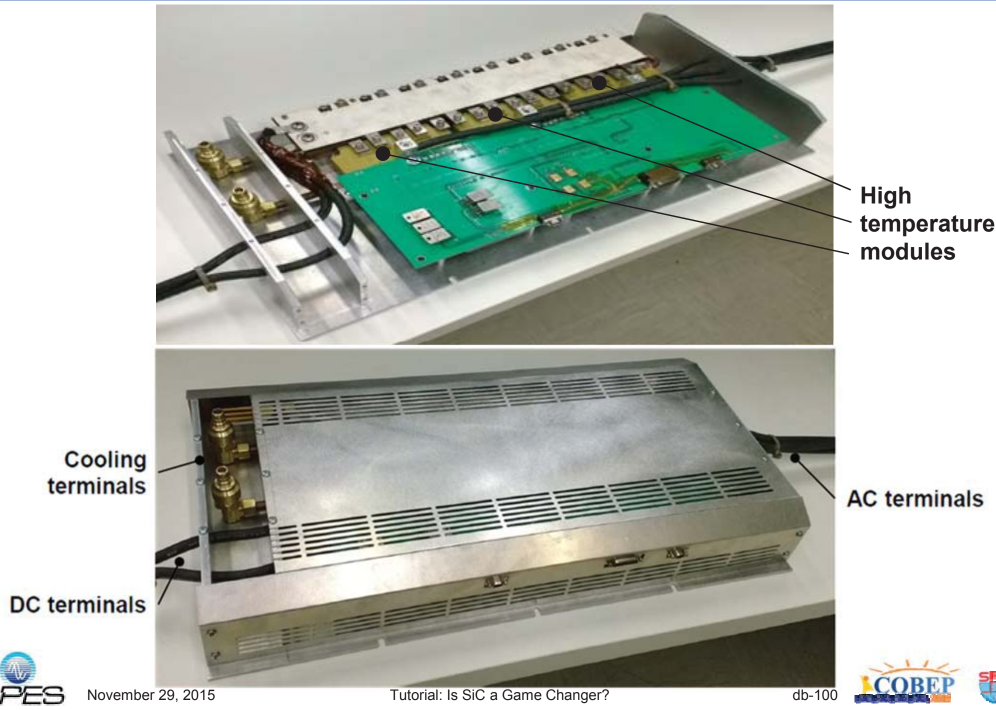


High-Temperature 3-Phase AC-DC Converter: Converter Layout

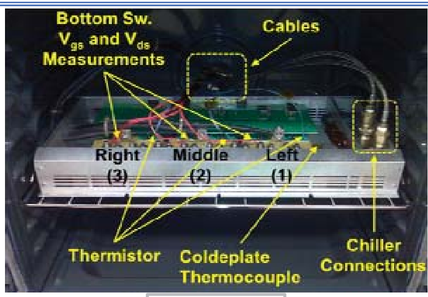




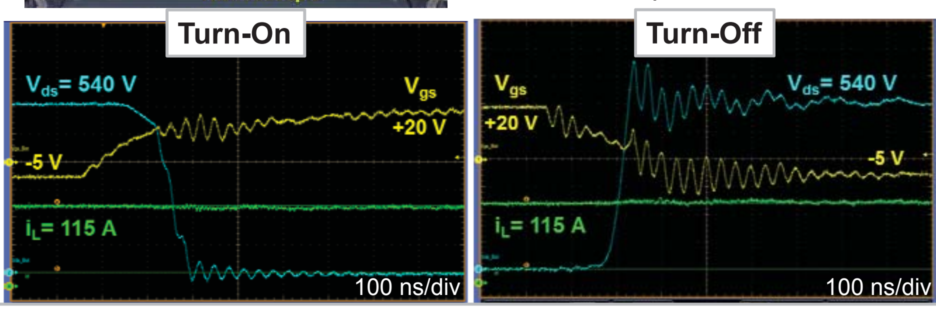
High-Temperature 3-Phase AC-DC Converter: Converter Layout



High-Temperature 3-Phase AC-DC Converter: Converter Double-Pulse Tests at 200 ºC



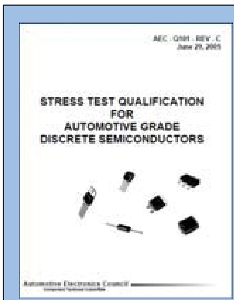
- ***200 ºC ambient***
- $R_{G,on}$ and $R_{G,off}$: 3.3 Ω
- Liquid cooling temperature: 70 ºC
- Protection:
  - over-voltage
  - over-current
  - over-temperature



Ringing due to the use of **long wires** to measure outside of the high-temperature environment. Testing at room-temperature with the probes directly on the modules showed little ringing.

SiC DMOSFETs Qualified at 200 ºC

1.2 kV, 30 A TO-247 part qualified per AEC-Q101.



Pass/fail criteria:

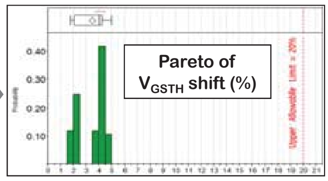
- DV_{TH}= +/-20 % Max
- DR_{ON}= +/-20 % Max
- $DI_{DSS,1200}$ < 5x Max

⋮

→ **0/77 failures**

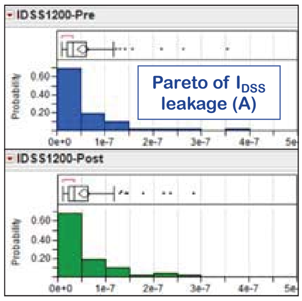
HTGB: 1000 hr, 200 ˚C, V_{GS}=23 V

✔ **passed**



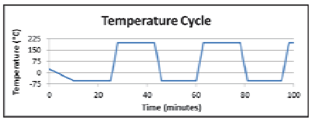
HTRB: 1000 hr, 200 ˚C, V_{DS}=960 V

✔ **passed**



1000 temp. cycles (-55 to +200 ˚C)

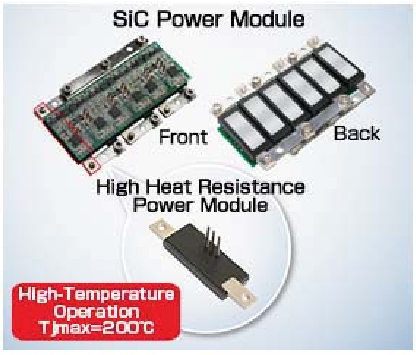
✔ **passed**



P. Losee, et al., "1.2kV class SiC MOSFETs with improved performance over wide operating temperature," IEEE ISPSD, pp. 297-300, 2014.

600 V, 600 A, T_J= 200 ºC SiC Trench MOSFET Module for 3-Phase Motor Drive

- **1/10th the volume** of conventional Si power modules
- Ultra-compact **600 V, 600 A** drive
- Ultra-high efficiency! Less than **half the loss** of existing products
- Ideal for **60 kW-class motors**
- High temperature operation (**T_{jmax}= 200 ºC**)



http://www.rohm.com/web/global/intelligent-high-heat-resistance-power-module

Outline

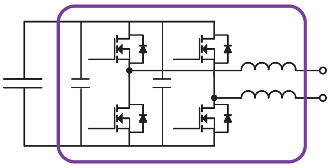
1. Introduction
2. High Frequency and High Efficiency
   – Comparison with Si
   – Characterization of 1.2 kV SiC discrete transistors
3. High Temperature
   – For power density in normal temperature ambient
   – For operation in high-temperature ambient
4. **Medium Voltage**
5. High Voltage
6. Conclusions
7. References

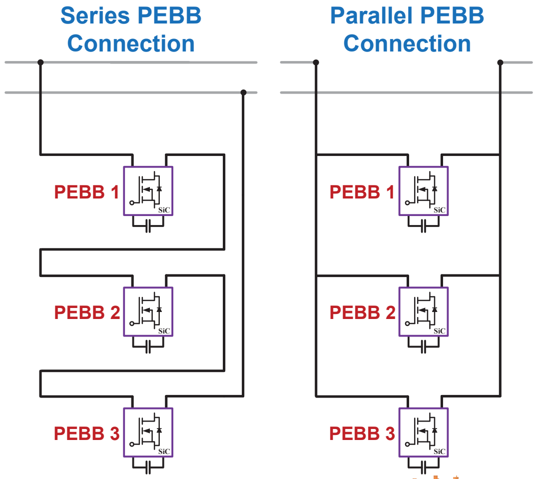
SiC Devices

	Device	Advantages	Disadvantages	Voltage Rating
Unipolar	**DMOSFET**	**Scalable**	**MOS Interface**	**0.4 kV – 15 kV**
Unipolar	Trench MOSFET	High V_{TH}, Low R_{ON}	High Electric Field	0.6 kV – 1.2 kV
Unipolar	Normally-On JFET	High Temp.	Normally-On	1.2 kV – 6.5 kV
Unipolar	Normally-Off JFET	Normally-Off	High R_{ON}	1.2 kV – 6.5 kV
Bipolar	BJT	No Gate Oxide	Current Driven	1.2 kV – 10 kV
Bipolar	IGBT	High Voltage	Reliability	15 kV – 27 kV
Bipolar	GTO	Low Conduction Loss	Difficult Control	> 8 kV
	Schottky Diode	No Reverse Recovery	High Leakage	0.1 kV – 8 kV
	JBS Diode	Low Leakage	High Forward Voltage	0.65 kV – 10 kV
	PiN Diode	Forward Voltage	Degradation	10 kV

SiC H-Bridge Modules
Power Electronics Building Block (PEBB)

- Concept: **Integration of fundamental components into blocks** with defined functionality that can be used in a variety of applications.
- Motivation: The **versatility** reduces the cost, size, weight, loss, design complexity, installation, and maintenance of power electronic systems.

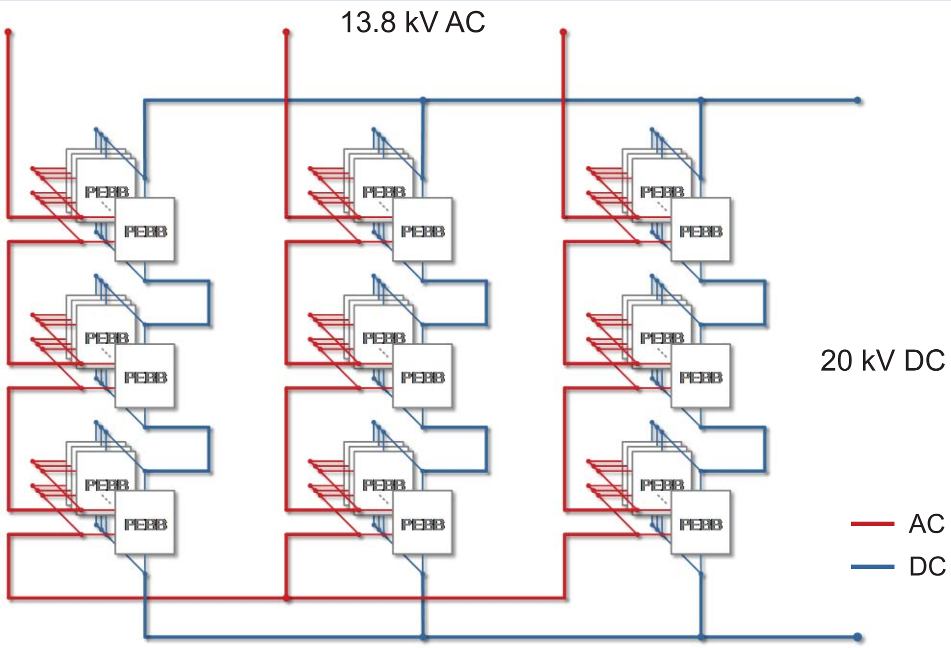




PEBB 1000

1.7 kV **SiC MOS**

Ex: 35 MW 3-phase AC to DC Power Converter for Bidirectional MV Motor Drive or Grid-Interface

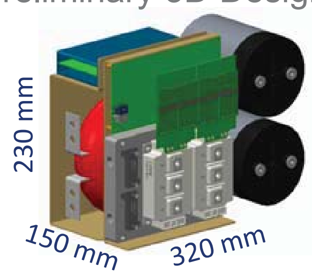


PEBB 1000 Design and Applications

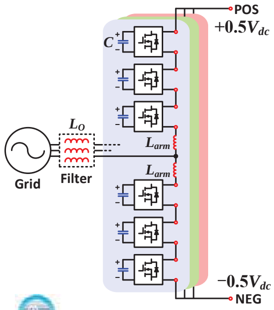
Specifications

- 1 kV dc, 200 A dc, 200 kW
- Power density > 10 MW/m^3
- High dv/dt slew rate immunity > 100 V/ns
- High efficiency > 98 %
- EMI containment
- Insulation > 100 kV
- **Modular distributed digital control system**

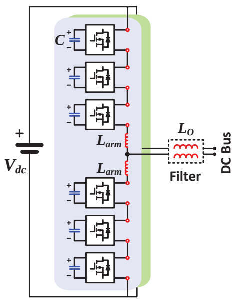
Preliminary 3D Design



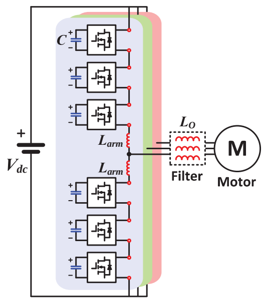
Active Front-End



DC-DC



Motor Drive



3M 3Φ Stack

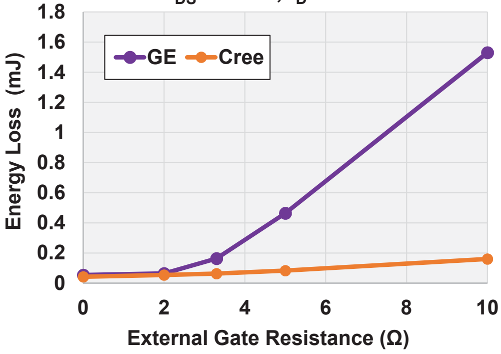
SiC MOSFET Candidates

	GE*		Cree	
Part No.	Not Commercial		CAS300M17BM2 (Commercial)	
Voltage Rating	1500 V		1700 V	
Current Rating	400 A @ T_j=25 °C		325 A @ T_j=25 °C, 225 A @ T_j=90 °C,	
$R_{DS(on)}$	8.3 mΩ @ V_{GS}=20 V, I_{DS}=240 A		8.0 mΩ @ V_{GS}=20 V, I_{DS}=225 A	
E_{ON}	11.1 mJ	@ V_{DS}=800 V, V_{GS}=-5/+20 V, I_{DS}=300 A, R_{G_ex}=1.9 Ω, T_j=25°C	9.56 mJ	@ V_{DS}=800 V, V_{GS}=-5/+20 V, I_{DS}=300 A, R_{G_ex}=1.9 Ω, T_j=25°C
E_{OFF}	9.3 mJ		9.42 mJ	
T_{j_max}	175 °C		150 °C	
C_{oss}	2.151 nF (800 V)		3.954 nF (800 V)	

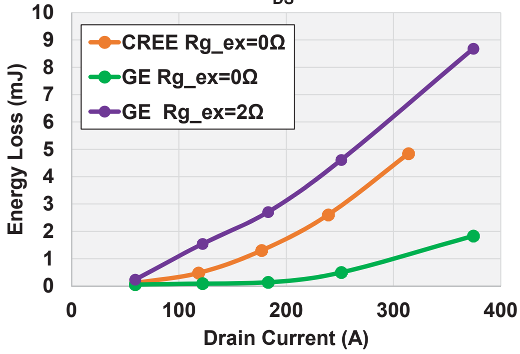
*1st generation

Device Comparison: Turn off Energy

Turn-off Loss vs. External Gate Resistance at V_{DS}= 800 V, I_D= 30 A

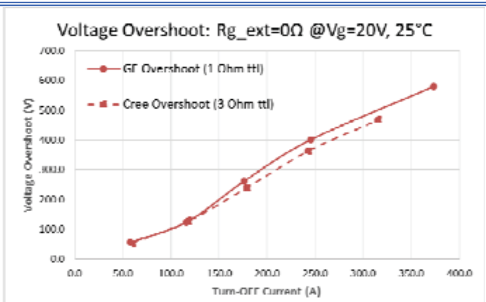


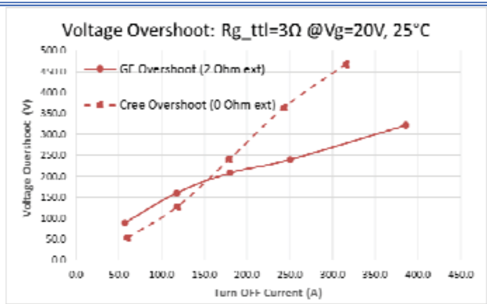
Turn-off Loss vs. Drain Current at V_{DS}= 800 V

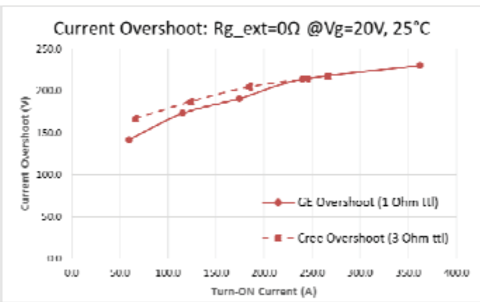


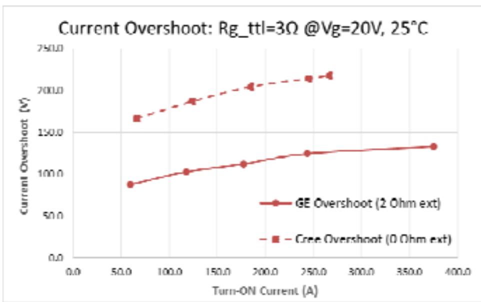
- At ***low*** R_{g_ex}, the **turn-off losses** are ***similar***
- At ***high*** R_{g_ex}, the **GE** module has ***higher*** **turn-off loss**
- At R_{g_ex} **= 0 Ω**, the Cree module has *higher* turn-off loss
- At **same *total*** R_g, the GE module has *higher* turn-off loss

Device Comparison: Overvoltage and Overcurrent



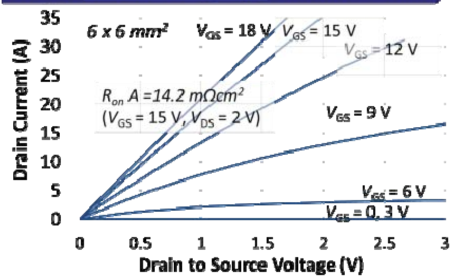




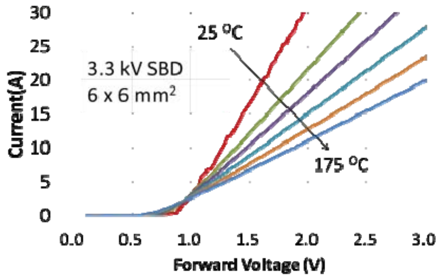


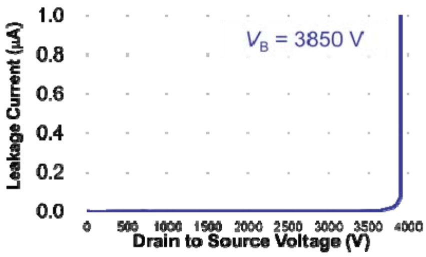
Characteristics of Discrete 3.3 kV SiC Devices

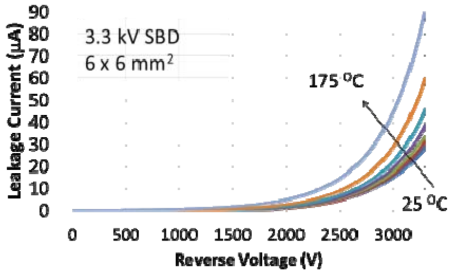
3.3 kV DMOSFET I-V characteristics



3.3 kV SBD I-V characteristics

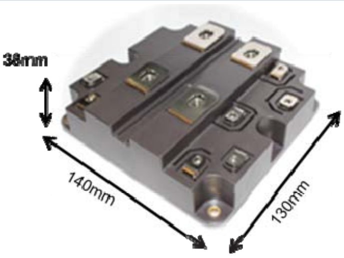




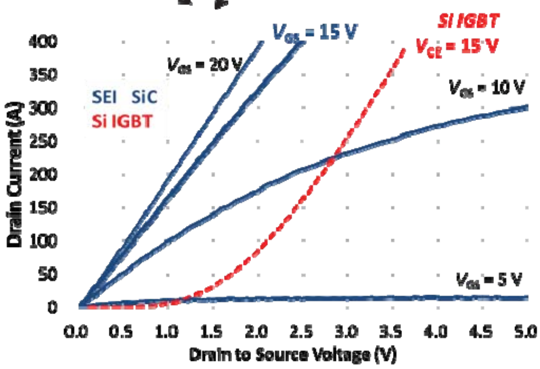


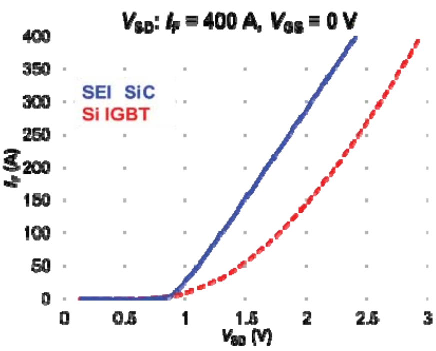
K. Wada et al., ECSCRM, vol. 821–823, pp. 592–595, 2014.

3.3 kV, 400 A Full SiC 2-in-1 Module



	$R_{DS(on)}$(mΩ)	V_{SD}(V)
SEI Full SiC Module	6.0	2.3
Si IGBT Module	(8.5)	2.8





K. Wada et al., Proc. 1st Advanced power devices, pp. 172–173, 2014.

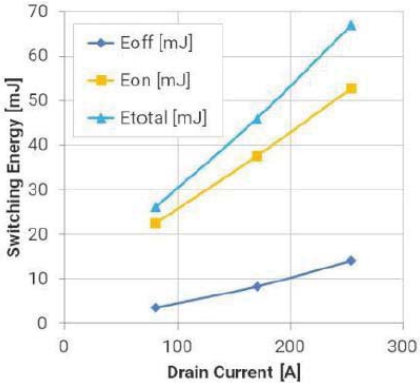
3.3 kV SiC MOSFETs have *10-15x lower* switching losses than 3.3 kV Si IGBTs.

3.3kV SiC MOSFET chip

V_{DS}	3300 V
$I_D(T_C=90°C)$	45 A
$R_{DS}(25°C)$	45 mΩ

Double Pulse Test

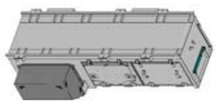
- V_{link} = 2.2 kV, R_g_ext = 2.5 Ω



- At 2.2 kV, 180 A switching, **<u>45 mJ</u>** total switching energy loss

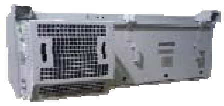
The World's First All-SiC Traction Inverter

3.3 kV, 1500 A all-SiC Power Modules with SiC MOSFETs and SiC SBDs



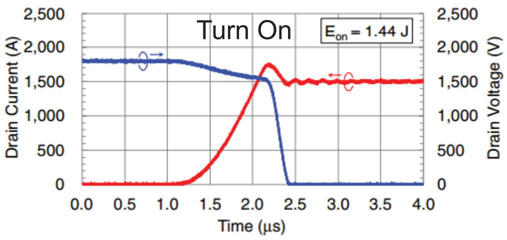
Conventional Traction Inverter with IGBTs

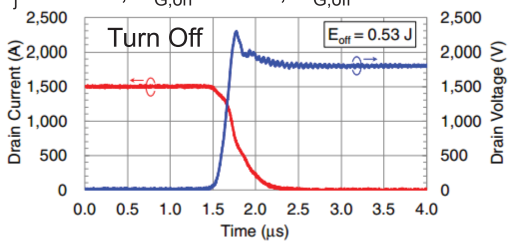
All-SiC Inverter



*The all-SiC inverter has **55 % lower switching losses** than conventional silicon-based inverters.*

V_{DS}= 1.8 kV, I_D= 1500 A, V_{GS}= +-15 V, T_j= 175 ºC, $R_{G,on}$= 2.4 Ω, $R_{G,off}$= 4.1 Ω





"Mitsubishi Electric: Silicon Carbide gets traction at 3.3kV and 1500A," Oct. 2015, http://www.pointthepower.com/mitsubishi-electric-silicon-carbide-gets-traction-at-3-3kv-and-1500a/

Outline

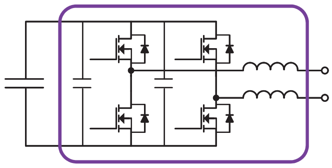
1. Introduction
2. High Frequency and High Efficiency
   – Comparison with Si
   – Characterization of 1.2 kV SiC discrete transistors
3. High Temperature
   – For power density in normal temperature ambient
   – For operation in high-temperature ambient
4. Medium Voltage
5. **High Voltage**
6. Conclusions
7. References

SiC Devices

	Device	Advantages	Disadvantages	Voltage Rating
Unipolar	**DMOSFET**	**Scalable**	**MOS Interface**	**0.4 kV – 15 kV**
Unipolar	Trench MOSFET	High V_{TH}, Low R_{ON}	High Electric Field	0.6 kV – 1.2 kV
Unipolar	Normally-On JFET	High Temp.	Normally-On	1.2 kV – 6.5 kV
Unipolar	Normally-Off JFET	Normally-Off	High R_{ON}	1.2 kV – 6.5 kV
Bipolar	BJT	No Gate Oxide	Current Driven	1.2 kV – 10 kV
Bipolar	IGBT	High Voltage	Reliability	15 kV – 27 kV
Bipolar	GTO	Low Conduction Loss	Difficult Control	> 8 kV
	Schottky Diode	No Reverse Recovery	High Leakage	0.1 kV – 8 kV
	JBS Diode	Low Leakage	High Forward Voltage	0.65 kV – 10 kV
	PiN Diode	Forward Voltage	Degradation	10 kV

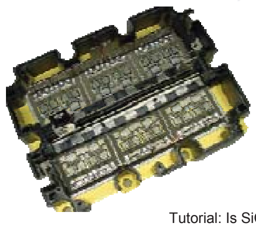
SiC H-Bridge Modules
Power Electronics Building Block (PEBB)

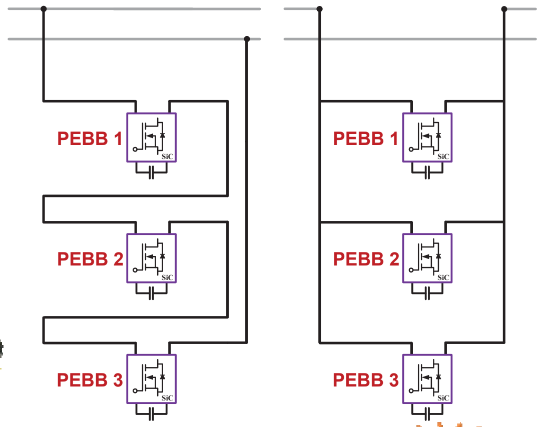
- <u>Concept</u>: **Integration of fundamental components into blocks** with defined functionality that can be used in a variety of applications.
- <u>Motivation</u>: The **versatility** reduces the cost, size, weight, loss, design complexity, installation, and maintenance of power electronic systems.



PEBB 1000
1.7 kV **SiC MOS**

PEBB 6000
10 kV **SiC MOS**



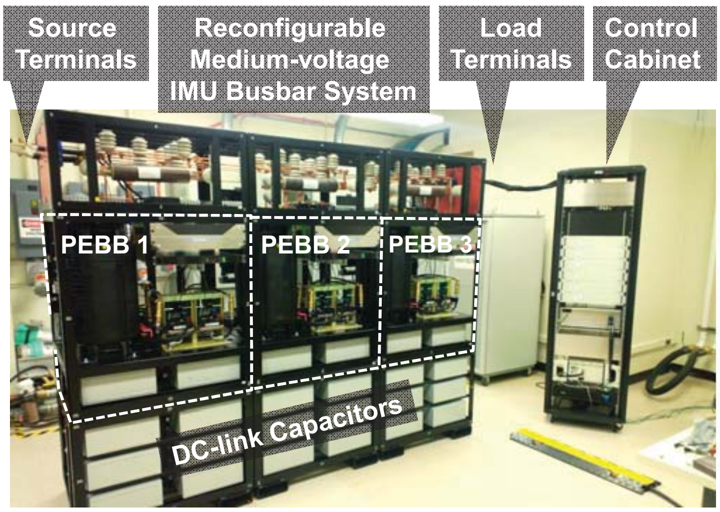


Impedance Measurement Unit using 10 kV SiC MOSFETs for Medium Voltage (4.16 kV) Medium Power (2 MW) Systems

System Ratings: 10 kV dc or 4.16 kV rms ac
300 A dc or rms ac
DC, 50 Hz, 60 Hz or 400 Hz

CREE POWEREX Power Semiconductor Solutions

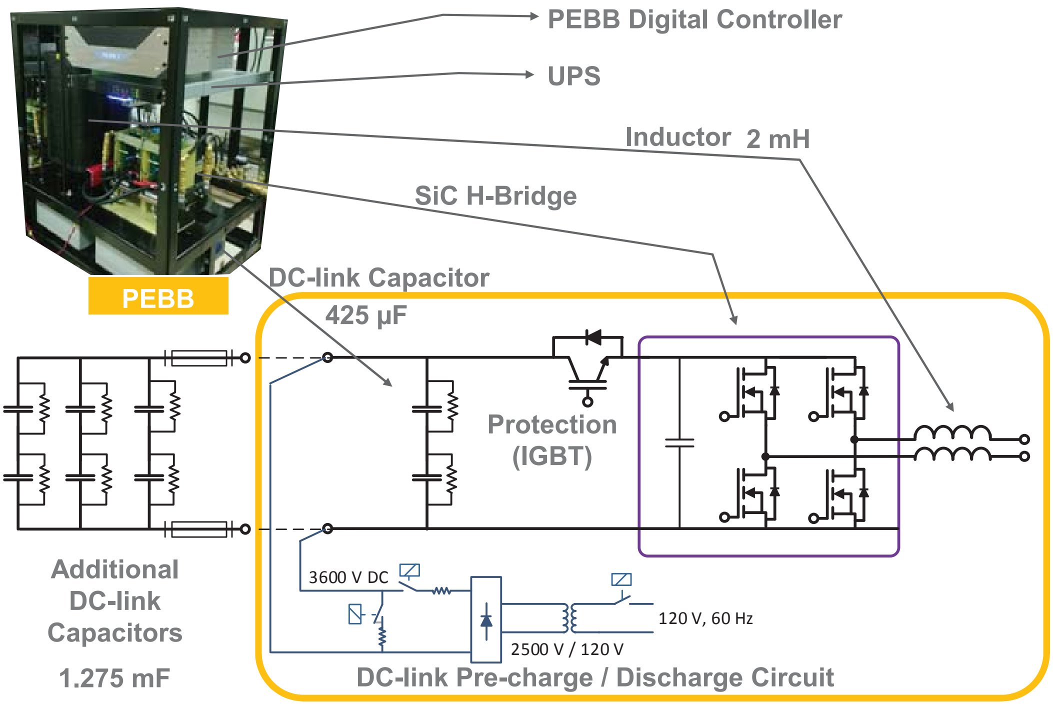
10 kV / 120 A
SiC half-bridge



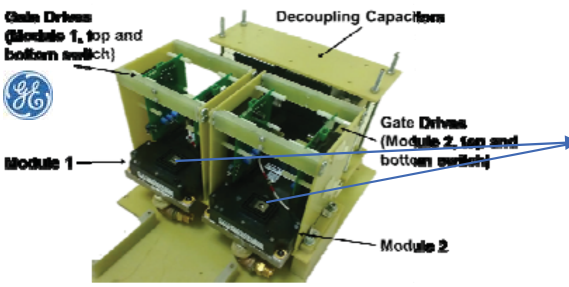
5 kV / 100 A H-bridge

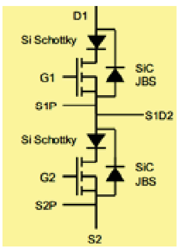
Measurement frequency range: 0.1 Hz - 1 kHz

Power Electronic Building Block (PEBB) Design



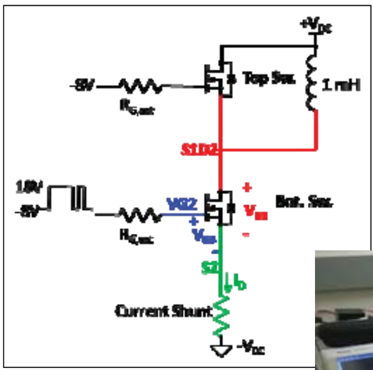
SiC H-Bridge



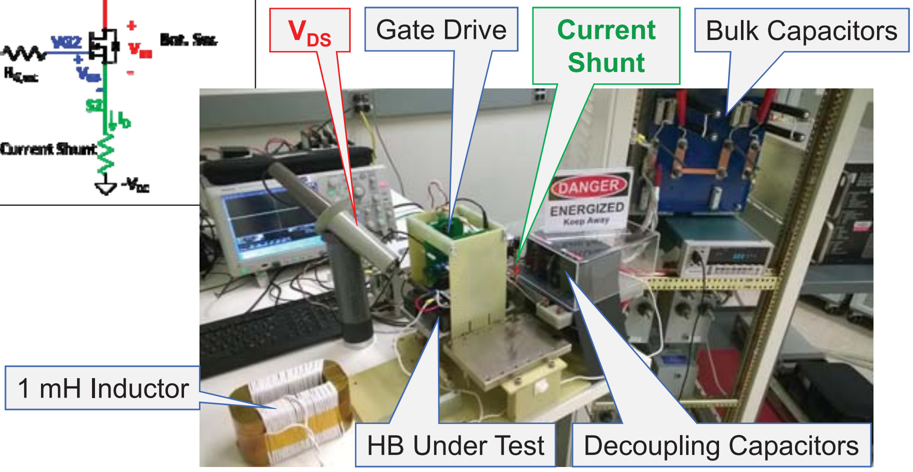


Parameter	Full Module
Voltage Rating	10 kV
Current Rating	120 A
No. of SiC MOSFETs	12
No. of SiC JBS Diodes	6
$V_{DS,ON}$	5 V at 100 A

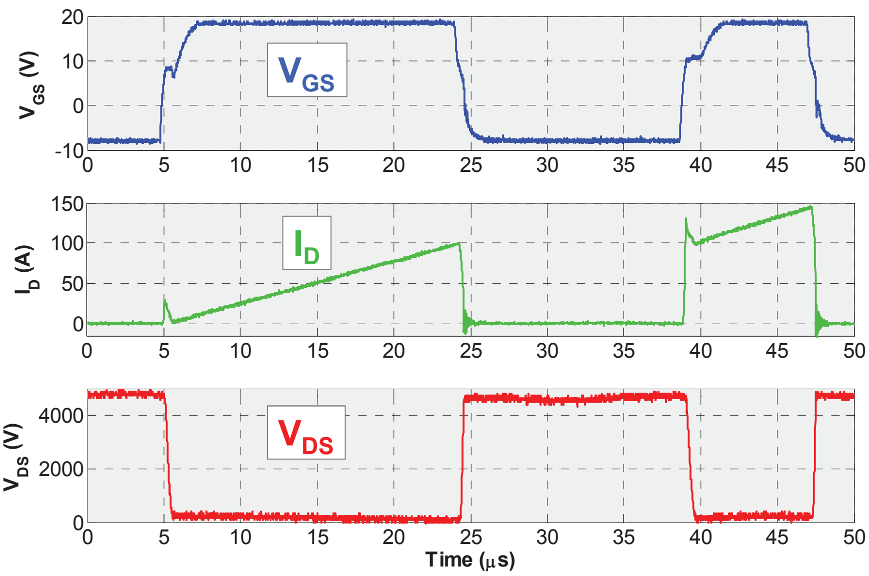
High-Voltage Double-Pulse Test Setup



This DPT setup allows us to quickly test all of the 10 kV SiC modules and gate drives.

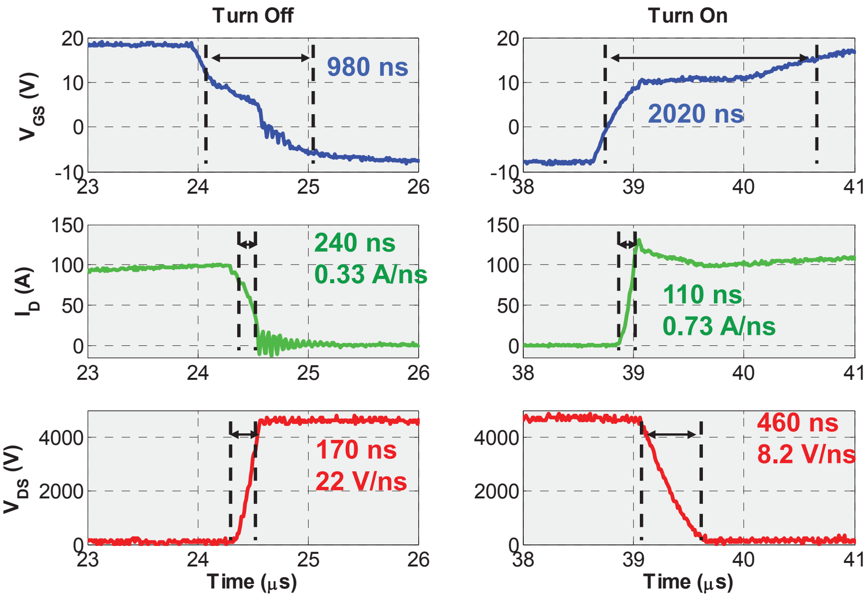


Experimental Double-Pulse Test: 4.7 kV, 100 A



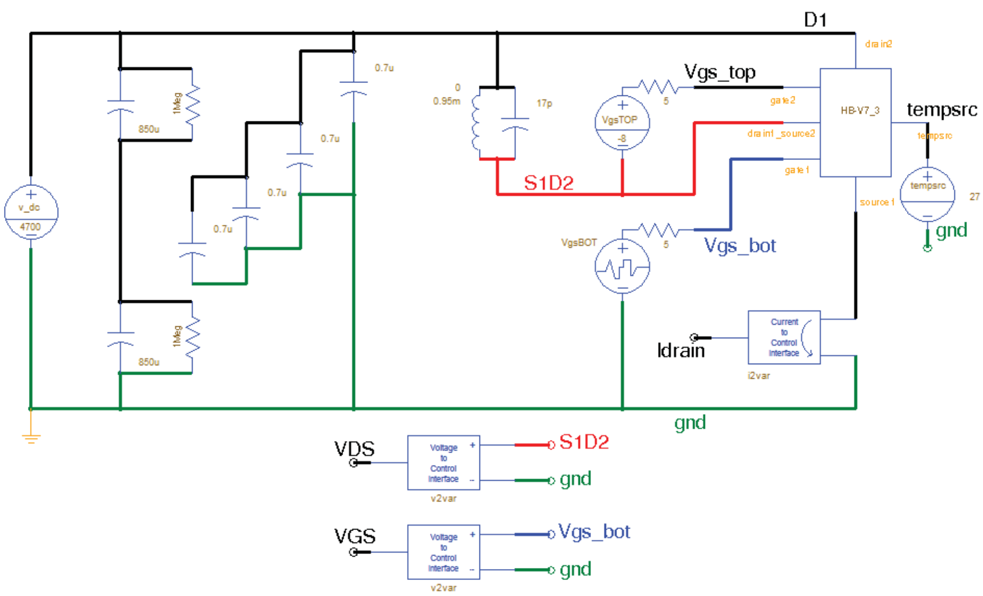
V_{DS}= 4.7 kV, I_D= 100 A, V_{GS}= +18 V to -8 V, $R_{G,ext}$= 5 Ω

Experimental Double-Pulse Test: 4.7 kV, 100 A



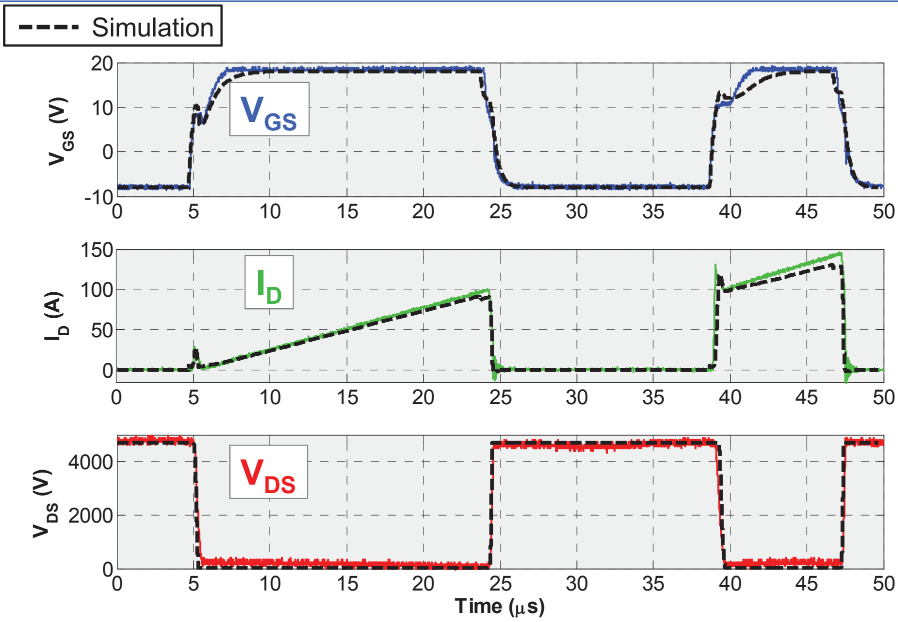
V_{DS}= 4.7 kV, I_D= 100 A, V_{GS}= +18 V to -8 V, $R_{G,ext}$= 5 Ω

Saber Simulation: Double-Pulse Test Schematic

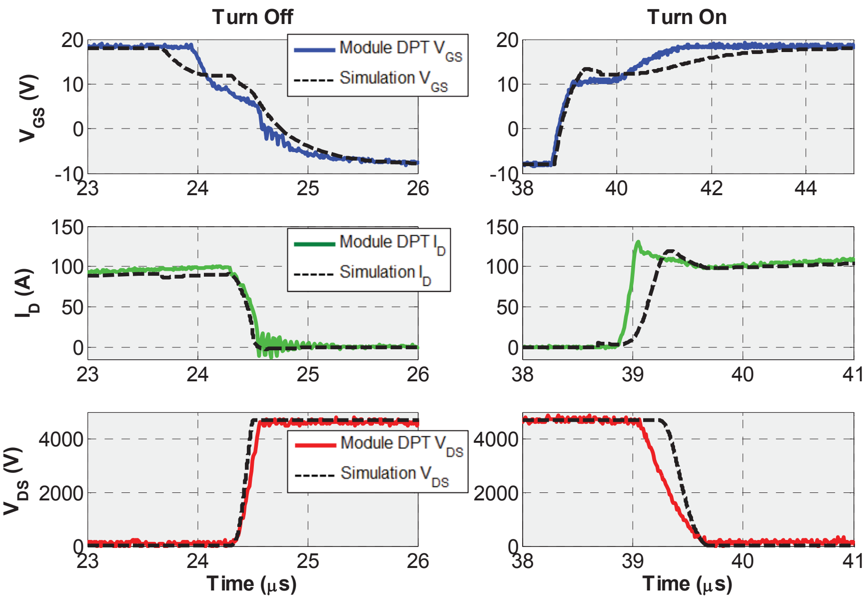


SiC Saber models developed by NIST.

Experimental and Simulation Comparison

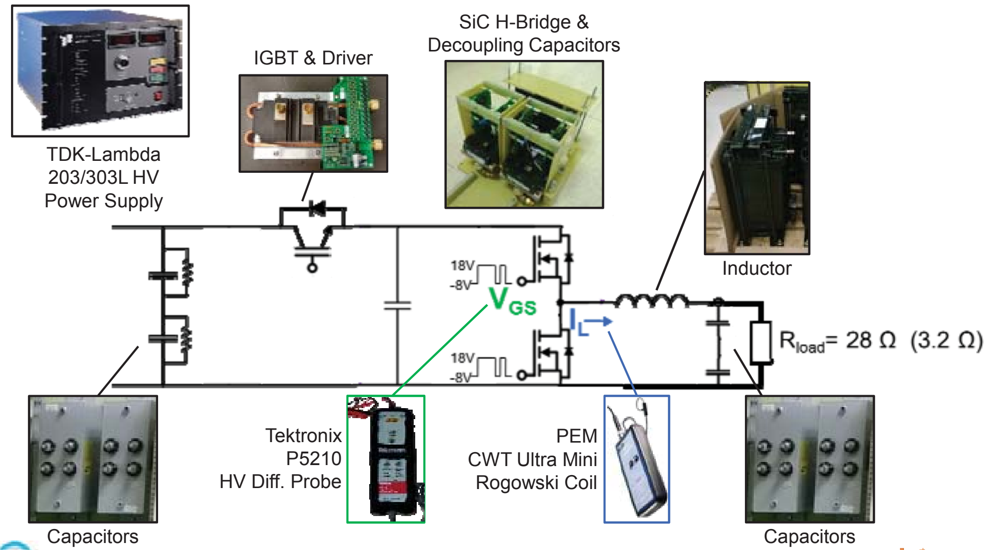


Experimental and Simulation Comparison

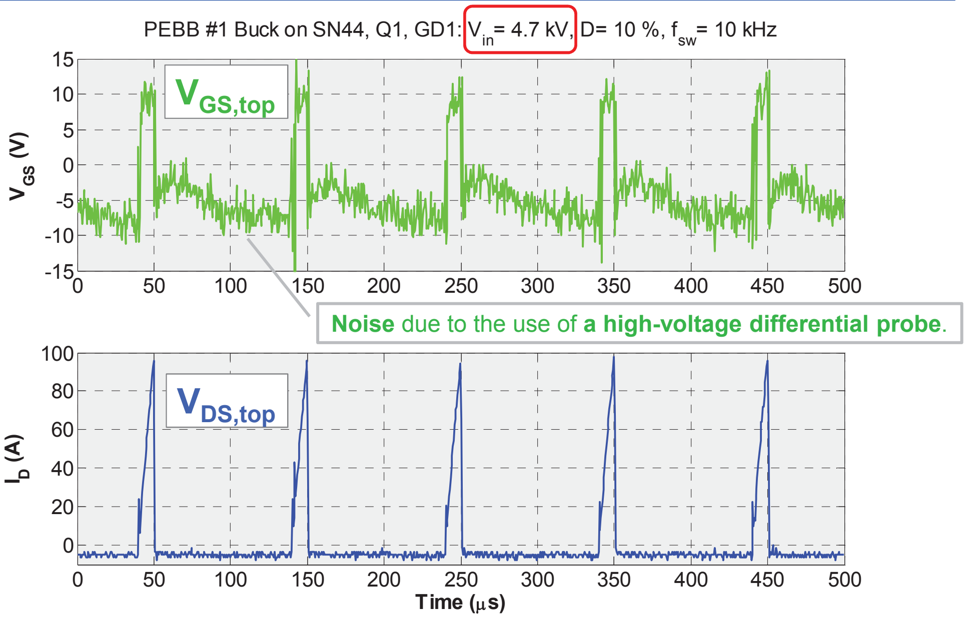


PEBB Buck Testing

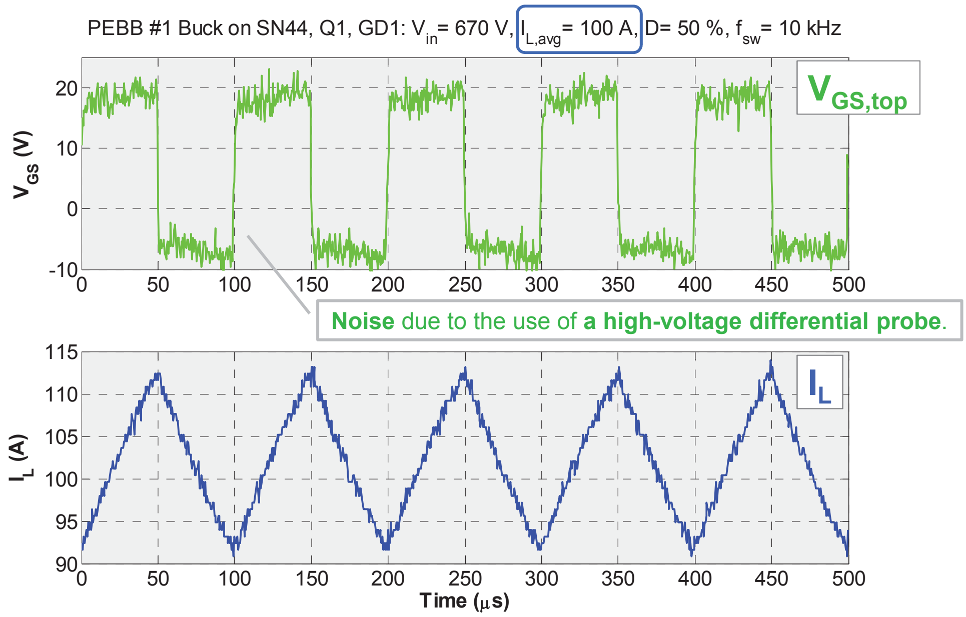
1. **High voltage**: V_{in}= **4.7 kV**, I_{out}= 4 A, V_{out}= 470 V, f_{sw}= 10 kHz, D= 10 %
2. **High current**: V_{in}= 670 V, I_{out}= **100 A**, V_{out}= 320 V, f_{sw}= 10 kHz, D= 50 %



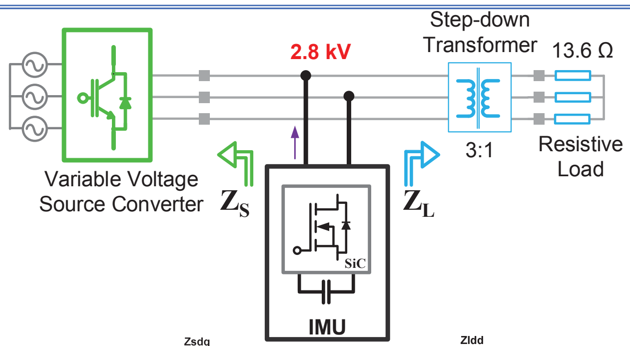
PEBB Buck Test at Full Voltage

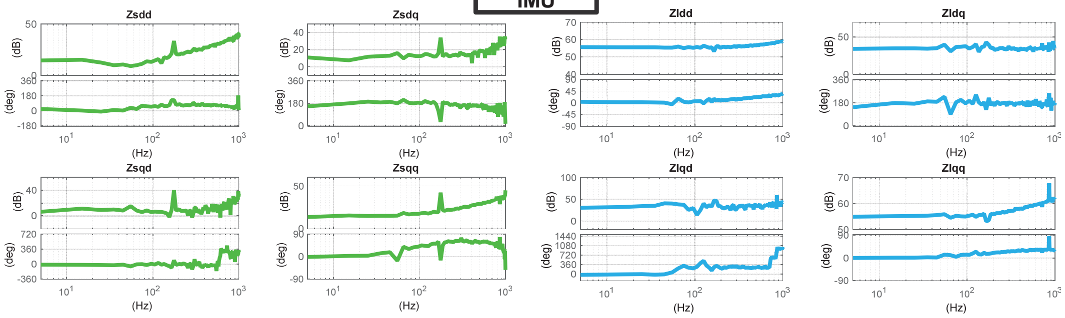


PEBB Buck Test at Full Current

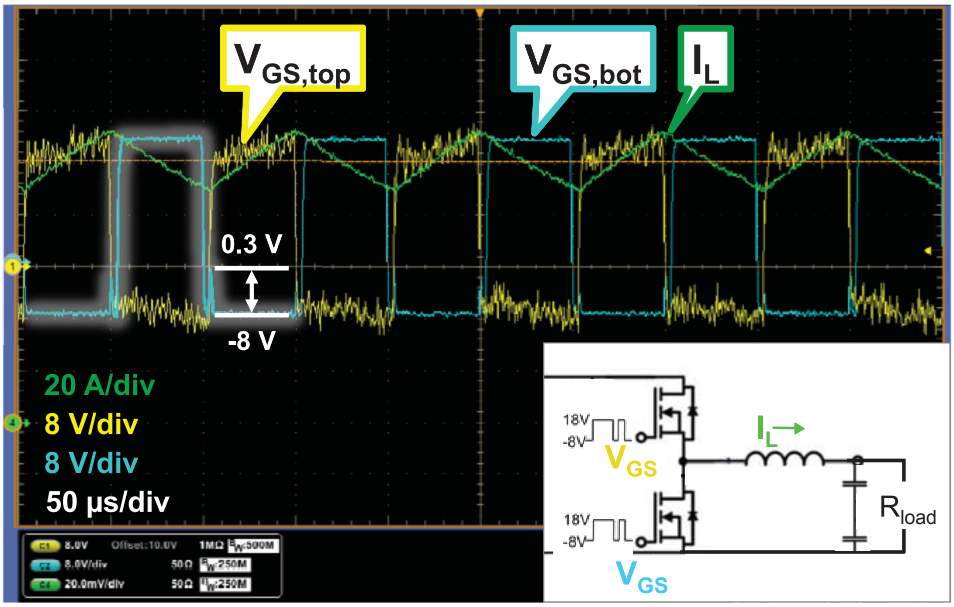


First-ever impedance measurement at 2.8 kV.

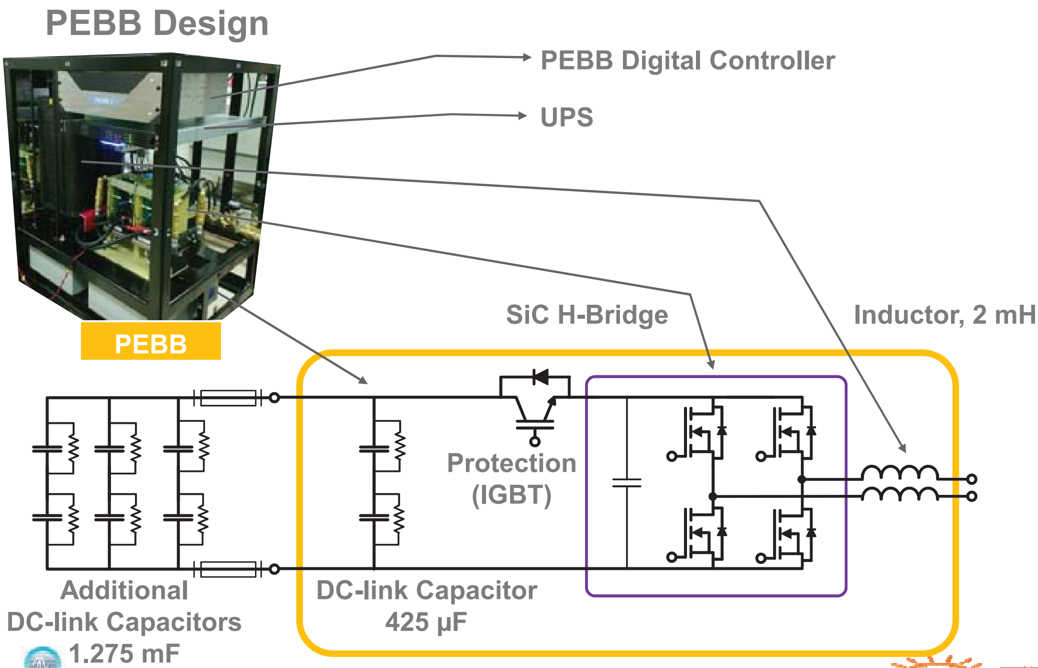




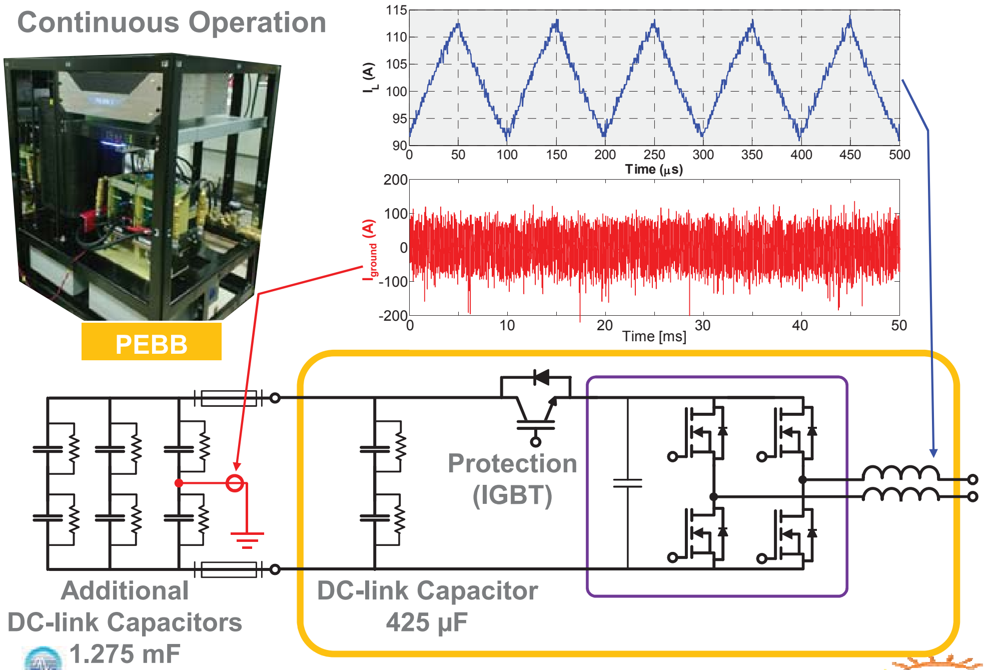
Significant Miller effect and common-mode currents limited the operation of the converter.



Significant Miller effect and common-mode currents limited the operation of the converter.

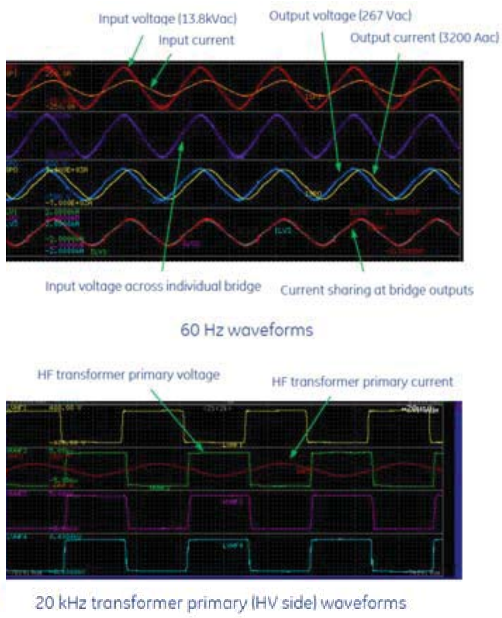


Significant Miller effect and common-mode currents limited the operation of the converter.



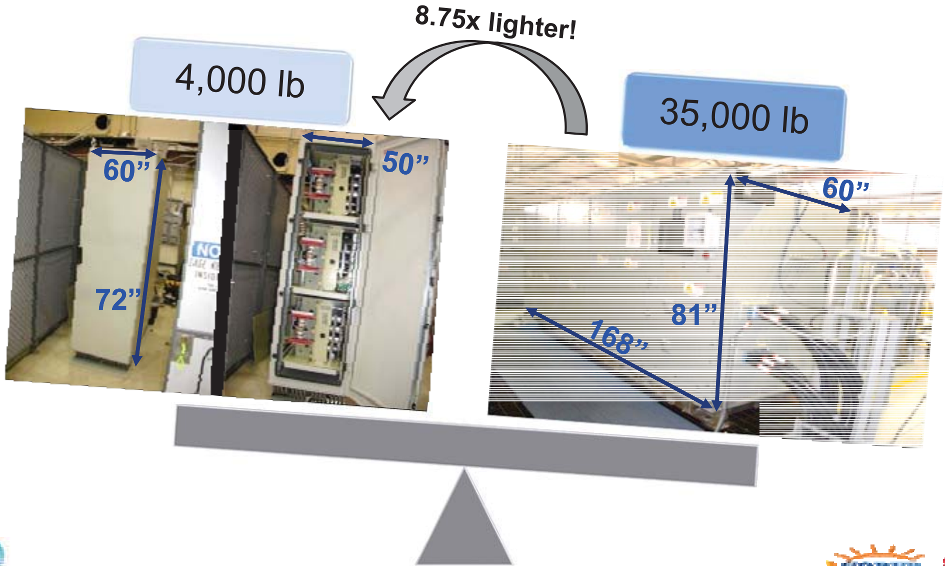
High Power Electronics (HPE) program – DARPA/ONR Solid-State Power Substation (SSPS)

Single-phase SSPS at Navy test lab



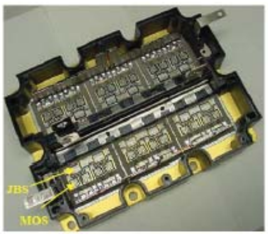
- ✓ Demonstrated at 1 MVA, 13.8 kV/265 V
- ✓ Efficiency at full load > 97%
- ✓ 1/3rd weight of conventional transformer
- ✓ AC input current/ output voltage THD < 5%

Comparison of 3 MW Transformers



Significant common-mode current could be flowing through the baseplate parasitic capacitance.

Example – EMI, dv/dt

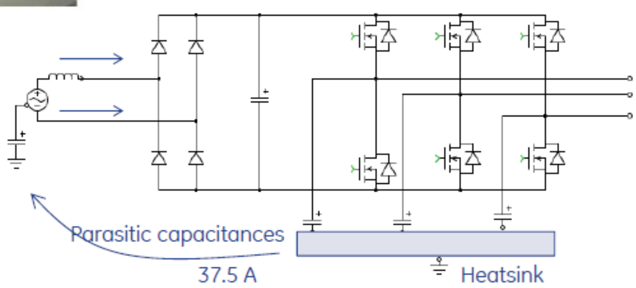


Chips to baseplate capacitance , C ~750 pF

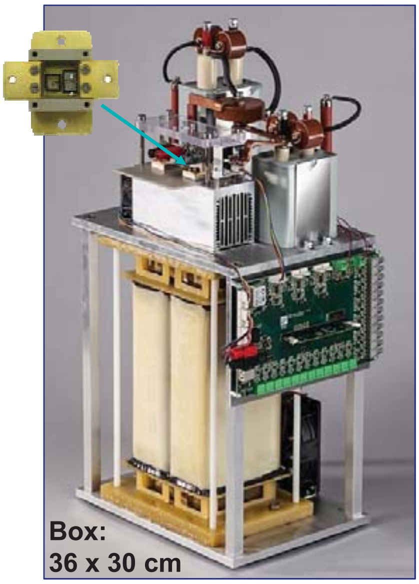
Assume slew rate, dv/dt ~ 5 kV / 100 ns

Common mode current = C. dv/dt = 37.5 amps
(same order of magnitude as rated currents)

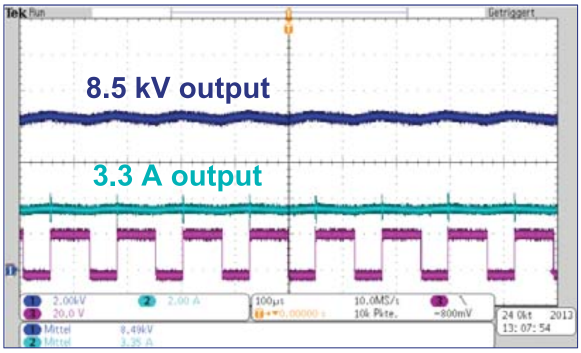
Solutions - Decoupling capacitors, synchronized out-of-phase switching of phase-legs to cancel CM currents, etc. can be used.



10 kV SiC MOSFETs in 30 kW Boost Converter



Efficient, "Transformer-Less" Power Distribution Medium Voltage Grid

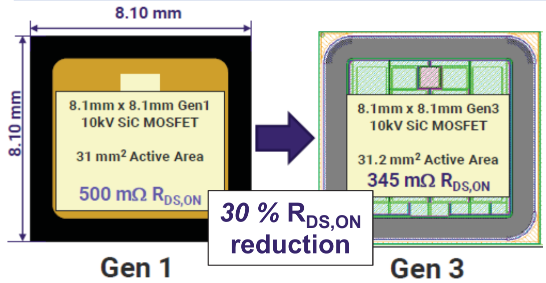


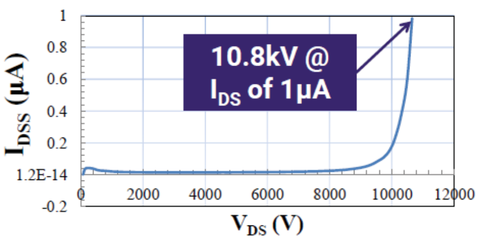
- **98.5 % efficiency**
- **8 kHz switching frequency**, ***>10X higher*** than possible with conventional silicon-based medium voltage converters.

Fraunhofer ISE

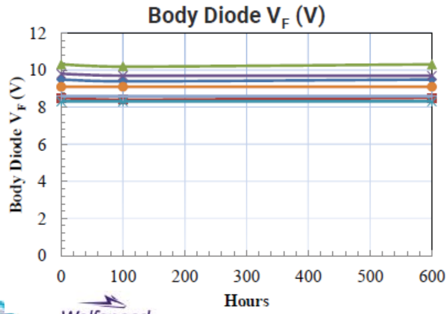
J. Thoma, et al., "A highly efficient dc-dc converter for medium-voltage applications," IEEE ENERGYCON, pp. 127-131, 2014.

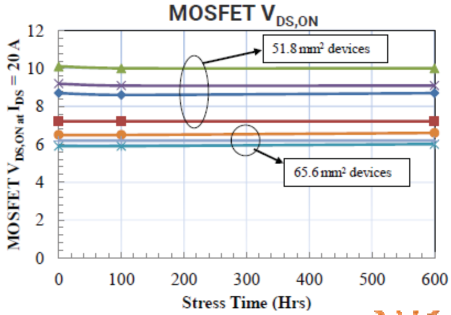
3rd Generation 10 kV SiC MOSFET



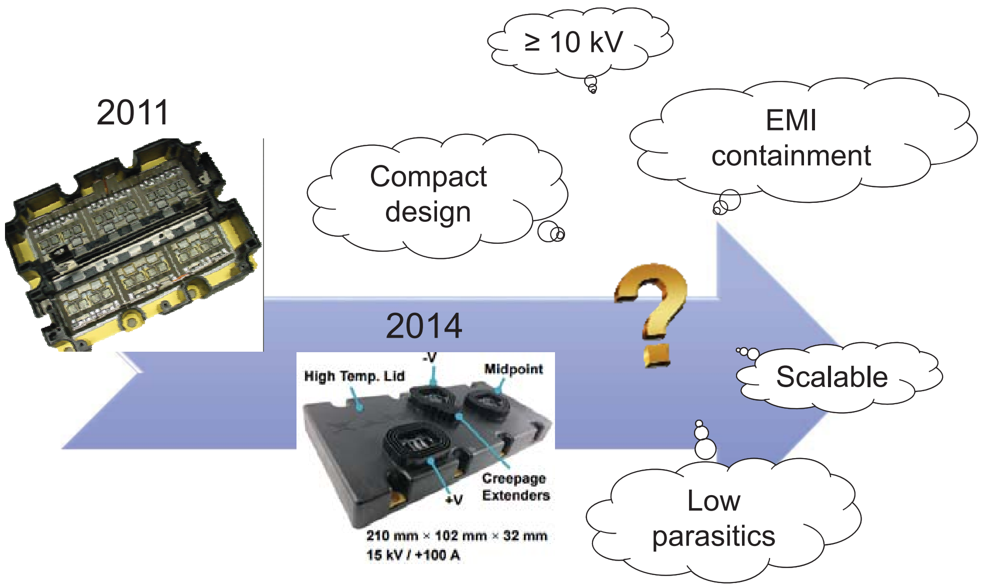


10 kV SiC MOSFET body diode stability after stressing at 10 A, 150 ºC for 600 hrs.

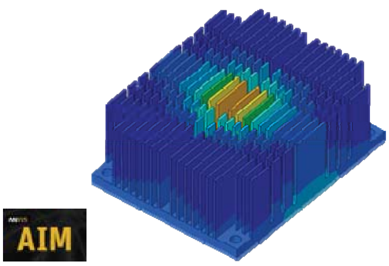




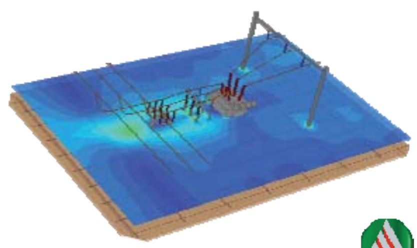
It is necessary to investigate the multi-physics design optimization of a high voltage SiC power module.



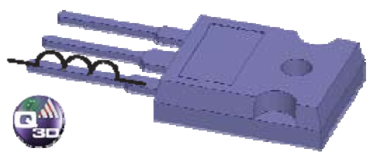
3D finite element analysis tools can be used to optimize the high voltage module design.



Temperature distribution of a finned heatsink solved by ANSYS **AIM**.

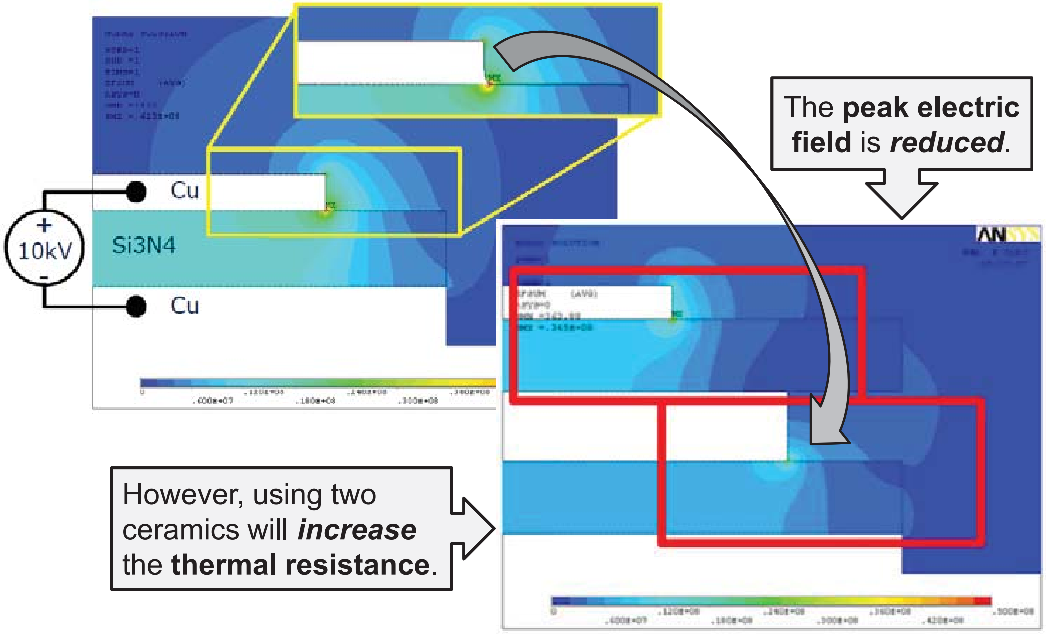


Electric field distribution from substation solved by ANSYS **Maxwell**.



Parasitic extraction of a TO-247 package solved by ANSYS **Q3D**.

Stacking substrates can reduce the peak electric field at the triple point.



O. Hohlfeld, et al., "Stacked substrates for high voltage applications," IEEE CIPS, pp. 1-4, Mar. 2012.

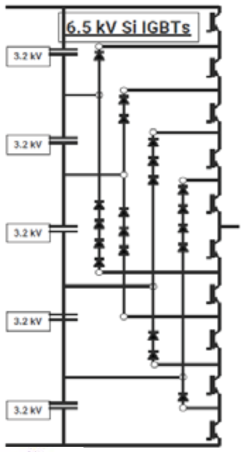
SiC Devices

	Device	Advantages	Disadvantages	Voltage Rating
Unipolar	DMOSFET	Scalable	MOS Interface	0.4 kV – 15 kV
Unipolar	Trench MOSFET	High V_{TH}, Low R_{ON}	High Electric Field	0.6 kV – 1.2 kV
Unipolar	Normally-On JFET	High Temp.	Normally-On	1.2 kV – 6.5 kV
Unipolar	Normally-Off JFET	Normally-Off	High R_{ON}	1.2 kV – 6.5 kV
Bipolar	**BJT**	**No Gate Oxide**	**Current Driven**	**1.2 kV – 10 kV**
Bipolar	**IGBT**	**High Voltage**	**Reliability**	**15 kV – 27 kV**
Bipolar	GTO	Low Conduction Loss	Difficult Control	> 8 kV
	Schottky Diode	No Reverse Recovery	High Leakage	0.1 kV – 8 kV
	JBS Diode	Low Leakage	High Forward Voltage	0.65 kV – 10 kV
	PiN Diode	Forward Voltage	Degradation	10 kV

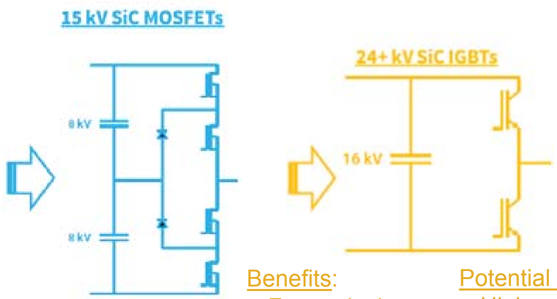
Switching loss benefits and simplified topologies are possible with high voltage SiC MOSFETs and IGBTs.

Device	Max T_J	Bus Voltage	Rated Current	V_{DSON} @ Max T_J	$E_{SW,ON}$	$E_{SW,OFF}$	$E_{SW,TOT}$
6.5 kV Si IGBT	125 °C	3.6 kV	25 A	5.4 V	200 mJ	130 mJ	330 mJ
10 kV SiC MOSFET	150 °C	7 kV	20 A	10.2 V	8.4 mJ	1.3 mJ	9.7 mJ
15 kV SiC MOSFET	150 °C	10 kV	10 A	16.3 V	10.2 mJ	3 mJ	13.2 mJ

3x bus voltage, 25x smaller E_{SW}



Example: 16 kV Input

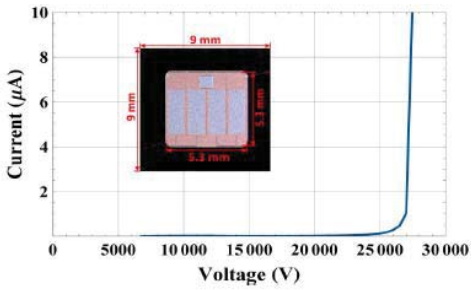


Benefits:
- Fewer devices
- Simpler control
- Less power loss

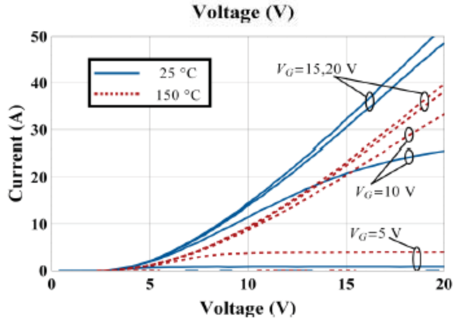
Potential Issues:
- Higher *dv/dt*
- Worse EMI

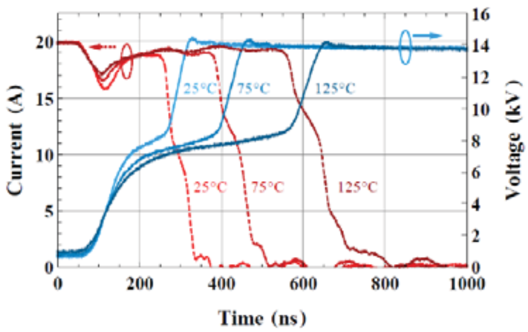
27.5 kV, 20 A SiC n-IGBT
The world's highest-voltage semiconductor switch!

ARL

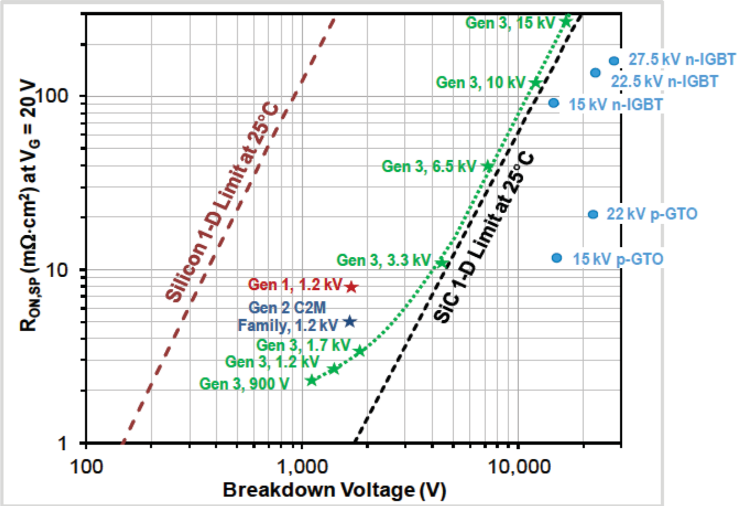


- 0.9 cm x 0.9 cm SiC n-IGBT
- 0.25 cm^2 active area
- 230 mm, $1x10^{14}$ $/cm^3$ doped drift layer
- **27.5 kV blocking** at I_C= 11.8 µA (V_{GE}= 0 V)

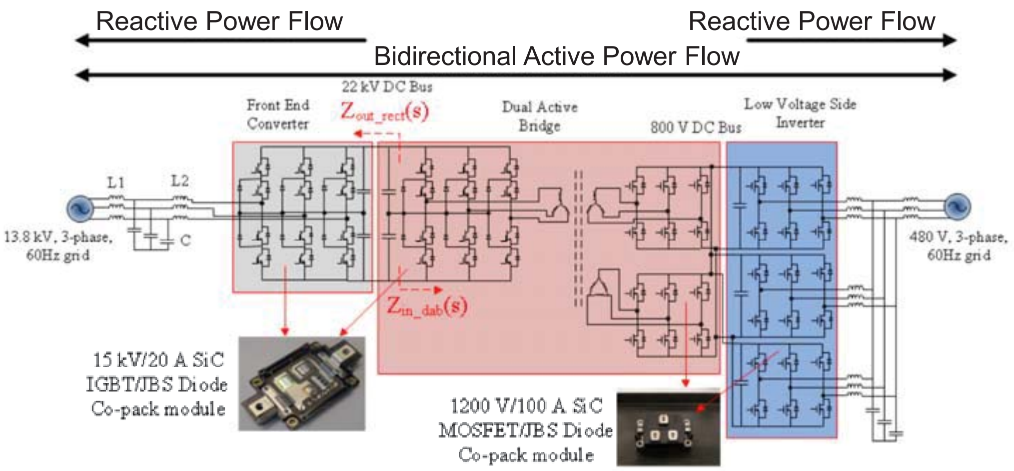




Bipolar SiC devices yield lower on-resistance for higher voltages.



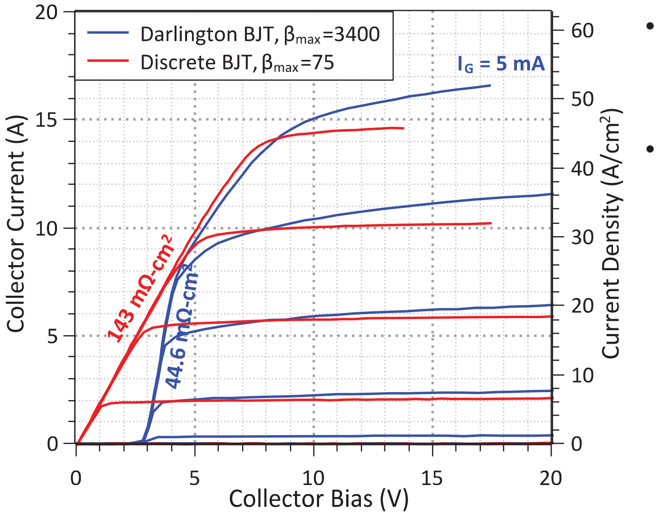
Transformer-less Intelligent Power Substation with 15 kV SiC IGBT and 1.2 kV SiC MOSFET



- SiC-based 3-phase solid state transformer for 13.8 kV – 480 V grid interconnection
- Features: High efficiency, small size, bidirectional, reactive power compensation, improved power quality, renewable integration

A. Kadavelugu, et al., "Medium voltage power converter design and demonstration using 15 kV SiC n-IGBTs," IEEE APEC, pp. 1396-1403, 2015.

On-State Characteristics of 10 kV SiC BJTs

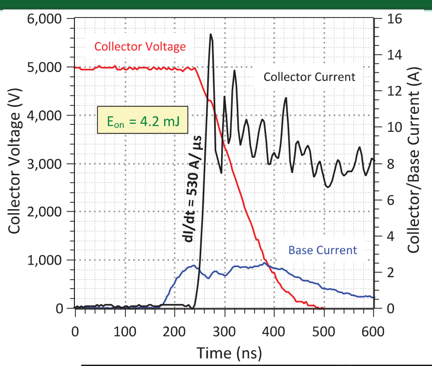


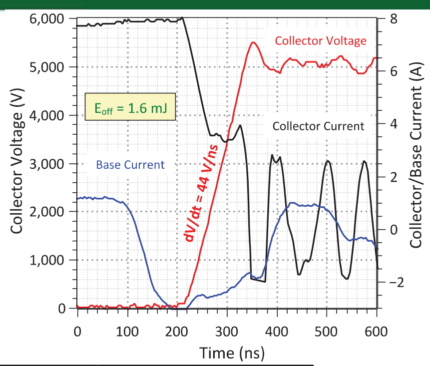
7.3 mm x 7.3 mm BJTs (active area = 28 mm²)

- Ron = 143 mΩ-cm² and β = 75 measured on single-stage BJT
- **Darlington** BJT shows diff. R_{on} = **44.6 mΩ-cm²** in saturation region
  - R_{on} is not constrained by collector current load line in this region
  - **70% lower** than discrete BJT
  - **Unipolar** limit= **94 mΩ-cm²**

Information courtesy of GeneSiC™

10 kV SiC BJT Inductive Switching Test at 5 kV, 8 A and 150ºC





Device	BV	I_C	Temp.(C)	$V_{CE,sat}$ (V)	Eon (mJ)	Eoff (mJ)
SiC BJT	10 kV	8 A	150°C	6.4	4.2	1.6
Si IGBT*	6.5 kV	10 A	125°C	4	80	40
				↑ 1.6 x	19 x ↓	25 x ↓

* Si IGBT switching data sourced from device datasheet

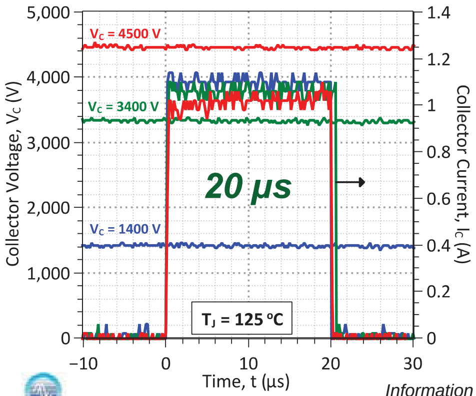
Information courtesy of GeneSiC™

10 kV SiC BJT Inductive Switching and Short-Circuit Ruggedness

5 kV, 8 A and 150 ºC

Device	BV	I_C	Temp.(C)	$V_{CE,sat}$ (V)	Eon (mJ)	Eoff (mJ)
SiC BJT	10 kV	8 A	150ºC	6.4	4.2	1.6
Si IGBT*	6.5 kV	10 A	125ºC	4	80	40
				↑ 1.6 x	19 x ↓	25 x ↓

* Si IGBT switching data sourced from device datasheet



- 3.65 mm x 3.65 mm SiC BJT **turned on to a short-circuited** load at a DC link voltage of 4.5 kV.
- A **short-circuit withstand time of ≥ 20 μs** observed at **V_{CE} = 4.5 kV and T_C= 125ºC**
  - Near-infinity output resistance (and Early voltage) results in V_{CE} invariance of I_{SC}

Information courtesy of GeneSiC™

Outline

1. Introduction
2. High Frequency and High Efficiency
   - Comparison with Si
   - Characterization of 1.2 kV SiC discrete transistors
3. High Temperature
   - For power density in normal temperature ambient
   - For operation in high-temperature ambient
4. Medium Voltage
5. High Voltage
6. **Conclusions**
7. References

Conclusions

For Vdc < 500 V:

- SiC SBD + Si Super-junction MOSFET will compete with GaN-on-Si

For 0.5 kV < Vdc < 1 kV:

- SiC Schottky (SBD) will be increasingly used instead of Si PiN
- SiC transistors will start competing with Si MOSFETs and IGBTs based on converter cost, efficiency, size and performance
  - (A tough proposition!)
- For high switching frequencies (> 10 kHz) better module and converter packaging must be developed

For 1 kV < Vdc < 6 kV:

- SiC could be overtaking Si within 3-8 years
- Improved packaging for higher switching frequencies, higher voltage, higher temperatures, and longer lifetime will provide competitive advantage
- Much improved systems based on new designs for electric machines, passives, and converters will be a game changer

Conclusions

For Medium and High Voltage (Vdc > 6 kV):

- SiC is the future! (*Not a game changer, but a New Game.*)
- Very innovative packaging and system design for high voltage, higher switching frequencies and long lifetime is required
- Completely new systems and new applications will be developed
- This will become huge when the new electronic grid will start to be built

For High Ambient Temperature (> 200 ºC):

- SiC is the future! (*Not a game changer, but a New Game.*)
- Very innovative packaging for high temperature, higher switching frequencies and long lifetime is required
- Novel components for the “balance of system” (sensing, control, passives, interconnects, …) will have to be invented and developed
- Completely new systems and new applications will be developed
  - (“Physics” will remain the problem!)

Outline

1. Introduction
2. High Frequency and High Efficiency
   – Comparison with Si
   – Characterization of 1.2 kV SiC discrete transistors
3. High Temperature
   – For power density in normal temperature ambient
   – For operation in high-temperature ambient
4. Medium Voltage
5. High Voltage
6. Conclusions
7. **References**

List of References – Applications

[1] S. Aso, M. Kizaki, and Y. Nonobe, "Development of fuel cell hybrid vehicles in TOYOTA," in Proc. IEEE Power Conversion Conf. 2007, pp. 1606-1611, 2007.

[2] K. Rajashekara, "Converging technologies for electric/hybrid vehicles and more electric aircraft systems," SAE Technical Paper 2010-01-1757, 2010, doi: 10.4271/2010-01-1757, 2010.

[3] J. A. Rosero, J. A. Ortega, E. Aldabas, and L. Romeral, "Moving towards a more electric aircraft," in IEEE Aerospace and Electronic Systems Magazine, vol. 22, issue 3, pp. 3-9, Mar. 2007.

[4] A. A. Abd-Elhafez, and A. J. Forsyth, "A review of more-electric aircraft," in Proc. 13th Int'l Conf. Aerospace Sciences & Aviation Technology, May 2009.

[5] H. Zhang, C. Saudemont, B. Robyns, and M. Petit, "Comparison of technical features between a more electric aircraft and a hybrid electric vehicle," in Proc. IEEE Vehicle Power and Propulsion Conf. (VPPC) 2008, pp. 1-6, Sept. 2008.

[6] C. R. Avery, S. G. Burrow, and P. H. Mellor, "Electrical generation and distribution for the more electric aircraft," in Proc. 42nd Int'l Universities Power Engineering Conf. 2007, pp. 1007-1012, Sept. 2007. Chapter 1 13

[7] R. E. Quigley, Jr., "More electric aircraft," in Proc. IEEE APEC 1993, pp. 906-911, 1993.

[8] A. Emadi, and M. Ehsani, "Aircraft power systems: technology, state of the art, and future trends," in IEEE Aerospace and Electronic Systems Magazine, vol. 15, issue 1, pp. 28-32, Jan. 2000.

[9] M. Sinnett, "787 no-bleed systems: saving fuel and enhancing operational efficiencies," in Boeing Aero Quarterly, QTR 04, 2007, available online at http://www.boeing.com/, accessed on Sept. 22, 2012.

[10] K. Rajashekara, J. Grieve, and D. Daggett, "Hybrid fuel cell in aircraft," in IEEE Industry Applications Magazine, vol. 14, issue 4, pp. 54-60, Jul.-Aug. 2008.

[11] C. C. Chan, "The state of the art of electric, hybrid, and fuel cell vehicles," in Proceedings of the IEEE, vol. 95, issue 4, pp. 704-718, Apr. 2007.

List of References – Applications

[12] T. J. McCoy, “Trends in ship electric propulsion,” in Proc. IEEE Power Engineering Society Summer Meeting, vol. 1, pp. 343-346, Jul. 2002.

[13] H. Zhang, L. M. Tolbert, and B. Ozpineci, “Impact of SiC devices on hybrid electric and plug-in hybrid electric vehicles,” in IEEE Trans. Industry Applications, vol. 47, no. 2, pp. 912-921, Mar.-Apr. 2011.

[14] B. Wrzecionko, J. Biela, and J. W. Kolar, “SiC power semiconductors in HEVs: influence of junction temperature on power density, chip utilization and efficiency,” in Proc. IEEE IECON 2009, pp. 3834-3841, Nov. 2009.

[15] B. Ozpineci, System Impact of Silicon Carbide Power Electronics on Hybrid Electric Vehicles, Ph. D. Dissertation, University of Tennessee, Knoxville, 2002.

List of References – High Temperature Components

[1] E. Cilio, J. Garrett., and H. Fraley., "High Temperature Electronics (>485°C) For Venus Exploration," presented at the 4th International Planetary Probe Workshop, Pasadena, California,, 2006.

[2] M. R. Werner and W. R. Fahrner, "Review on materials, microsensors, systems and devices for high-temperature and harsh-environment applications," Industrial Electronics, IEEE Transactions on, vol. 48, pp. 249-257, 2001.

[3] R. L. Greenwell, B. M. McCue, L. Zuo, M. A. Huque, L. M. Tolbert, B. J. Blalock, and S. K. Islam, "SOI-based integrated circuits for high-temperature power electronics applications," in Applied Power Electronics Conference and Exposition (APEC), 2011 Twenty-Sixth Annual IEEE, 2011, pp. 836-843.

[4] M. Stecher, N. Jensen, M. Denison, R. Rudolf, B. Strzalkoswi, M. N. Muenzer, and L. Lorenz, "Key technologies for system-integration in the automotive and Industrial Applications," Power Electronics, IEEE Transactions on, vol. 20, pp. 537-549, 2005.

[5] E.Cilio., J.Hornberger., and R.Schupbach., "A High-Temperature (225 °C+) Silicon-On-Insulator (SOI) Gate Driver IC For Silicon Carbide (SiC) JFET," presented at the International Conference on High Temperature Electronics (HiTEC 2008), Albuquerque, New Mexico, 2008.

[6] M. A. Huque, R. Vijayaraghavan, M. Zhang, B. J. Blalock, L. M. Tolbert, and S. K. Islam, "An SOI-based High-Voltage, High-Temperature Gate-Driver for SiC FET," in Power Electronics Specialists Conference, 2007. PESC 2007. IEEE, 2007, pp. 1491-1495.

[7] Cissoid Datasheet. Available: http://www.cissoid.com/images/stories/pdf/Datasheets/cmtopa.pdf

[8] MIL-STD-883H. Available: http://www.dscc.dla.mil/downloads/milspec/docs/mil-std- 883/std883.pdf

[9] S. Waffler, S. D. Round, and J. W. Kolar, "High temperature (>200C) isolated gate drive topologies for Silicon Carbide (SiC) JFET," in Industrial Electronics, 2008. IECON 2008. 34th Annual Conference of IEEE, 2008, pp. 2867-2872.

[10] S. Waffler, S. D. Round, and J. W. Kolar, "High temperature (≫200°C) isolated gate drive topologies for Silicon Carbide (SiC) JFET," in Industrial Electronics, 2008. IECON 2008. 34th Annual Conference of IEEE, 2008, pp. 2867-2872.

List of References – High Temperature Components

[11] R. Constapel, J. Freytag, P. Hille, V. Lauer, and W. Wondrak, "High temperature electronics for automotive applications," in Proc. *Int. Conf. Integrated Power Systems* (CIPS'00), pp. 46–53.

[12] A. Gurav, X. Xu, J. Magee, P. Staubli, J. Bultitude, T. Ashburn, "Advanced ceramic capacitor solutions for high temperature applications," in *Proc. IMAPs Conf. and Expo. on HiTEN 2013*, pp. 25-32.

[13] Presidio Components, Inc., "High temperature ceramic capacitors," Catalog 3500. Rev. K. (2013). [On-line]. Available: http://www.presidiocomponents.com/catalog/HighTempCeramicCapsRevK-Sept2013.pdf.

List of References – High Temperature Converters

[1] K. Acharya, S. K. Mazumder, and P. Jedraszczak, "Efficient, High-Temperature Bidirectional Dc/Dc Converter for Plug-in-Hybrid Electric Vehicle (PHEV) using SiC Devices," in Applied Power Electronics Conference and Exposition, 2009. APEC 2009. Twenty-Fourth Annual IEEE, 2009, pp. 642-648.

[2] D. C. Hopkins, D. W. Kellerman, R. A. Wunderlich, C. Basaran, and C. J. Gomez, "High temperature, high-density packaging of a 60kW converter for >200°C embedded operation," in Applied Power Electronics Conference and Exposition, 2006. APEC '06. Twenty-First Annual IEEE, 2006, p. 7 pp.

[3] High Temperature and High Power Density SiC Power Electronic Converters. Available: http://www.sandia.gov/ess/docs/pr_conferences/2005/Schupbach.pdf

[4] D. Bergogne, H. Morel, D. Planson, D. Tournier, P. Bevilacqua, B. Allard, R. Meuret, S. Vieillard, S. Rael, and F. MeibodyTabar, "Towards an airborne high temperature SiC inverter," in Power Electronics Specialists Conference, 2008. PESC 2008. IEEE, 2008, pp. 3178-3183.

[5] W. Ruxi, N. Puqi, D. Boroyevich, M. Danilovic, F. Wang, and R. Kaushik, "Design of high temperature SiC three-phase AC-DC converter for >100°C ambient temperature," in Energy Conversion Congress and Exposition (ECCE), 2010 IEEE, 2010, pp. 1283-1289.

[6] M. Gerber, J. A. Ferreira, I. W. Hofsajer, and N. Seliger, "An improved 3D integrated DC/DC converter for high temperature environments," in Power Electronics Specialists Conference, 2004. PESC 04. 2004 IEEE 35th Annual, 2004, pp. 2779-2785 Vol.4.

[7] C. Buttay, J. Rashid, C. M. Johnson, F. Udrea, G. Amaratunga, P. Ireland, and R. K. Malhan, "Compact Inverter Designed for High-Temperature Operation," in Power Electronics Specialists Conference, 2007. PESC 2007. IEEE, 2007, pp.

[8] E. Cilio, J. Hornberger, B. McPherson, R. Schupbach, and A. Lostetter, "Design and Fabrication of a High Temperature (250 Â°C Baseplate), High Power Density Silicon Carbide (SiC) Multichip Power Module (MCPM) Inverter," in IEEE Industrial Electronics, IECON 2006 - 32nd Annual Conference on, 2006, pp. 1822-1827.2241-2247.

List of References – High Temperature Converters

[9] R. Wang, "High Power Density and High Temperature Converter Design for Transportation Applications," PhD Dissertation, Virginia Tech, June 2012.

[10] B. Ray, H. Kosai, J.D. Scofield, James, and B. Jordan, "200°C operation of a DC-DC converter with SiC power devices," in Proc. of IEEE APEC 2007, Feb.-Mar. 2007, pp. 998 – 1002.

[11] J. M. Hornberger, E. Cilio, B. McPherson, R. M. Schupbach and A. B. Lostetter, "A fully integrated 300 ºC, 4 KW, 3-phase, SiC motor drive module," Proc. of PESC 2007, pp. 1048-1053.

[12] V. R. Garuda, M. K. Kazimierczuk, M. L. Ramalingam, L. Tolkkinen, M. D. Roth, "High temperature testing of a buck converter using silicon and silicon carbide diodes," in *Proc. Energy Conversion Engineering Conference*, vol.1, pp.317-322, 1997.

List of References – High Temperature SiC

[1] J. Hornberger, A. B. Lostetter, K. J. Olejniczak, T. McNutt, S. M. Lal, and A. Mantooth, "Silicon-carbide (SiC) semiconductor power electronics for extreme high-temperature environments," in Aerospace Conference, 2004. Proceedings. 2004 IEEE, 2004, pp. 2538- 2555 Vol.4.

[2] T. Funaki, J. C. Balda, J. Junghans, A. S. Kashyap, H. A. Mantooth, F. Barlow, T. Kimoto, and T. Hikihara, "Power Conversion With SiC Devices at Extremely High Ambient Temperatures," Power Electronics, IEEE Transactions on, vol. 22, pp. 1321-1329, 2007.

[3] R. Mousa, D. Planson, H. Morel, B. Allard, and C. Raynaud, "Modeling and high temperature characterization of SiC-JFET," in Power Electronics Specialists Conference, 2008. PESC 2008. IEEE, 2008, pp. 3111-3117.

[4] T. Burke, K. Xie, J. R. Flemish, H. Singh, T. Podlesak, and J. H. Zhao, "Silicon carbide power devices for high temperature, high power density switching applications," in Power Modulator Symposium, 1996., Twenty-Second International, 1996, pp. 18-21.

[5] R. Mousa, D. Planson, H. Morel, and C. Raynaud, "High temperature characterization of SiC JFET and modelling," in Power Electronics and Applications, 2007 European Conference on, 2007, pp. 1-10.

[6] M. S. Chinthavali, B. Ozpineci, and L. M. Tolbert, "High-temperature and high-frequency performance evaluation of 4H-SiC unipolar power devices," in Applied Power Electronics Conference and Exposition, 2005. APEC 2005. Twentieth Annual IEEE, 2005, pp. 322-328 Vol. 1.

[7] J. M. Homberger, S. D. Mounce, R. M. Schupbach, A. B. Lostetter, and H. A. Mantooth, "High-temperature silicon carbide (SiC) power switches in multichip power module (MCPM) applications," in Industry Applications Conference, 2005. Fourtieth IAS Annual Meeting. Conference Record of the 2005, 2005, pp. 393-398 Vol. 1.

[8] T. Funaki, A. S. Kashyap, H. A. Mantooth, J. C. Balda, F. D. Barlow, T. Kimoto, and T. Hikihara, "Characterization of SiC JFET for Temperature Dependent Device Modeling," in Power Electronics Specialists Conference, 2006. PESC '06. 37th IEEE, 2006, pp. 1-6.

List of References – High Temperature SiC

[9] A. Lostetter, J. Hornberger, B. McPherson, B. Reese, R. Shaw, M. Schupbach, B. Rowden, A. Mantooth, J. Balda, T. Otsuka, K. Okumura, and M. Miura, "High-temperature silicon carbide and silicon on insulator based integrated power modules," in Vehicle Power and Propulsion Conference, 2009. VPPC '09. IEEE, 2009, pp. 1032-1035.

[10] J. Hornberger, A. Lostetter, T. McNutt, S. Magan Lal, and A. Mantooth, "The application of siliconcarbide (SiC) semiconductor power electronics to extreme high-temperature extra terrestrial environments," Proceedings of the 2004 IEEE Aerospace Conference, MT, March 2004.

[11] J. Hornberger, S. Mounce, R. Schupbach, B.McPherson, H. Mustain, A. Mantooth, W.Brown, and A.B. Lostetter, "High-temperature integration of silicon carbide (SiC) and Silicon-on-Insulator Reference 146 (SOI) electronics in multichip power modules (MCPMs)," 11th European Conference on Power Electronics and Applications (EPE2005), Dresden Germany, September 2005.

[12] S. Mounce, B. McPherson, R. Schupbach, A.B. Lostetter, "Ultra-lightweight, high efficiency SiC based power electronic converters for extreme environments," Aerospace Conference, 2006 IEEE 4- 11 March 2006 pp.1-19.

[13] H.A. Mustain, A.B. Lostetter, W.D. Brown, "Evaluation of gold and aluminum wire bond performance for high temperature (500 /spl deg/C) silicon carbide (SiC) power modules",Electronic Components and Technology Conference, 2005. Proceedings. 55th 31 May-3 June 2005 Page(s):1623 - 1628 Vol. 2.

[14] A. Lindgren, and M. Domeij, "1200 V 6 A high temperature SiC BJTs," in Proc. IMAPS Int'l Conference and Exhibition on High Temperature Electronics (HiTEC) 2010, pp. 160-166, 2010.

[15] R. Singh, S. Sundaresan, E. Lieser, and M. Digangi, "1200 V SiC 'super' junction transistors operating at 250 °C with extremely low energy losses for power conversion applications," in Proc. IEEE APEC 2012, pp. 2516-2520, Feb. 2012.

List of References – High Temperature SiC

[16] L. Cheng, A. K. Agarwal, S. Dhar, S.-H. Ryu, and J. W. Palmour, "Static performance of 20 A, 1200 V 4H-SiC power MOSFETs at temperatures of -187 °C to 300 °C," in Journal of Electronic Materials, vol. 41, no. 5, pp. 910-914, 2012.

[17] S. Araujo, P. Zacharias, "Reducing expenditure with cooling in renewable power conversion systems with innovative SiC switches," *Integrated Power Electronics Systems (CIPS)*, pp.1-6, 6-8 March 2012.

[18] C. DiMarino, "High Temperature Characterization and Analysis of Silicon Carbide (SiC) Power Semiconductor Transistors," MS Thesis, Virginia Tech, May 2014.

[19] R. Singh, S. Sundaresan, E. Lieser, M. Digangi, "1200 V SiC 'super' junction transistors operating at 250 ºC with extremely low energy losses for power conversion applications," IEEE APEC, pp. 2516-2520, Feb. 2012.

[20] Z. Chen, Y. Yao, M. Danilovic, D. Boroyevich, "Performance evaluation of SiC power MOSFETs for high temperature applications," IEEE ECCE, pp. DS1a.8-1- DS1a.8-9, Sept. 2012.

[21] P. Losee, A. Bolotnikov, L. Yu, R. Beaupre, et al., "1.2kV class SiC MOSFETs with improved performance over wide operating temperature," IEEE ISPSD, pp. 297-300, 2014.

List of References – High Temperature Packaging

[1] Z. Liang, J. Yin, and J. D. v. Wyk, "An advanced packaging approach of sic high temperature power electronics modules by embedding chip interconnection," presented at the IMPAS HiTEC 2006, 2006.

[2] N. Puqi, T. G. Lei, F. Wang, L. Guo-Quan, and K. D. T. Ngo, "A Novel High-Temperature Planar Package for SiC Multi-Chip Phase-Leg Power Module," in Applied Power Electronics Conference and Exposition, 2009. APEC 2009. Twenty-Fourth Annual IEEE, 2009, pp. 2061- 2067.

[3] Y. Sugawara, D. Takayama, K. Asano, R. Singh, H. Kodama, S. Ogata, and T. Hayashi, "3 kV 600 A 4H-SiC high temperature diode module," in Power Semiconductor Devices and ICs, 2002. Proceedings of the 14th International Symposium on, 2002, pp. 245-248.

[4] Y. Jian, L. Zhenxian, and J. D. van Wyk, "High temperature embedded power module," in Applied Power Electronics Conference and Exposition, 2005. APEC 2005. Twentieth Annual IEEE, 2005, pp. 357-361 Vol. 1.

[5] B. Reese, B. McPherson, and R. Shaw, "High Temperature (250 °C) Silicon Carbide Power Modules With Integrated Gate Drive Boards," presented at the International Conference on High Temperature Electronics (HiTEC 2010), Albuquerque, New Mexico, 2010.

[6] J. Guofeng Bai, Y. Jian, Z. Zhiye, L. Guo-Quan, and J. D. van Wyk, "High-Temperature Operation of SiC Power Devices by Low-Temperature Sintered Silver Die-Attachment," Advanced Packaging, IEEE Transactions on, vol. 30, pp. 506-510, 2007

[7] P. Ning, “Design and Development of High Density High Temperature Power Module with Cooling System,” PhD Dissertation, Virginia Tech, May 2010.

[8] R. W. Johnson, M. Palmer, C. Wang, Y Liu, "Packaging materials and approaches for high temperature SiC power devices", Advancing Microelectronics, vol. 31 no. 1, pp. 8-11, Jan.-Feb. 2004.

[9] L. Coppola, D. Huff, F. Wang, R. Burgos, D. Boroyevich, "Survey on high-temperature packaging materials for SiC-based power electronics modules," in Proc. IEEE PESC, pp. 2234 – 2240, 2007.

List of References – High Temperature Packaging

[10] P. Ning, R. Lai, D. Huff, F. Wang, and K. D. T. Ngo, "250°C SiC power module package dDesign," in Proc. SAE PSC 2008, Nov. 2008, pp. 217-223.

[11] D. C. Katsis and Z. Yunqi, "Development of an extreme temperature range silicon carbide power module for aerospace applications," in Power Electronics Specialists Conference, 2008. PESC 2008. IEEE, 2008, pp. 290-294.

[12] S. Kulkarni, F. Barlow, A. Elshabini, and R. Edgeman, "SiC and GaN die attach for extreme environment electronics," in Proc. IMAPS 2008, November, 2008, pp. 1119-1125.

[13] N. Yue, thesis, “Planar packaging and electrical characterization of high temperature SiC power electronic devices,” Virginia Polytechnic Institute and State University, 2008.

[14] T. G. Lei, J. N. Calata, G-Q Lu, “Low-temperature sintering of nanoscale silver paste for hightemperature power chip attachment”, 5th Inter. Conf. on Integrated Power Electronics Systems, CIPS 2008.

[15] J. N. Calata, T. G. Lei, G-Q. Lu, "Sintered nanosilver paste for high-temperature power semiconductor device attachment," Int. J. Materials and Product Technology, Vol. 34, No. 1/2, 2009, pp. 95-110.

[16] B. Grummel, R. McClure, L. Zhou, A. P. Gordon, L. Ghow, and Z. J. Shen, “Design consideration of high temperature SiC power modules,” in Proc. IEEE IECON 2008, pp. 2861-2866, Nov. 2008.

[17] Y. Yao, Z. Chen, G.-Q. Lu, D. Boroyevich, and K. D. T. Ngo, “Characterization of encapsulants for high-voltage high-temperature power electronic packaging,” in IEEE Trans. Components, Packaging and Manufacturing Technology, vol. 2, no. 4, pp. 539-547, Apr. 2012.

[18] Y. Yao, Z. Chen, D. Boroyevich, and K. D. T. Ngo, “High-temperature reliability of direct-bond-copper substrates with sealed edges,” in Proc. IMAPS HiTEC 2012, pp. 1-5, May 2012.

[19] J. D. Scofield, J. N. Merrett, J. Richmond, A. Agarwal, and S. Leslie, "Performance and Reliability Characteristics of 1200V, 100A, 200C Half-Bridge SiC MOSFET-JBS Diode Power Modules," presented at the International Conference on High Temperature Electronics (HiTEC 2010), 2010.

List of References – High Density SiC

[1] S. Round, M. Heldwein, J. Kolar, I. Hofsajer, and P. Friedrichs, "A SiC JFET driver for a 5 kW, 150 kHz three-phase PWM converter," in Industry Applications Conference, 2005. Fortieth IAS Annual Meeting. Conference Record of the 2005, 2005, pp. 410-416 Vol. 1.

[2] D. Boroyevich, C. Zheng, L. Fang, N. Khai, N. Puqi, W. Ruxi, Z. Di, F. Wang, R. Burgos, L. Rixin, and W. Shuo, "High-density system integration for medium power applications," in Integrated Power Electronics Systems (CIPS), 2010 6th International Conference on, 2010, pp. 1-10.

[3] H. R. Chang, E. Hanna, and A. V. Radun, "Demonstration of silicon carbide (SiC) -based motor drive," in Industrial Electronics Society, 2003. IECON '03. The 29th Annual Conference of the IEEE, 2003, pp. 1116-1121 Vol.2.

[4] C.Rebbereh, H.Schierling, and M.Braun, "First inverter using silicon carbide power switches only," in EPE 2003, 2003.

[5] R. Lai, Analysis and Design for a High Power Density Three-Phase AC Converter Using SiC Devices, dissertation, 2008, Virginia Polytechnic institute and state university.

[6] R. M. Cuzner and J. C. VanderMeer, “Impacts to the power density of ship electric drives,” IEEE Power Electronics Society Newsletter, vol. 16, no. 3, pp.10-12, 2004.

[7] D. Aggeler, J. Biela and J. W. Kolar, “A compact, high voltage 25 kW, 50 kHz dc-dc converter based on SiC JFETs,” Proc. of APEC 2008, pp. 801-807.

[8] C. Cass, R. Burgos, F. Wang and B. Dushan, “Three-phase ac buck rectifier using normally-on SiC JFETs at 150 kHz switching frequency,” Proc. of PESC 2007, pp. 2162-2167.

[9] E. Cilio, J. M. Hornberger, B. McPherson, R. M. Schupbach, A. B. Lostetter and J. Garrett, “A novel high density 100 kW three-phase silicon carbide (SiC) multichip power module (MCPM) inverter,” Proc. of APEC 2007, pp. 666-672.

List of References – High Density SiC

[10] C. Callaway, Y. Wang, R. Burgos, T. P. Chow, F. Wang, and D. Boroyevich, “Evaluation of SiC JFETs for a three-phase current-source rectifier with high switching frequency,” Proc. IEEE Appl. Power Electron. Conf. (APEC), pp. 345-351, 2007.

[11] Z. Chen, “Electrical Integration of SiC Power Devices for High-Power-Density Applications,” PhD Dissertation, Virginia Tech, Sept. 2013.

List of References – High Voltage SiC

[1] Zhao, P. Alexandrov, and X. Li, "Demonstration of the First 10-kV 4HSiC Schottky Barrier Diodes," IEEE Electron Device Letters, vol. 24, no. 6, June 2003, pp. 402–404.

[2] A. Bolotnikov, P. Losee, K. Matocha, J. Glaser, J. Nasadoski, and L. Wang et al, "3.3 kV SiC MOSFETs designed for low on-resistance and fast switching," in Proc. Int'l Symposium on Power Semiconductor Devices and ICs (ISPSD) 2012, pp. 389-392, Jun. 2012.

[3] S. H. Ryu, S. Krishnaswami, M. O'Loughlin, J. Richmond, A. Agarwal, and J. Palmour et al, "10-kV 123-mΩ·cm 2 , 4H-SiC power DMOSFETs," in IEEE Electron Device Letters, vol. 25, no. 8, pp. 556-558, Aug. 2004.

[4] S. H. Ryu, S. Krishnaswami, B. Hull, J. Richmond, A. Agarwal, and A. R. Hefner, "10 kV, 5 A 4H-SiC power DMOSFET," in Proc. IEEE ISPSD 2006, pp. 1-4, 2006.

[5] M. K. Das, C. Capell, D. E. Grider, R. Raju, M. Schutten, and J. Nasadoski et al, "10 kV, 120 A SiC half H-bridge power MOSFET modules suitable for high frequency, medium voltage applications," in Proc. IEEE ECCE 2011, pp. 2689- 2692, Sept. 2011.

[6] B. Callanan, "Characteristics, application, and high power demonstration of 1.7 kV 100 mΩ silicon carbide MOSFETs," Special Presentation in IEEE APEC 2011, SP2.3.4, Mar. 2011.

[7] B. A. Hull, J. J. Sumakeris, M. J. O'Loughlin, Q. Zhang, J. Richmond, A. R. Powell, E. A. Imhoff, K. D. Hobart, A. Rivera-Lopez, A. R. Hefner, "Performance and stability of large-area 4H-SiC 10-kV junction barrier Schottky rectifiers," IEEE Trans. Electron. Devices, vol. 55, no. 8, pp. 1864-1870, 2008.

[8] H. Mirzaee, A. De, A. Tripathi, S. Bhattacharya, "Design comparison of high-power medium-volage converters based on a 6.5-kV Si-IGBT/Si-PiN diode, a 6.5-kV Si-IGBT/SiC-JBS diode, and a 10-kV SiC-MOSFET/SiC-JBS diode," IEEE Trans. Ind. Appl., vol. 50, no. 4, July/Aug. 2014.

[9] D. Grider, M. Das, R. Raju, M. Schutten, S. Leslie, J. Ostop, A. Hefner, "10 kV/120 A SiC DMOSFET half H-bridge power modules for 1 MVA solid state power substation," in IEEE ESTS, pp. 131-134, 2011.

[10] T. H. Duong, A. Rivera-Lopez, A. R. Hefner, "Circuit simulation model for a 100 A, 10 kV half-bridge SiC MOSFET/JBS power module," in Proc. IEEE APEC, pp. 913-917, 2008.

List of References – High Voltage SiC

[11] J. Thoma, D. Chilachava, D. Kranzer, "A highly efficient dc-dc converter for medium-voltage applications," IEEE ENERGYCON, pp. 127-131, 2014.

[12] O. Hohlfeld, R. Bayerer, T. Hunger, H. Hartung, "Stacked substrates for high voltage applications," IEEE CIPS, pp. 1-4, 2012.

[13] A. Kadavelugu, K. Mainali, D. Patel, et al., "Medium voltage power converter design and demonstration using 15 kV SiC n-IGBTs," IEEE APEC, pp. 1396-1403, 2015.

List of References – SiC Transistors

[1] I. Sankin, D.C. Sheridan, W. Draper, V. Bondarenko, R. Kelley, M.S. Mazzola, and J.B. Casady, "Normally-off SiC VJFETs for 800 V and 1200 V power switching applications," Proceedings of the 20th International Symposium on Power Semiconductor Devices & IC's May 18-22, 2008 Oralando, FL, pp. 260-262.

[2] R.J. Callanan, A. Agarwal, A. Burk, M. Das, B. Hull, F. Husna, A. Powell, J. Richmond, S. Ryu, Q. Zhang, "Recent progress in SiC DMOSFETs and JBS diodes at Cree," Industrial Electronics, 2008. IECON 2008. 34th Annual Conference of IEEE,10-13 Nov. 2008, pp. 2885 – 2890.

[3] Z. Chen, D. Boroyevich, R. Burgos, and F. Wang, "Characterization and modeling of 1.2 kV, 20 A SiC MOSFETs," in Proc. IEEE ECCE 2009, pp. 1480-1487, Sept. 2009.

[4] Z. Chen, Characterization and Modeling of High-Switching-Speed Behavior of SiC Active Devices, M. S. Thesis, Virginia Polytechnic Institute and State University, Dec. 2009.

[5] M. Domeij, H. S. Lee, C. M. Zetterling, M. Ostling, "Analysis of the base current and saturation voltage in 4H-SiC power BJTs," IEEE EPE, pp. 1-7, Sept. 2007.

[6] Y. Gao, "Analysis and optimization of 1200V silicon carbide bipolar junction transistor," Ph.D. dissertation, Dept. Elect. Eng., NC State Univ., Raleigh, NC, 2007.

[7] Claudio, H. Wang, A. Q. Huang, A. K. Agarwal, "Static and dynamic characterization of silicon carbide bipolar junction transistor," IEEE IECON, vol. 2, pp. 1173-1178, Nov. 2003.

[8] Buono, "Simulation and characterization of silicon carbide power bipolar junction transistors," Ph.D. dissertation, Integr. Dev. Circuits Dept., KTH Royal Inst. Techol., Stockholm, Sweden, 2012.

[9] B. Buono, R. Ghandi, M. Domeij, B. G. Malm, C. M. Zetterling, M. Ostling, "Modeling and characterization of current gain versus temperature in 4H-SiC power BJTs," IEEE Trans. Electron. Dev., vol. 57, no. 3, pp. 704-711, March 2010.

[10] M. J. Kumar, P. Vinod, "Enhanced current gain in SiC power BJTs using surface accumulation layer transistor (SALTran) concept," J. Microelectron. Eng., vol. 81, pp. 90-95, April 2005.

List of References – SiC Transistors

[11] X. Li, Y. Luo, L. Fursin, J. H. Zhao, M. Pan, P. Alexandrov, M. Weiner, "On the temperature coefficient of 4H-SiC BJT current gain," Solid-State Electron., vol. 47, pp. 233-239, April 2003.

[12] R. Siemieniec, U. Kirchner, "The 1200V direct-driven SiC JFET power switch," IEEE EPE, pp. 1-10, Sept. 2011.

[13] W. Berger, F. Bjoerk, D. Domes, G. Deboy, "Infineon's 1200V SiC JFET- The new way of efficient and reliable high voltages switching," www.infineon.com, accessed: Apr. 2014.

[14] I. Sankin, D. C. Sheridan, W. Draper, V. Bondarenko, R. Kelley, M. S. Mazzola, J. B. Casady, "Normally-off SiC VJFETs for 800 V and 1200 V power switching applications," IEEE ISPSD, pp. 260-262, May 2008.

[15] R. Burgos, Z. Chen, D. Boroyevich, and F. Wang, "Design considerations of a fast 0-Ω gate-drive circuit for 1.2 kV SiC JFET devices in phase-leg configuration," in Proc. IEEE ECCE 2009, pp. 2293–2300, Sept. 2009.

[16] K Okumura, N. Hase, K. Ino, T. Nakamura, M. Tanimura, "Ultra low on-resistance SiC trench devices," Power Semiconductors Mag., no. 4, pp. 22-25, 2012.

[17] A. Agarwal, Q. Zhang, A. Burk, R. Callanan, S. Maxumder, "Prospects of bipolar power devices in silicon carbide," IEEE IECON, pp. 2879-2884, 2008.

[18] K. Uchida, Y. Saitoh, T. Hiyoshi, T. Masuda, et al., "The optimised design and characterization of 1200 V / 2.0 mΩ cm^2 4H-SiC V-groove trench MOSFETs," IEEE ISPSD, pp. 85-88, 2015.

[19] V. Pala, A. Barkley, B. Hull, G. Wang, et al., "900 V silicon carbide MOSFETs for breakthrough power supply design," IEEE ECCE, pp. 4145-4150, 2015.

List of References – Device Comparisons

[1] T. Zhao, J. Wang, A. Huang, and A. Agarwal, “Comparisons of SiC MOSFET and Si IGBT based motor drive systems,” in Proc. IEEE Industrial Applications Conf., pp. 331-335, Sept. 2007.

[2] J. S. Glaser, J. J. Nasadoski, P. A. Losee, A. S. Kashyap, K. S. Matocha, and J. L. Garret et al, “Direct comparison of silicon and silicon carbide power transistors in high-frequency hard-switched applications,” in Proc. IEEE APEC 2011, pp. 1049- 1056, Mar. 2011.

[3] A. Kadavelugu, V. Baliga, S. Bhattacharya, M. Das, and A. Agarwal, “Zero voltage switching performance of 1200 V SiC MOSFET, 1200 V silicon IGBT and 900 V CoolMOS MOSFET,” in Proc. IEEE ECCE 2011, pp. 1819-1826, Sept. 2011.

[4] L. D. Stevanovic, K. S. Matocha, P. A. Losee, J. S. Glaser, J. J. Nasadoski, S. D. Arthur, “Recent advances in silicon carbide MOSFET power devices,” IEEE APEC, pp. 401-407, Feb. 2010.

[5] J. McBryde, A. Kadavelugu, B. Compton, S. Bhattacharya, M. Das, A. Agarwal, “Performance comparison of 1200 V silicon and SiC devices for UPS application,” IEEE IECON, pp. 2657-2662, Nov. 2010.

[6] S. Piasecki, A. M. Cantarellas, J. Rabkowski, P. Rodriguez, “Design of AC-DC power converters with LCL + tuned trap line filter using Si IGBT and SiC MOSFET modules,” IEEE IECON, pp. 5957-5962, Nov. 2013.

[7] W. T. Franke, “Comparison of six different SiC power switching devices in the 1200 V range,” PCIM, 2012.

[8] A. Lemmon, M. Mazzola, J. Gafford, K. M. Speer, “Comparative analysis of commercially available silicon carbide transistors,” IEEE APEC, pp. 2509-2515, 2012. [35] B. Rubino, M. Macauda, M. Nania, S. Buonomo, “Direct comparison among different technologies in silicon carbide,” PCIM, 2012.

[9] K. Haehre, M. Meisser, F. Denk, R. Kling, “Characterization and comparison of commercially available silicon carbide (SiC) power switches,” PEMD, pp. 1-6, 2012.

[10] S. H. Ryu, S. Krishnaswami, B. A. Hull, B. Heath, F. Husna, J. Richmond, A. Agarwal, J. Palmour, J. Scofield, “A comparison of high temperature performance of SiC DMOSFETs and JFETs,” Mater. Sci. Forum, vols. 556-557, pp. 775-778, Sept. 2007.

List of References – Device Comparisons

[11] C. DiMarino, Z. Chen, M. Danilovic, D. Boroyevich, R. Burgos, P. Mattavelli, “High-temperature characterization and comparison of 1.2 kV SiC power MOSFETs,” IEEE ECCE, pp. 3235-3242, Sept. 2013.

[12] C. DiMarino, Z. Chen, D. Boroyevich, R. Burgos, P. Mattavelli, “Characterization and comparison of 1.2 kV SiC power semiconductor devices,” IEEE EPE, pp. 1- 10, Sept. 2013.

[13] C. DiMarino, Z. Chen, D. Boroyevich, R. Burgos, P. Mattavelli, “High-temperature characterization and comparison of 1.2 kV SiC power semiconductor devices,” J. Microelectron. Electron. Packaging, vol. 10, no. 4, pp. 138, 2013

[14] A. Ong, J. Carr, J. Balda, A. Mantooth, “A comparison of silicon and silicon carbide MOSFET switching characteristics,” IEEE Region 5 Tech. Conf., pp. 273-277, Apr. 2007.

List of References – SiC Reliability

[1] M. Maranowski, and J. Cooper Jr., "Time-dependent-dielectric breakdown measurements of thermal oxides on N-type 6H-SiC," in IEEE Trans. Electron Devices, vol. 46, no. 3, pp. 520-524, Mar. 1999.

[2] R. Singh, "Reliability and performance limitations in SiC power devices," in Microelectronics Reliability, vol. 46, pp. 713-730, 2006.

[3] A. Agarwal, S. Seshadri, and L. Rowland, "Temperature dependence of Fowler Nordheim current in 6H- and 4H-SiC MOS capacitors," in IEEE Electron Device Letters, vol. 18, no. 12, pp. 592-594, Dec. 1997.

[4] L. Yu, K. Cheung, J. Campbell, J. Suehle, and K. Sheng, "Oxide reliability of SiC MOS devices," in IEEE Int'l Integrated Reliability Workshop Final Report 2008, pp. 141-144, Oct. 2008.

[5] L. Yu, G. Dunne, K. Matocha, K. Cheung, J. Suehle, and K. Sheng, "Reliability issues of SiC MOSFETs: a technology for high temperature environments," in Chapter 2 44 IEEE Trans. Device and Materials Reliability, vol. 10, no. 4, pp. 418-426, Dec. 2010.

[6] A. Lelis, D. Habersat, R. Green, A. Ogunniyi, M. Gurfinkel, and J. Suehle et al, "Time dependence of bias-stress-induced SiC MOSFET threshold-voltage instability measurements," in IEEE Trans. Electron Devices, vol. 55, no. 8, pp. 1835-1840, Aug. 2008.

[7] M. Gurfinkel, H. D. Xiong, K. P. Cheung, J. S. Suehle, J. B. Bernstein, and Y. Shapira et al, "Characterization of transient gate oxide trapping in SiC MOSFETs using fast I-V techniques," in IEEE Trans. Electron Devices, vol. 55, no. 8, pp. 2004-2012, Aug. 2008.

[8] A. J. Lelis, R. Green, and D. Habersat, "High-temperature reliability of SiC power MOSFETs," in Materials Science Forum, vol. 679-680, pp. 599-602, 2011.

[9] A. Lelis, R. Green, and D. Habersat, "Effect of threshold-voltage instability on SiC power MOSFET high-temperature reliability," in ECS Transactions, vol. 41, issue 8, pp. 203-214, 2011.

[10] A. Agarwal, H. Fatima, S. Haney, S.H. Ryu, "A new degradation mechanism in high-voltage SiC power MOSFETs," IEEE Electron. Device Lett., vol. 28, no. 7, pp. 587-589, 2007.

List of References – SiC Reliability

[11] R. Singh, "Reliability and performance limitations in SiC power devices," Microelectronics Rel., vol. 46, pp. 713-730, 2006.

[12] J. Liu, M. Skowronski, C. Hallin, R. Soderholm, H. Lendenmann, "Structure of recombination-induced stacking faults in high-voltage SiC p-n junctions," Appl. Physics Lett., vol. 80, no. 5, pp. 749-751, 2002.