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Changes for the Better

Replacing Silicon IGBT Modules with SiC MOSFET Modules

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Presentation Outline

- Market Status SiC Power Devices
  Overview, Market Trends
- SiC Technology Overview
  Material Properties, Performance, Applications
- 1200V SiC Modules
  Static and Dynamic Performance
- 1700V SiC Modules
  Static and Dynamic Performance
- 3300V SiC Modules
  Static and Dynamic Performance
- Summary & Concluding Remarks

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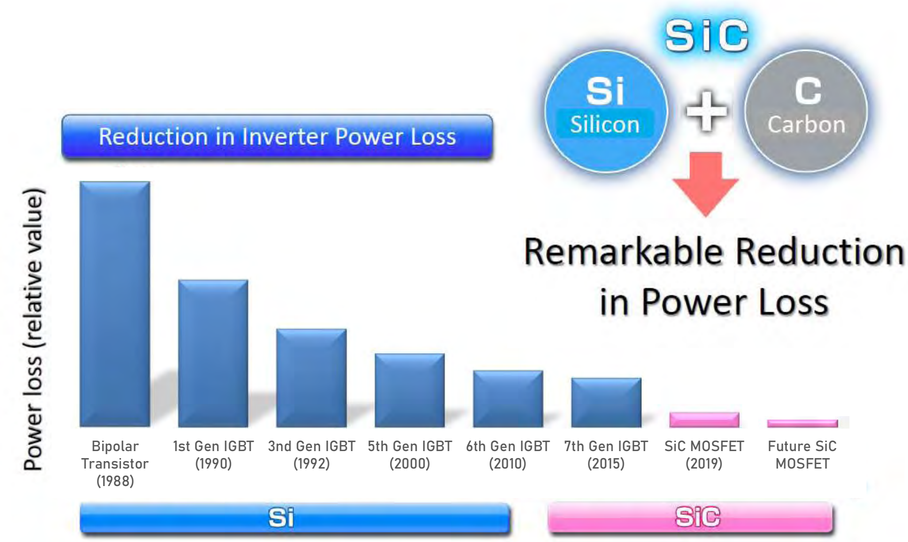
Power Device Technology Trend



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Current Status and Outlook

Use of SiC Devices in High Power Applications is on the rise

- Widely used in propulsion inverters for Electric Vehicles.
- Growing demand for traction applications (Subway, Light Rail, Locomotive).
- New applications such as Smart Grid and Alternative energy are also driving demand.
- Industrial and medical power supply applications also adopting SiC devices.

Silicon is not dead yet…

- The Silicon IGBT is expected to continue as the most cost effective power device for many industrial applications for the next five to ten years
- Currently a 7th generation family of silicon IGBT modules has been developed.
- Optimization and Variations such as the RCIGBT offer additional cost and performance advantages

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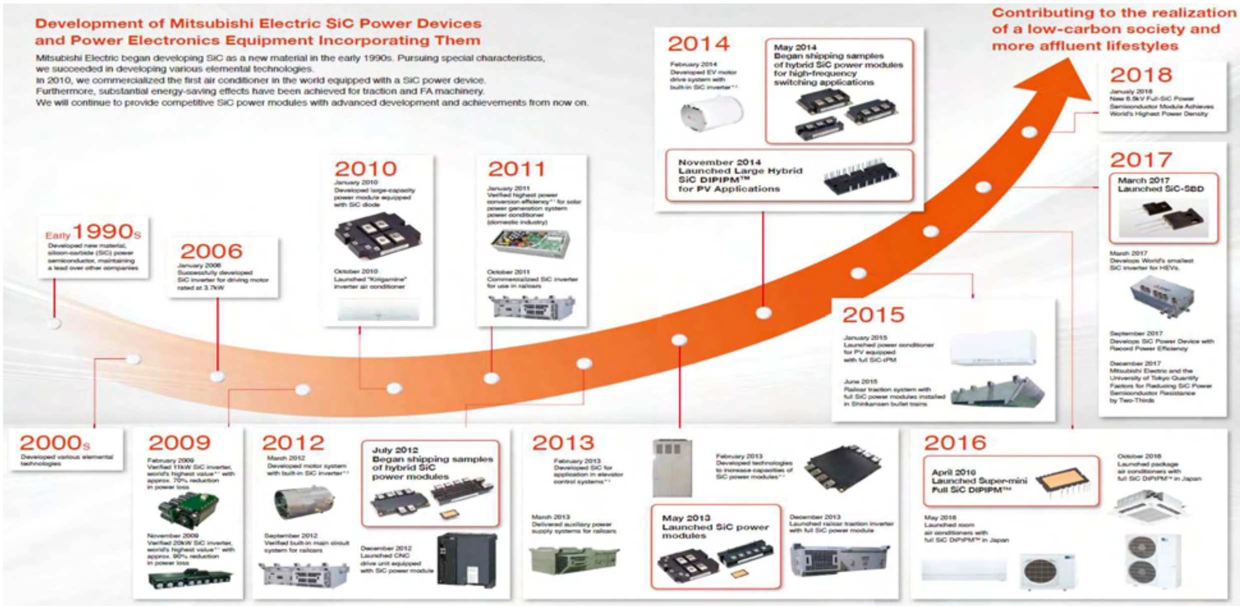
History of SiC Power Device Development



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Physical Properties of SiC

Material	Bandgap Energy (eV)	Dielectric Constant (dimension)	Electron Mobility (cm^2/Vs)	Break Down Electric Field ($10^6 V/cm$)
4H-SiC	3. 25	9. 7	1140	3
Si	1. 1	11. 8	1500	0. 3

Large Band Gap Energy makes higher temperature operation feasible.

High field break down means that a thinner blocking junction can be used for a given voltage. The thinner junction provides reduced switching and conduction losses especially at higher voltages

These properties allow us to make high performance Schottky Diodes and MOSFETs at voltages up to 3000V or more…

Also, IGBT structure has no significant benefit until about 5000V

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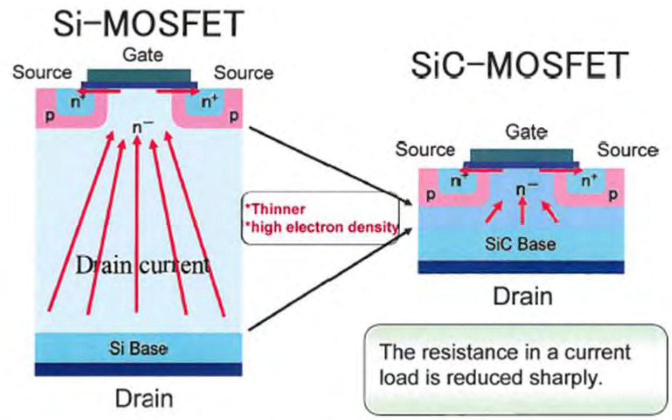
Si versus SiC MOSFET Structure



The thinner blocking junction of the SiC MOSFET makes the MOSFET structure practical to voltages up to about 4000V.
→ 1200V-3300V IGBTs will be replaced with SiC MOSFETs

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Mitsubishi 2nd Generation 1.7kV Planar SiC MOSFET

JFET Doping Technology

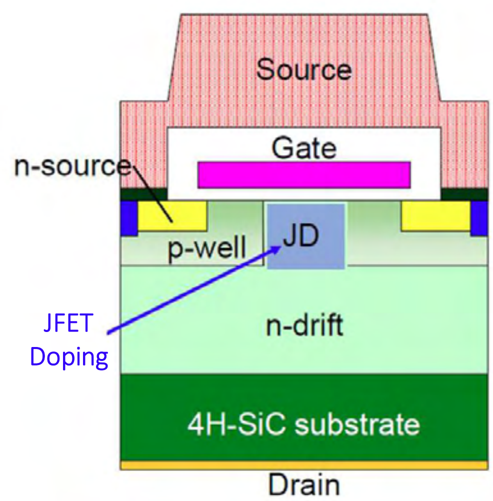
- Applicable to all SiC MOSFETs from 600V to 3.3kV+
- Simple and effective method to reduce on resistance (R_{on})

Improvement of MOS Cell Structure

- Thinner p-well, shrinking of JFET length, optimized channel doping profile
- R_{on} of 7.73mΩ at 300A/125°C
- Improved gate-oxide reliability

Switching Performance

- Miller capacitance reduction allows for faster switching speed than 1st Generation
- Eon and Eoff at 300A are 15mJ and 3.4mJ, respectively, which are among the lowest ever reported [900V bus, RGMIN, 150°C]



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SiC Modules for Traction Applications

3.3 kV/1500 A power modules for the world's first all-SiC traction inverter

Kenji Hamada[1], Shiro Hino[1,2], Naruhisa Miura[1,2], Hiroshi Watanabe[1,2], Shuhei Nakata[1,2], Eisuke Suekawa[3], Yuji Ebiike[3], Masayuki Imaizumi[3], Isao Umezaki[3], and Satoshi Yamakawa[1,2]

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We have successfully developed 4H-SiC devices including metal–oxide–semiconductor field-effect transistors (MOSFETs) and Schottky barrier diodes (SBDs) with a rated voltage of 3.3 kV. The conduction loss of the SiC-MOSFET was reduced to as low as that of the Si-insulated gate bipolar transistor (IGBT) by the n-type doping of the junction field-effect transistor region (JFET doping). The JFET doping technique is effective in reducing the temperature coefficient of resistance in the JFET region, leading to the decreased on-resistance of the SiC-MOSFET at high temperatures. These devices have been applied to 3.3 kV/1500 A modules for the world's first all-SiC traction inverter. The switching loss of the new traction inverter system is approximately 55% less than that of a conventional inverter system incorporating Si modules.

Siemens and Mitsubishi Electric to cooperate in SiC traction technology

SiC devices are increasingly used in train traction systems in Japan to reduce energy consumption.

Siemens Mobility and Munich City Authority (SWM) completed a one-year trial in August 2021 using semiconductor technology based on SiC devices fitted to a three-section Avenio LRV

"Mitsubishi Electric's SiC devices have proven long-term reliability in the most demanding of applications such as traction inverters in trains," Siemens says. "The potential for energy savings through the use of Mitsubishi Electric's SiC power devices in railway technology exists particularly in the area of traction drives. In particular, the full SiC 3300V power modules contribute to energy saving and the downsizing of traction inverters."

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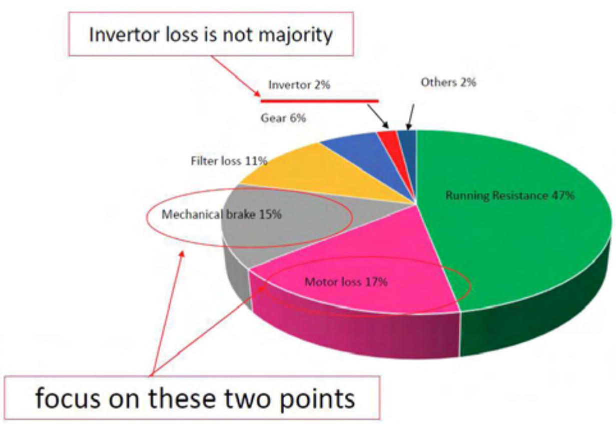
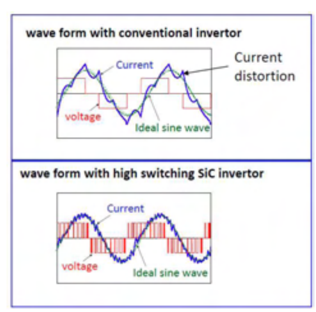
Benefits of SiC in Traction Applications





- Low SiC free wheel diode losses contribute to increased regenerative braking = Less mechanical braking
- Low SiC MOSFET switching losses allow high Fsw for reduced harmonics and higher motor efficiency

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SiC MOSFET SuperMini DIPIPM™

- SiC MOSFET with low ON voltage and low Forward voltage for improved power loss
- Reduced recovery current and EMI noise by applying the body Diode of the SiC MOSFET
- Package compatible with Silicon SuperMini versions

Line-up:

Part Number	Rating
PSF15S92F6	15A/600V
PSF25S92F6	25A/600V

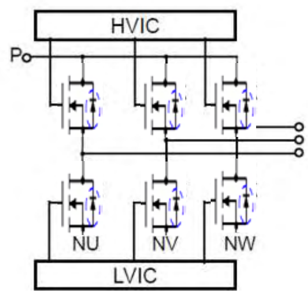
Applications:

Highest Efficiency Inverters
Flagship Models
Designs with Limited Cooling

Package:

24 x 38 [mm]

Circuit Configuration:



Body diode of SiC MOSFET is used as a freewheeling diode.

Features:

Circuit	3ϕ Inverter
Protection	SC, UV, Fo
Temperature Function	Select VOT or OT
Bootstrap Diode	Included
Input Logic	5V / 3.3V Active High
N-side Emitter	Open
Isolation Voltage	1500Vrms
UL1557	Approved

SC: Short Circuit
UV: Under Voltage of control supply
Fo: Fault Output notification
OT: Over-Temperature Protection
VOT: Temperature output information

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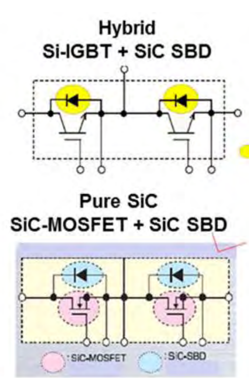
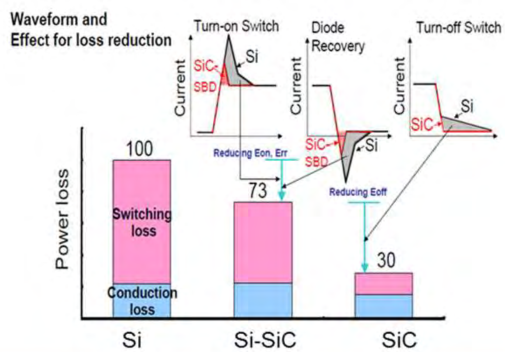
Hybrid Si-SiC .vs Pure SiC Modules





Module Type	Advantages	Disadvantages
Hybrid Si-SiC Module	➢ SiC SBD technology considered more mature ➢ Lower Cost than Pure SiC	➢ Si-IGBT has higher turn-off loss and/or On-state voltage drop. ➢ Frequency of operation limited by Si-IGBT speed ➢ Operating temperature limited by Si-IGBT
Pure SiC Module	➢ Higher temperature operation may be possible with new module designs and chip passivation ➢ Lowest switching losses	➢ Limited SiC MOSFET application experience. ➢ Low Impedance Short Circuit Survival Concerns

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Hybrid Si-SiC Modules for High Frequency Applications

Features

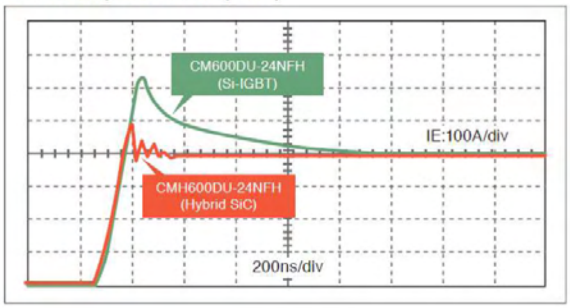
- Power loss reduction of approx. 40% contributes to higher efficiency, smaller size and weight reduction of total system
- Suppresses surge voltage by reducing internal inductance
- Package compatible with the conventional product*

* Conventional product: Mitsubishi Electric NFH Series IGBT Modules

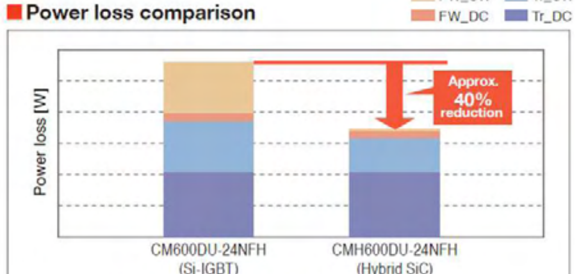
Product lineup

Applications	Model	Rated voltage	Rated current	Circuit configuration	External size (D x W)
Industrial equipment	CMH100DY-24NFH	1200V	100A	2-in-1	48 x 94mm
	CMH150DY-24NFH		150A		48 x 94mm
	CMH200DU-24NFH		200A		62 x 108mm
	CMH300DU-24NFH		300A		62 x 108mm
	CMH400DU-24NFH		400A		80 x 110mm
	CMH600DU-24NFH		600A		80 x 110mm

Recovery waveform (FWD)



Power loss comparison



Condition:Vcc=600V, Io=600Ap, fc=15kHz, P.F=0.8, Modulation=1, Three-phase modulation, Tj=125°C

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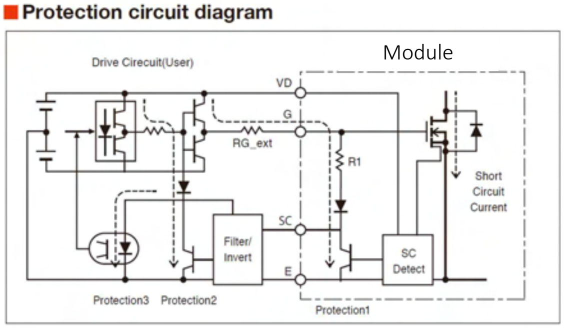
Low inductance SiC Module Packages with RTC

Features

- By using short circuit monitoring circuit in the module it is possible to transfer a short circuit detection signal to the system side
- Power loss reduced approx.70% compared to the conventional product*
- Low- inductance package adopted to deliver full SiC performance

Protection circuit diagram



BXZ (Four Pack) and DXZ(Dual)

Line-Up	
FMF300BXZ-24B	300A, 1200V, Four Pack
FMF400BXZ-24B	400A, 1200V, Four Pack
FMF600DXZ-24B	600A, 1200V, Dual
FMF800DXZ-24B	800A, 1200V, Dual
FMF300DXZ-34B	300A, 1700V, Dual
*FMF400DXZ-34B**	*400A,1700V (Under Consideration)*
FMF1200DXZ-24B	1200A, 1200V, Dual

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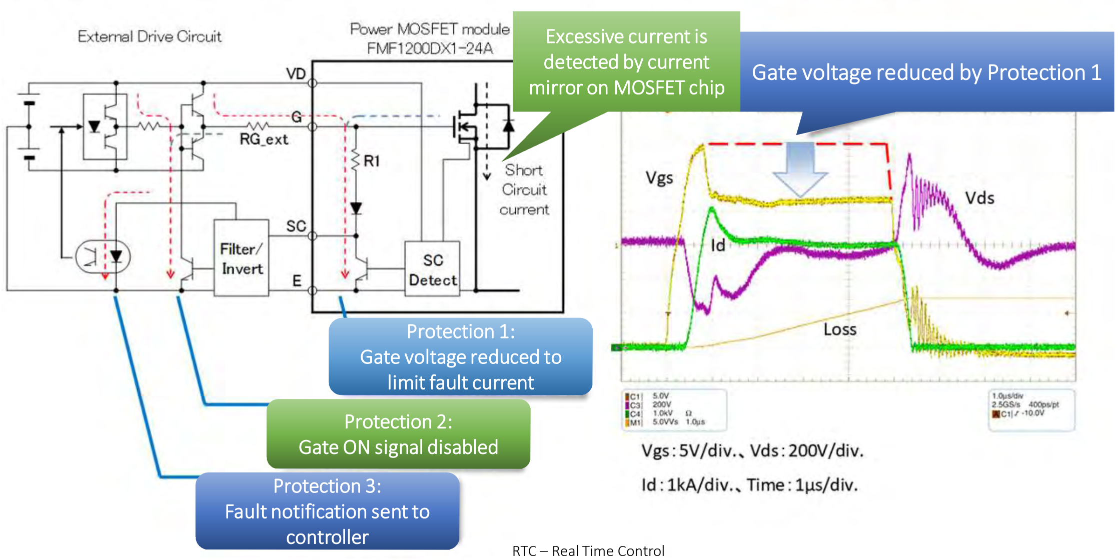
RTC: Short Circuit Protection for SiC Modules

■ **Example of drive circuit** ■ **Short Circuit waveform**



RTC – Real Time Control

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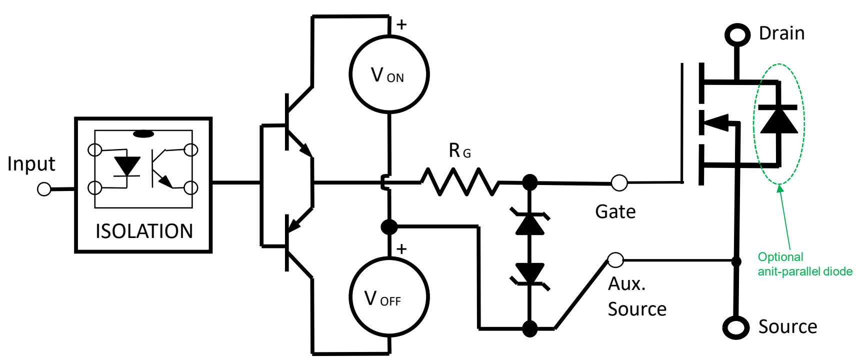
SiC Module Gate Drive



Gate Drive – Voltage applied to SiC MOSFET gate turns the device on and off.

- For most SiC MOSFET modules with included anti-parallel SBD +15V for On and -7V to -15V for Off is recommended
- For SiC MOSFET modules without SBD +15V for On and -5V to -8V for Off is recommended

Basically, SiC MOSFET gate drive is very similar to silicon IGBTs

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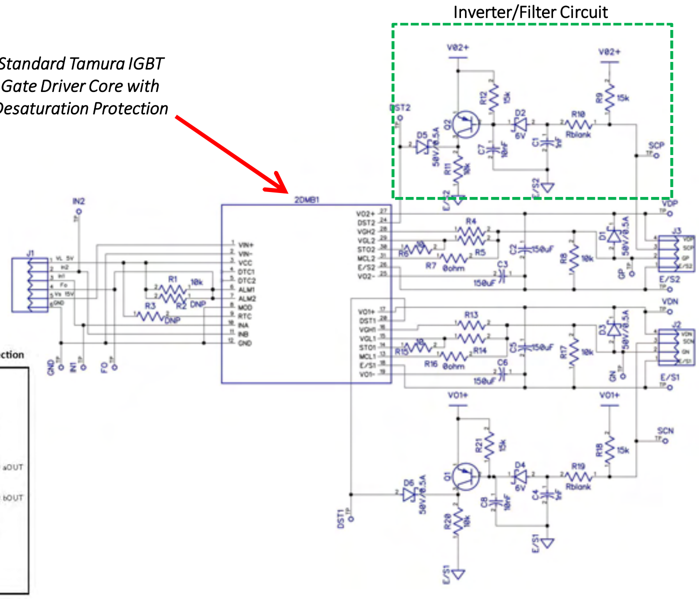
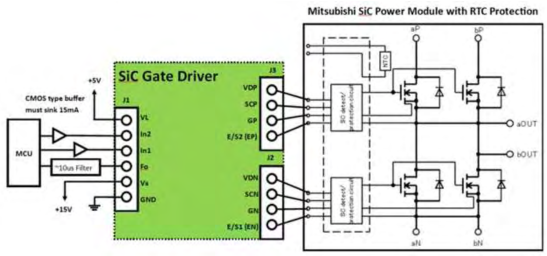
Example Gate Driver for SiC Modules with RTC

Standard Tamura IGBT Gate Driver Core with Desaturation Protection





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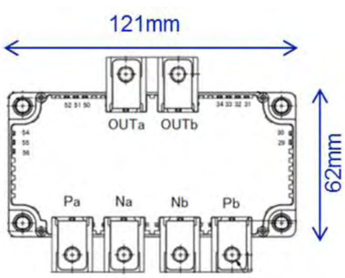
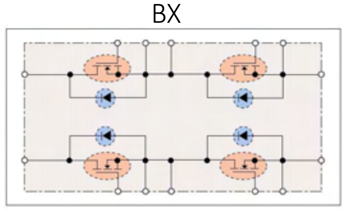
Low inductance packages without RTC



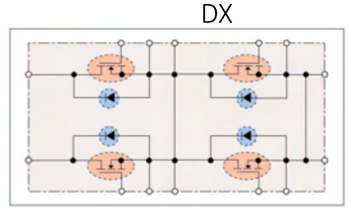
Package outline

Line-Up	
FMF400BX-24B	400A, 1200V
FMF800DX-24B	800A, 1200V

BX



DX



BX (Four pack) and DX (Dual)

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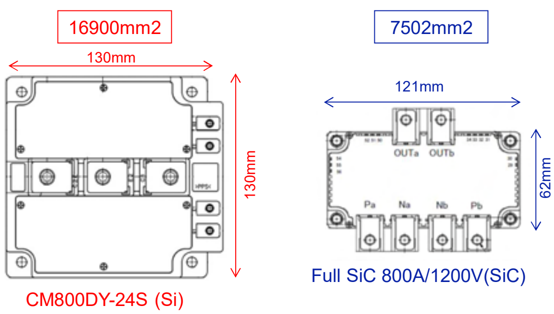
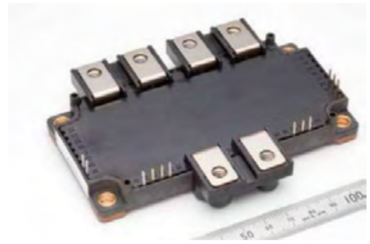
800A, 1200V IGBT vs. SiC MOSFET Module

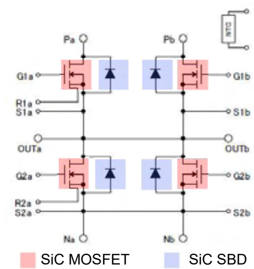
Feature
- ・SiC MOSFET & SiC SBD chip
- ・Low inductance package Ls=10nH (P-N)

Mounting area
- ・56% smaller mounting area





Package outline



Internal connection

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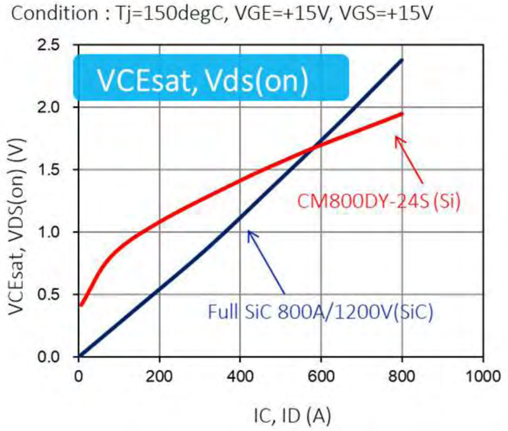
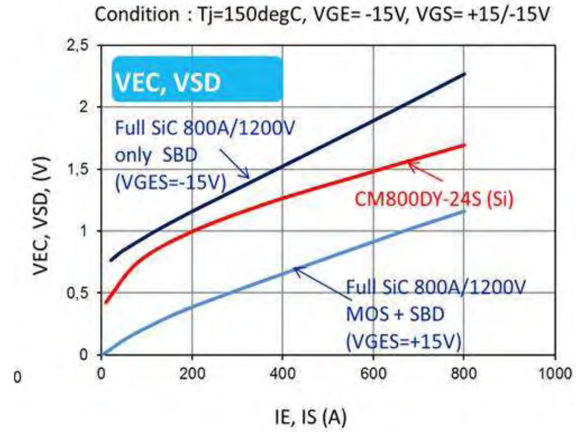
Static Characteristic Comparison

800A/1200V Full-SiC Module vs. Si IGBT

Condition : Tj=150degC, VGE=+15V, VGS=+15V



Condition : Tj=150degC, VGE= -15V, VGS= +15/-15V



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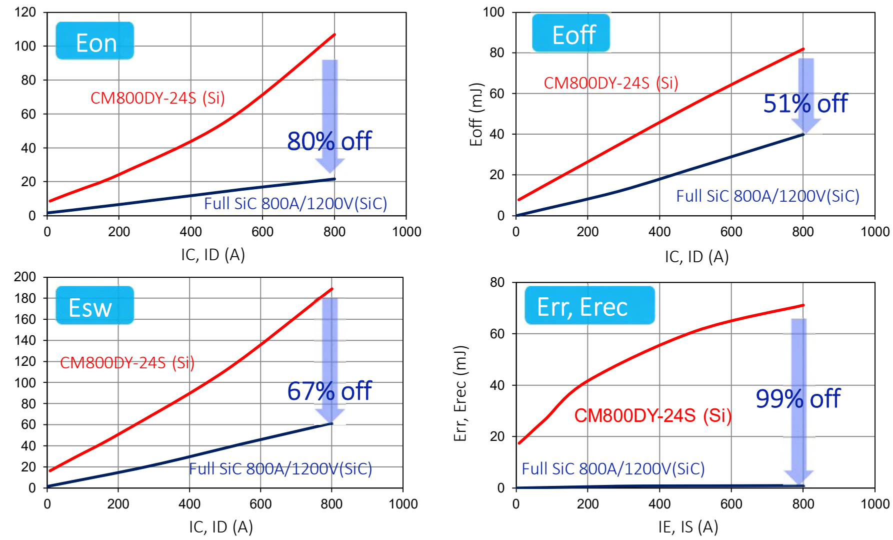
Dynamic Performance Comparison

800A/1200V Full-SiC Module vs. Si IGBT



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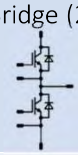
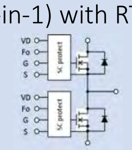
300A / 1700V Si vs. SiC: Module Specifications

	Silicon	Silicon Carbide
Chip Technology	7th Gen. Si CSTBT™ and Si RFC diode	2nd Gen. SiC MOSFET and SiC SBD
Rated Voltage / Current	1700V / 300A	1700V / 300A
Topology	Half Bridge (2-in-1) 	Half Bridge (2-in-1) with RTC Protection 
Dimensions	152 x 62mm	122 x 80mm
Weight	300g	454g

CSTBT™ – Carrier Stored Trench-gate Bipolar Transistor
RFC – Relaxed Field Cathode diode
RTC – Real Time Control

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Si vs. SiC 300A, 1700V Module Characteristics


	Silicon	Silicon Carbide
$T_{vjop\ (continuous)}$	150°C	150°C
Nominal Gate Drive Voltage	+15V / -15V	+15V / -15V
$R_{th(j-c)}$ per IGBT / MOSFET	99 K/kW	114 K/kW
$R_{th(j-c)}$ per FWD / SBD	149 K/kW	123 K/kW
V_{isol}	$4000V_{RMS}$	$4000V_{RMS}$
Gate Charge (Q_G)	2.35µC	1.8µC
Short Circuit SOA	8µs	3µs via RTC Protection

RTC – Real Time Control

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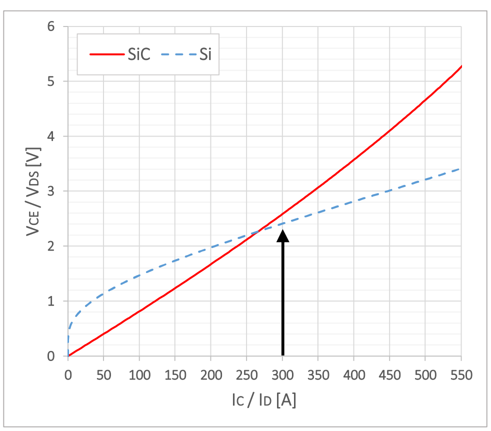
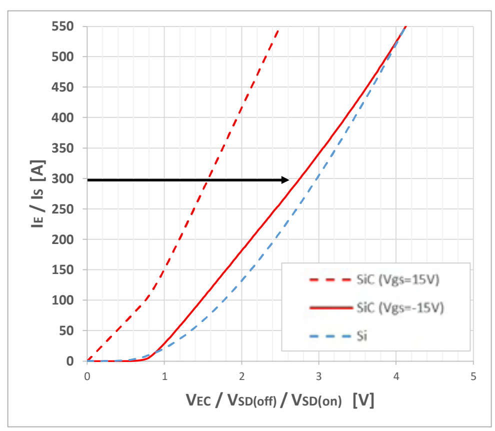
Si IGBT versus SiC MOSFET: Static Characteristics



V_{CE}/V_{DS} Forward Voltage Characteristics
Conditions: 125° C, $V_{GE/GS}$=15V



V_{EC}/V_{SD} Diode/MOSFET Reverse Characteristics
Conditions: 125° C, V_{GE}=-15V for V_{EC},$V_{SD(off)}$, V_{GE}=15V for $V_{SD(on)}$

The Si and SiC modules achieve similar conduction characteristics at rated current of 300A

When using MOSFET reverse characteristic, V_{SD} is reduced significantly

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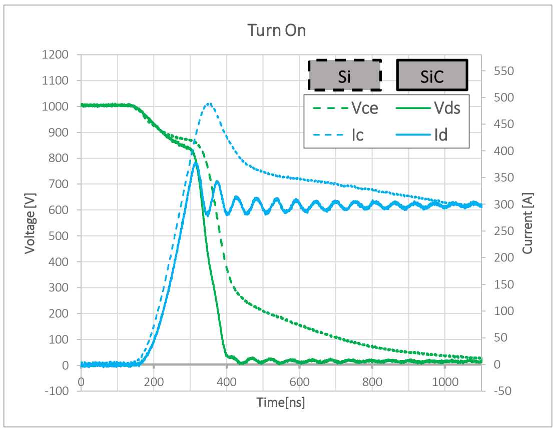
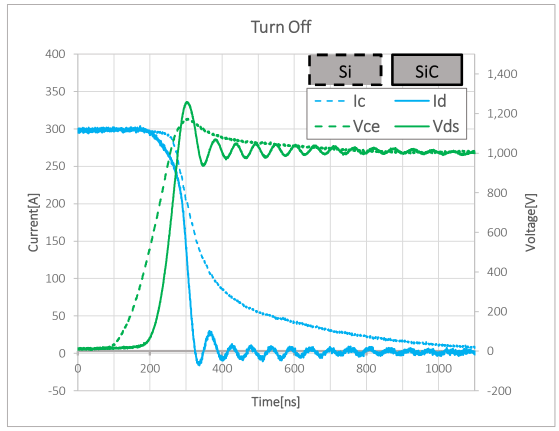
Si IGBT versus SiC MOSFET: Switching Waveforms





Conditions: 125° C, V_{GE}=+15V/-12V, 1000Vdc, R_G(Si)=0Ω, R_{Gon}(SiC)=3.4Ω, R_{Goff}(SiC)=10Ω, Inductive Load

Si Turn On	SiC Turn On	Si Turn Off	SiC Turn Off
Eon = 73.9mJ	Eon = 30.3mJ	Eoff = 69.4mJ	Eoff = 15.2mJ
I_{pk} = 488A	I_{pk} = 377A	V_{pk} = 1174V	V_{pk} = 1258V
di/dt = 3.3A/ns	di/dt = 3.3A/ns	dv/dt = 7.9kV/µs	dv/dt = 15.4kV/µs

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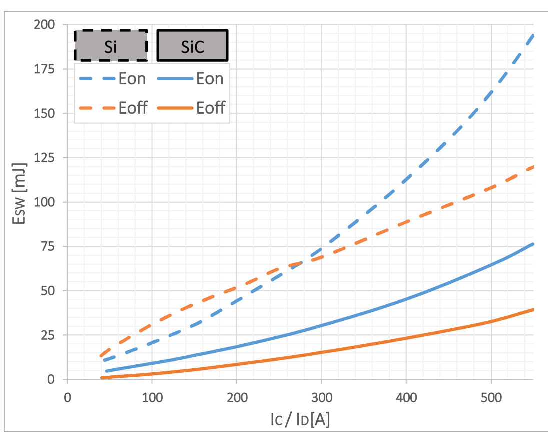
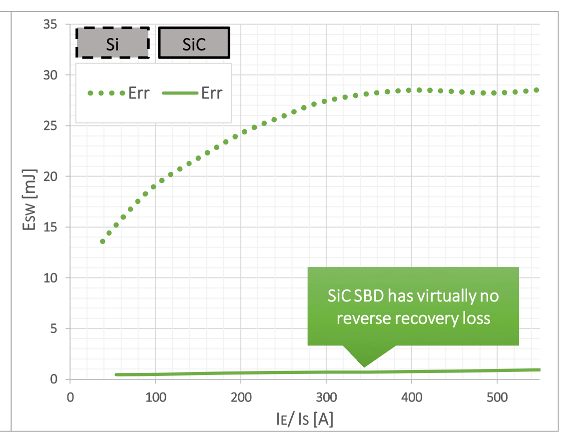
Si IGBT versus SiC MOSFET: Dynamic Characteristics





Conditions: 125° C, V_{GE}=+15V/-12V, 1000Vdc, R_G(Si)=0Ω, R_{Gon}(SiC)=3.4Ω, R_{Goff}(SiC)=10Ω, Inductive Load

Turn On: 300A	Turn Off: 300A	Reverse Recovery: 300A	Total Switching Losses
73.9mJ vs 30.3mJ	69.4mJ vs 15.2mJ	27.5mJ vs 0.7mJ	170.8mJ vs 46.2mJ
59% Lower	78% Lower	97% Lower	73% Lower

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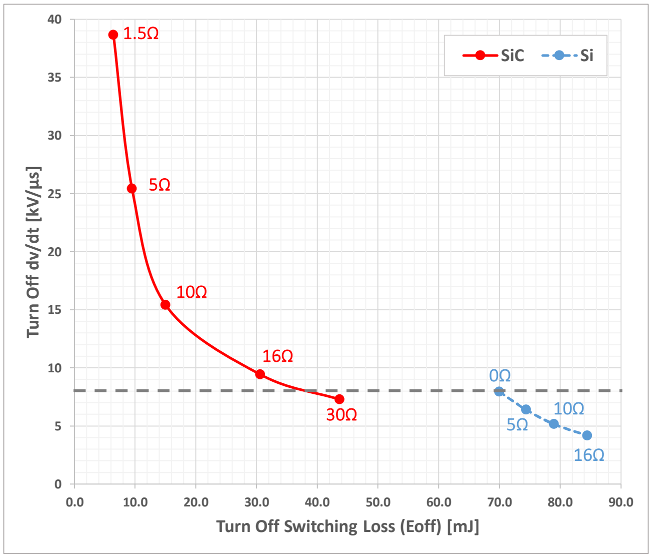
Si IGBT versus SiC MOSFET: R_G Turn Off Controllability



Conditions: Ic=300A, 125° C, V_{GE}=+15V/-12V, 1000Vdc, Inductive Load

SiC module has a larger range of controllability

With R_{GMIN}, SiC has 90% lower Eoff

At 8kV/µs turn off dv/dt, SiC has 45% lower Eoff

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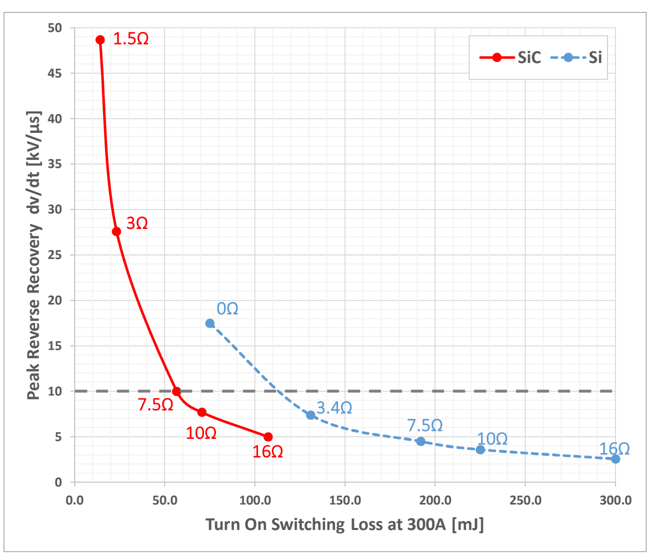
Si IGBT versus SiC MOSFET: R_G Turn On Controllability



Conditions: Ic=300A, 125° C, V_{GE}=+15V/-12V, 1000Vdc, Inductive Load
Peak dv/dt was measured at 0A for Si and 300A for SiC

SiC module has a larger range of controllability

With R_{GMIN}, SiC has 81% lower Eon

At 10kV/µs reverse recovery dv/dt, SiC has 54% lower Eon

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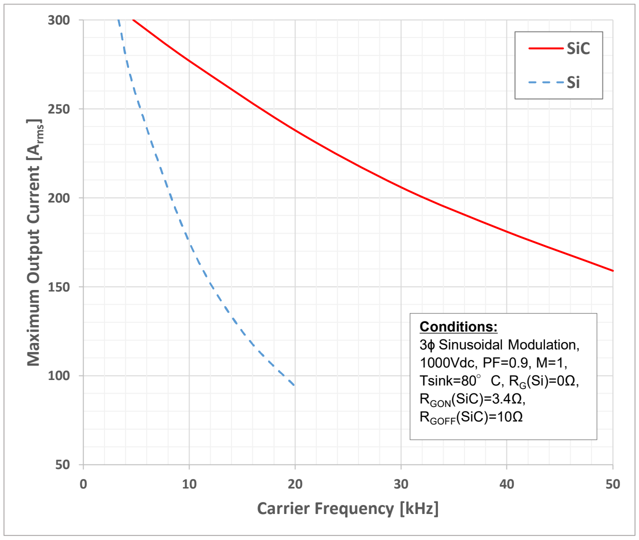
Maximum Inverter Output Current (Limited by Tj =150°C)



At all fc, the SiC module provides greater output current capability

At 10kHz, the Si module can support up to 175Arms while the SiC module is capable of 275Arms, a 57% increase.

At 160Arms the Si module is capable of a fc up to 11kHz while the SiC module is capable of 50kHz, 4.5 times higher fc

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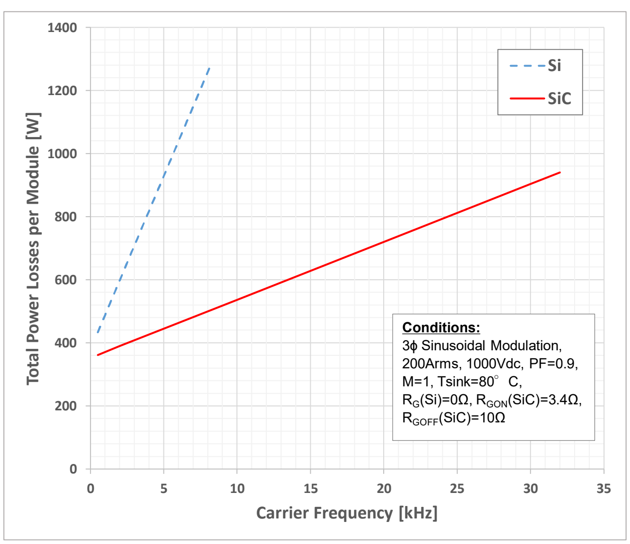
Inverter Losses (per module) vs. Carrier Frequency at 200Arms (Limited by Tj =150°C)



At 5kHz and 200Arms, the Si module has a total power loss of 930W while the SiC module has only 440W, a 53% reduction

At 8kHz, the Si module has total power losses of 1260W while the SiC module has only 500W loss, a 60% reduction

At 200Arms, the SiC module is able to operate at up to 31kHz before reaching the same losses as the Si module operating at 5kHz.

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NEW SiC in Industry Standard Packages

108mm x 62mm
Full SiC MOSFET with Anti-Parallel SiC SBD

Line-Up
*400A, 1200V Dual - **Available Now***

DX Package (*econodual*)
Full SiC MOSFET New Imbedded laminated bus structure to achieve P-N inductance ~10nH

Line-Up
*600A, 1200V Dual - **Sample Q4-2022***
*600A, 1700V Dual - **Samples Q4-2022 Full Release Q2-2023***

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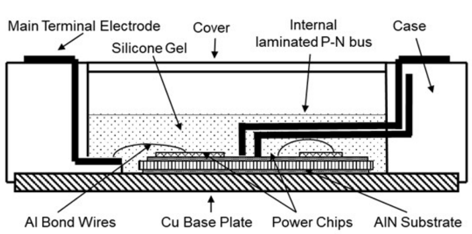
Low Inductance DX Package for SiC

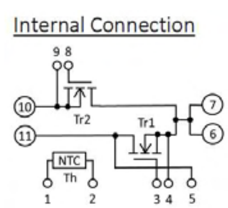
Features:

- Imbedded laminated terminal structure to minimize inductance. (simulation 10.2nH)
- Completely Pin-for-Pin and Mechanically Compatible with industry standard "econo-dual" style package
- Copper Baseplate, AlN DBC Substrate
- Does not include anti-parallel SBD

Proposed Line-Up
600A, 1200V Dual
600A, 1700V Dual

Low inductance internal laminated buswork





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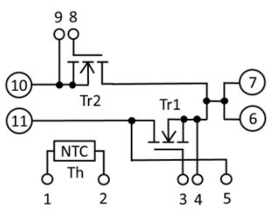
Changes for the Better

Main Characteristics of 1700V 600A SiC MOSFET



Actual measurement results

Items	Conditions	Evaluation results	unit
$V_{GS(th)}$	I_D=229mA, V_{DS}=10V, T_{vj}=25℃	2.7	V
$V_{ds(on)}$	I_D=600A, V_{GS}=15V,D(s)-S(s)*, T_{vj}=150℃	2.3	V
$V_{SD(on)}$	I_D=600A, V_{GS}=15V, S(s)-D(s), T_{vj}=150℃	2.1	V
V_{SD}	I_S=600A, V_{GS}=-6.5V,S(s)-D(s), T_{vj}=150℃	3.7	V
E_{on}	I_D=600A, V_{GS}=+15/-6.5V, R_G=0.75Ω, T_{vj}=150℃	25	mJ
E_{off}		20	mJ
E_{rr}		22	mJ
Ls	P-N	9.0	nH

*D(s): Drain sense terminal, S(s): Source sense terminal

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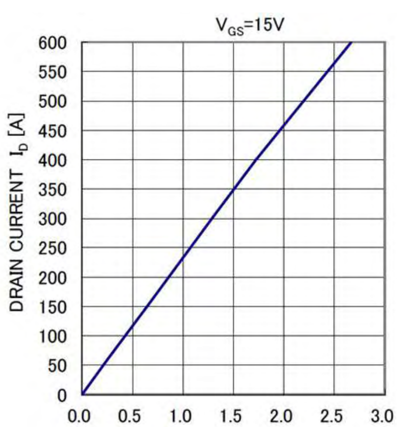
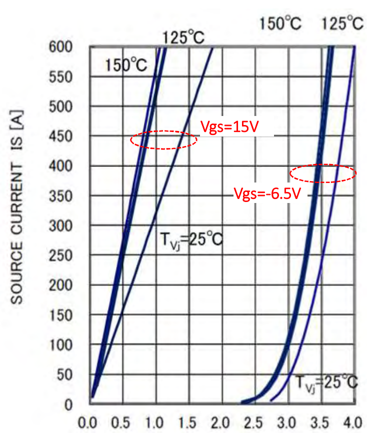
DX Package 600A,1700V SiC Module Characteristics

$V_{DS(on)}$ vs I_D

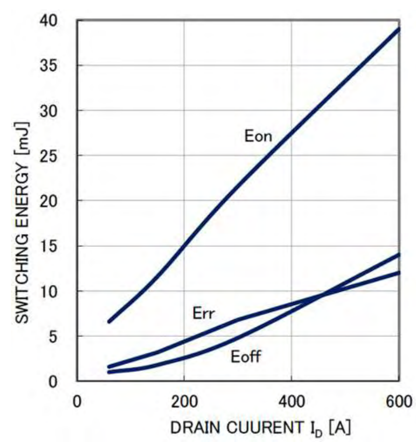


$V_{SD(on)}$ vs I_S



Tj=150C, Vgs=+15/-6.5, Vcc=900V,
Rg(on)=1.2ohm, Rg(off)=0.75ohm

Switching energy



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High Power SiC LV-100 Package

Industry Standard Dual (Half Bridge) Package for
Traction, Industrial and New Energy Applications

LV100 Package SiC Line-Up	
CMH1200DC-34X	1200A, 1700V Hybrid
CMH600DC-66X	600A, 3300V Hybrid
FMF185DC-66A	185A, 3300V Full SiC
FMF375DC-66A	375A, 3300V Full SiC
FMF750DC-66A	750A, 3300V Full SiC

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LV100/HV100 New Industry Standard High-Power Packaging

Industrial LV100
4 kV Isolation
1200V to 2000V
100mm x 140mm

LV100
6 kV Isolation
1700V to 3300V
100mm x 140mm

HV100
10.2 kV Isolation
3300V to 6500V
100mm x 140mm

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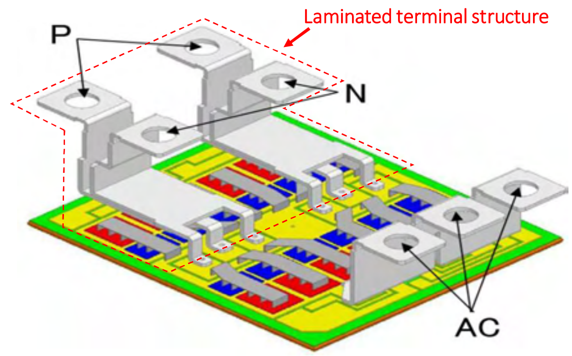
LV100 Low Internal Inductance Symmetrical Layout Design



- Reduced Surge Voltages
- **Suitable for SiC devices**
- Excellent current balance between paralleled chips

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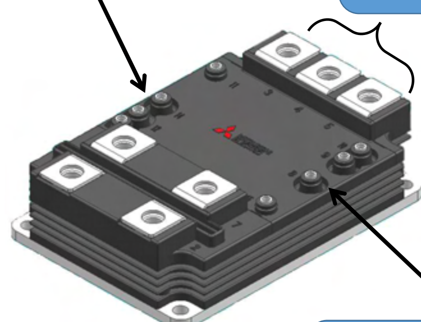
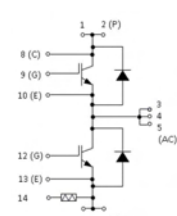
Advantages of LV100 & HV100 Designs

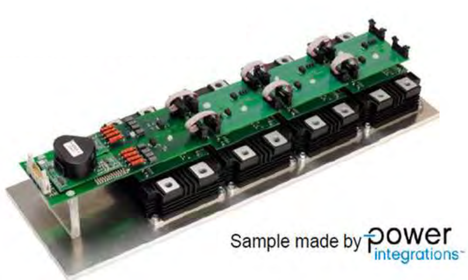
- Industry Standard Package
- Terminal layout allows for simplified DC bus and gate drive design
- Symmetrical layout – Easy to parallel modules
- Raised terminals permit topside and bottom side PCB components
- Extra AC terminals allow for high power density increases like 750A/3.3kV SiC
- Future ready as the low inductance dual topology is SiC compatible

Easy connection to one gate driver, under parallel usage by terminal layout

3 AC terminals for lowering terminal temperature.
Allows for future higher RMS current implementation such as the 750A SiC Module







Low inductance
10nH

Terminals raised to allow space for top/bottom side mounted PCB of Gate Driver

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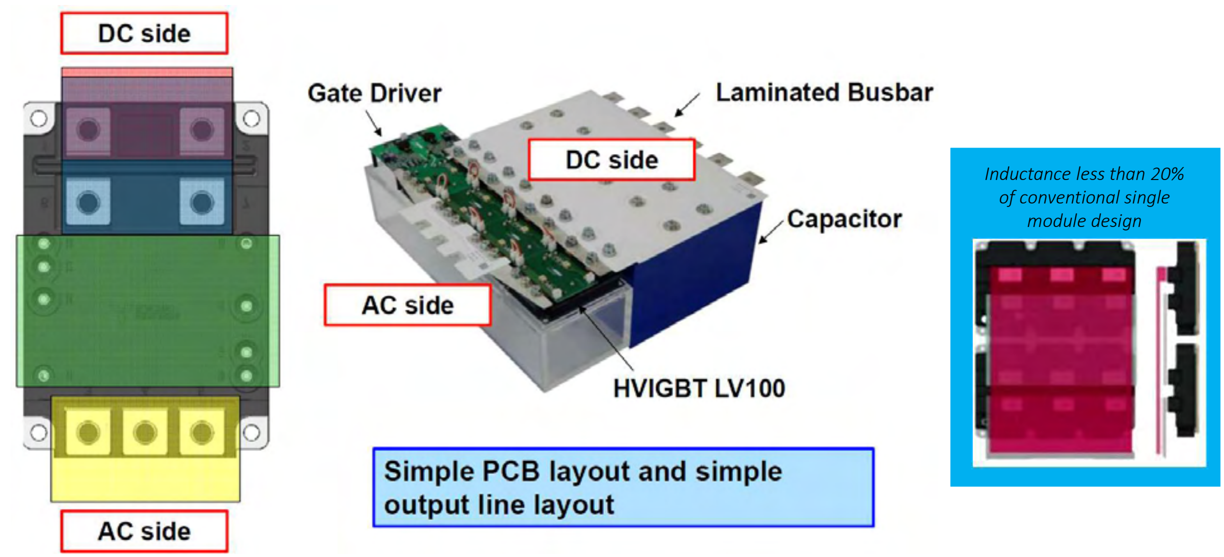
Simple Busbar Layout



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LV100/HV100 Module Line-Up

	Part Number	Voltage	Current	Package
Si module				
LV100 Industrial Viso=4KV	**CM1200DW-24T**	1200V	1200A	
	CM800DW-34T	1700V	800A	
	CM800DW-34TA	1700V	800A IGBT, 1200A FWDi	
	CM1200DW-34T	1700V	1200A	
	CM1200DW-40T	**2000V**	1200A (Under Development)	
LV100 Viso=6KV (Traction Use)	**CM1000DA-34X**	1700V	1000A	
	CM1200DA-34X	1700V	1200A	
	CM450DA-66X	3300V	450A	
	CM600DA-66X	3300V	600A	
HV100 Viso=10.2KV (Traction & Medium Voltage Drives)	**CM450DE-66X**	3300V	450A	
	CM600DE-66X	3300V	600A	
	CM450DE-90X	4500V	450A (Under Development)	
	CM300DE-130X	6500V	300A (Under Development)	
SiC module				
SiC LV100 Viso=6KV	**CMH1200DA-34X**	1700V	1200A (Hybrid-Si IGBT+SiC Schottky)	
	CMH600DA-66X	3300V	600A (Hybrid-Si IGBT+SiC Schottky)	
	FMF185DC-66A	3300V	185A	
	FMF375DC-66A	3300V	375A	
	FMF750DC-66A	3300V	750A	

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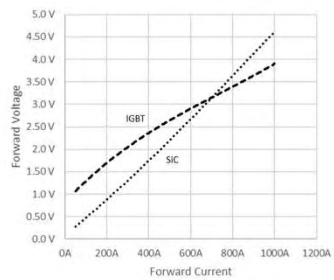
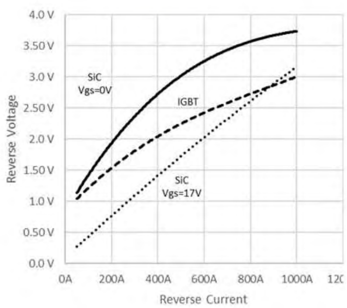
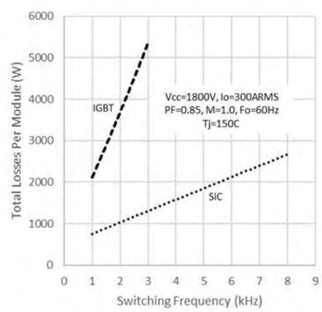
3.3kV SiC MOSFET vs. Si IGBT Module Comparison







Main Characteristic Comparison		
Type Number	CM600DA-66X	FMF750DC-66A
Technology	Si IGBT / Si RFC Diode	SiC MOSFET / SiC SBD
Package	140mm X 100mm (LV100)	
Off-State Blocking Voltage	3300V	
Nominal Current Rating	600A	750A
On-State Forward Voltage 600A, 150C	2.9V	2.6V
Reverse Voltage 600A, 150C	2.4V	1.75V
Turn-On Switching Energy 1800V, 600A, 150C	0.95J	0.45J
Turn-Off Switching Energy 1800V, 600A, 150C	1.05J	0.22J
Reverse Recovery Energy 1800V, 600A, 150C	1.02J	0.03J

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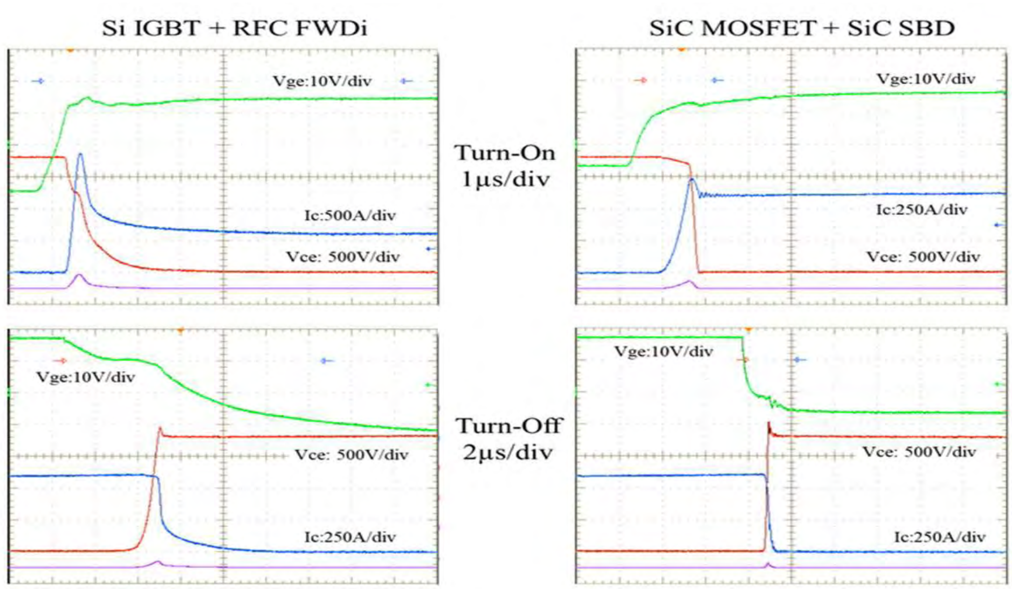
3.3KV SiC MOSFET versus Si IGBT Switching



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Inverter Loss Comparisons 3.3KV Si vs. SiC

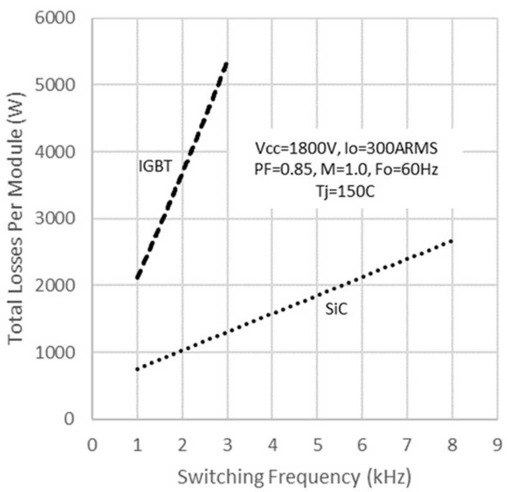

Figure 10: Total Module Losses

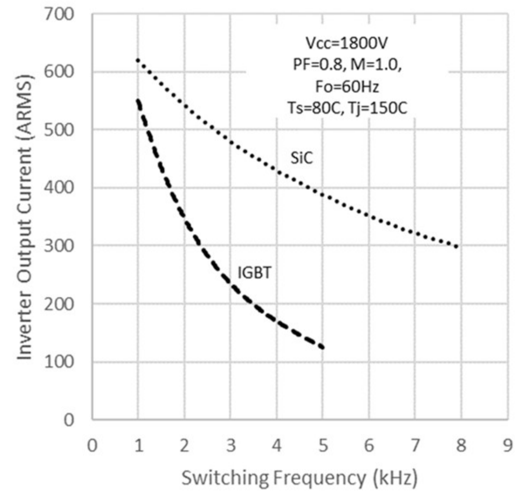

Figure 11: Inverter Output Current

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