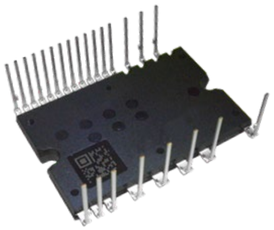
MITSUBISHI ELECTRIC

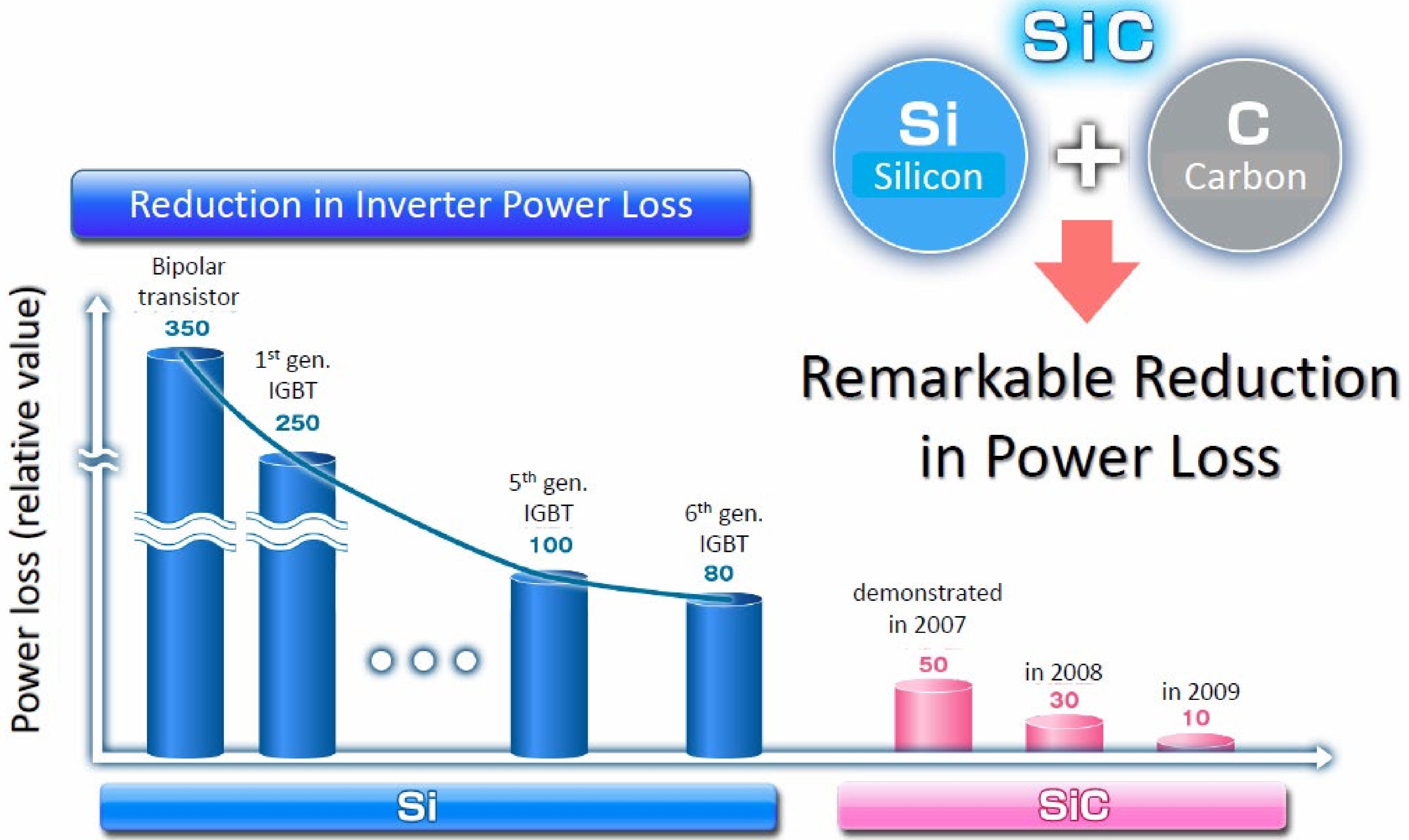
SiC High Power Modules



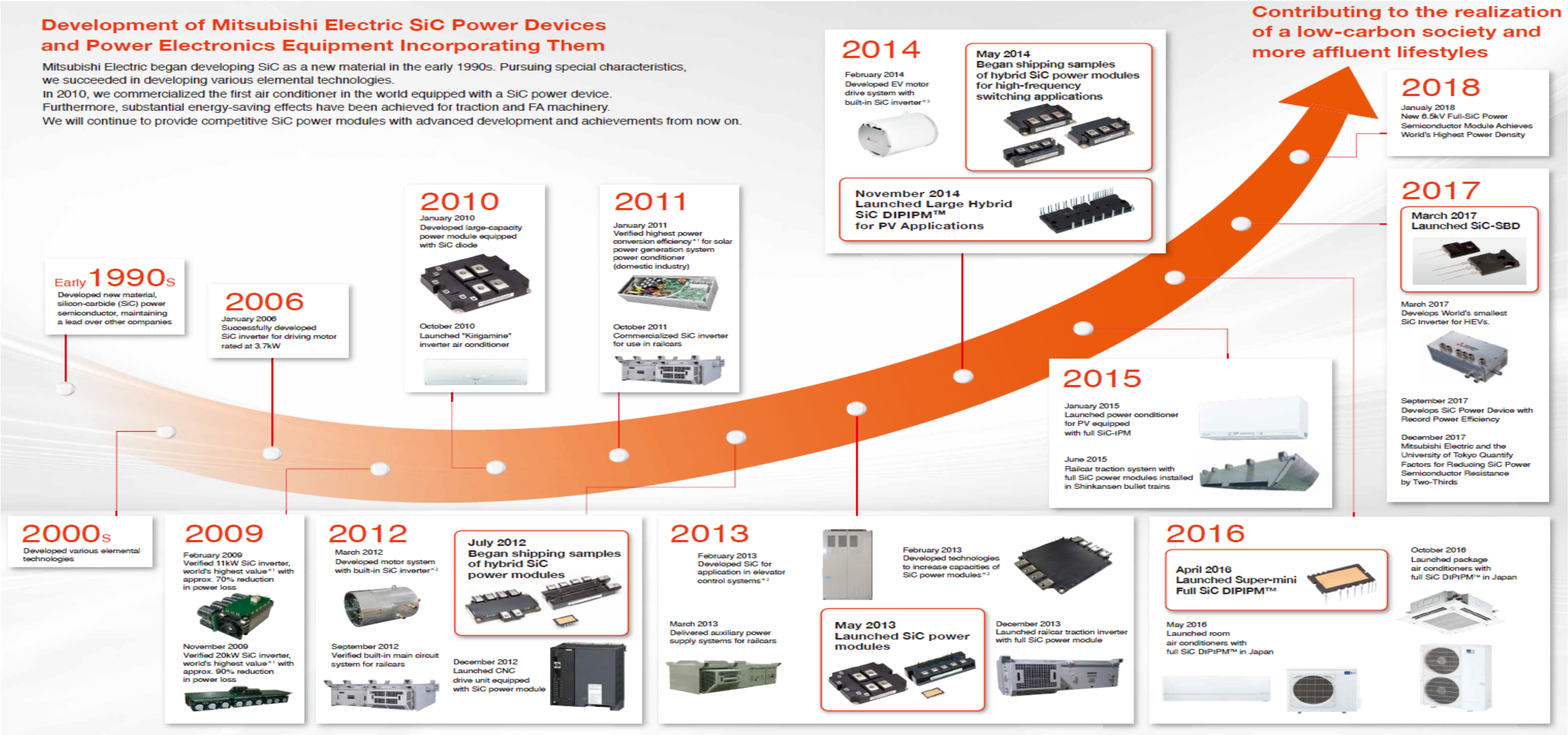
Presentation Outline

- SiC Technology Trend
- Development Progress & Status
- Commercialization of SiC Modules
- Products, Performance and Applications
- Summary and Future Outlook

Motivation to Develop SiC Power Devices



Mitsubishi SiC Development History



SiC Capacity Expansion

In order to address the growing market for SiC modules we have commissioned a new SiC wafer fabrication line in our Kumamoto factory.

(1) Production Capacity

Wafer size of SiC will be enlarged from 4-inch to 6-inch, which leads to the expansion of production capacity.

(2) Production Control and Quality Improvement

We will apply our rich experience of Si wafer processing to SiC. Including advanced factory automation management systems and high level clean room for better control of yield and electrical characteristic distributions.

(3) Expansion of Product Line-up

In addition to the existing line-up of 1st gen. modules, we will newly develop the small-middle range (100~300A) and additional voltage classes to satisfy market demands.

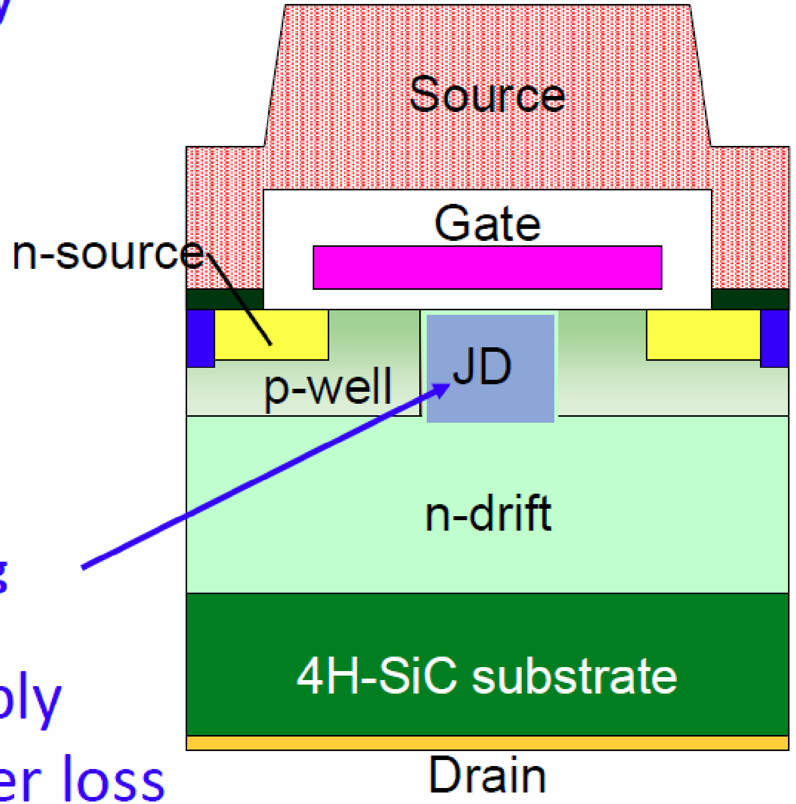
2nd generation SiC MOSFET

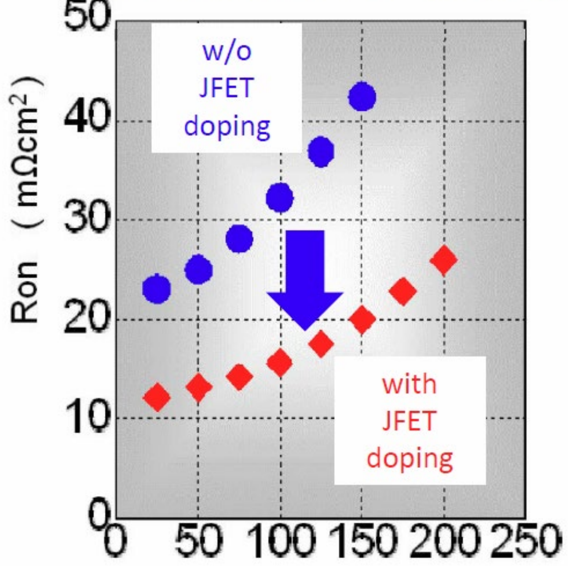
JFET doping technology

JFET doping (JD) technology

Simple and very effective

Applicable
to all SiC-MOSFET;
600V, 1200V, 1.7V, 3.3kV･･･





Example: 3.3KV SiC MOSFET

On resistance is remarkably reduced, resulting in lower loss

Review: Physical Properties of SiC Compared to Si

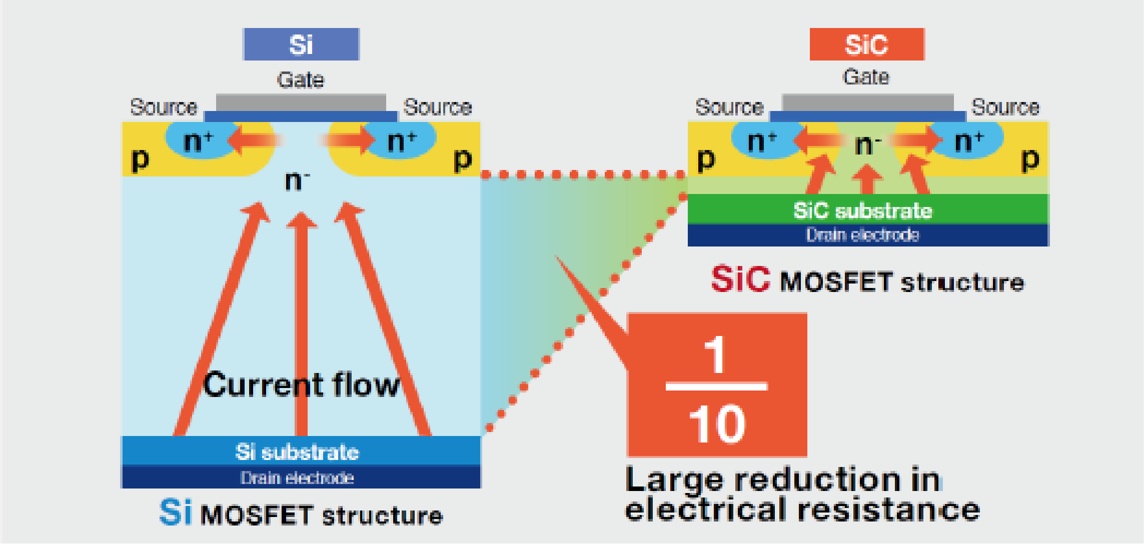
Material	Bandgap Energy (eV)	Dielectric Constant (dimension)	Electron Mobility (cm^2/Vs)	Break Down Electric Field ($10^6 V/cm$)
4H-SiC	3. 25	9. 7	1140	3
Si	1. 1	11. 8	1500	0. 3

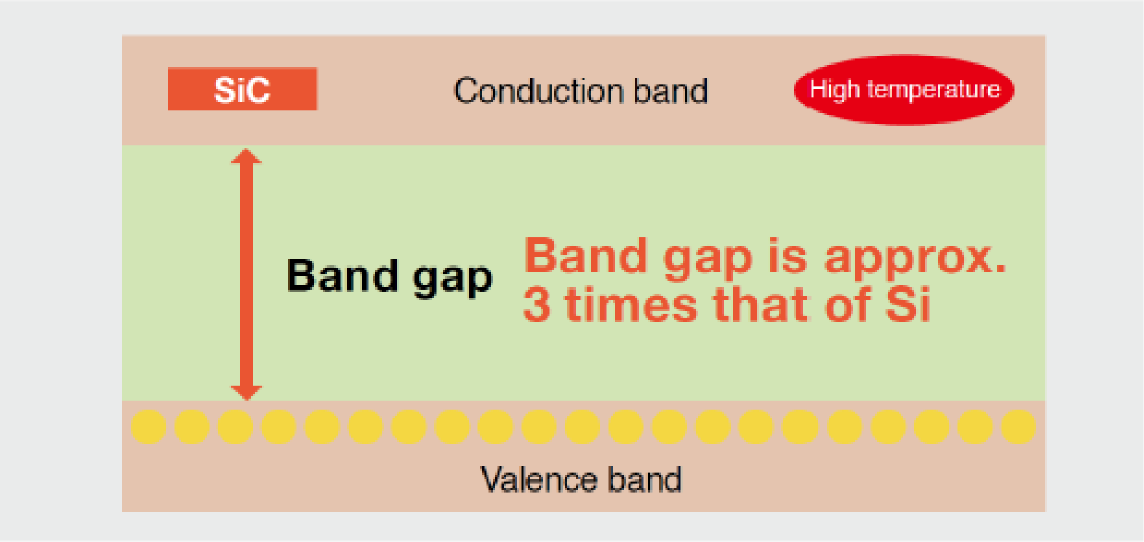
Large Band Gap Energy makes higher temperature operation feasible.

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 practical **Schottky Diodes and MOSFETs** at voltages up to about 5000V… IGBT and PIN diode structures not needed until much higher voltages*

Main Features of SiC





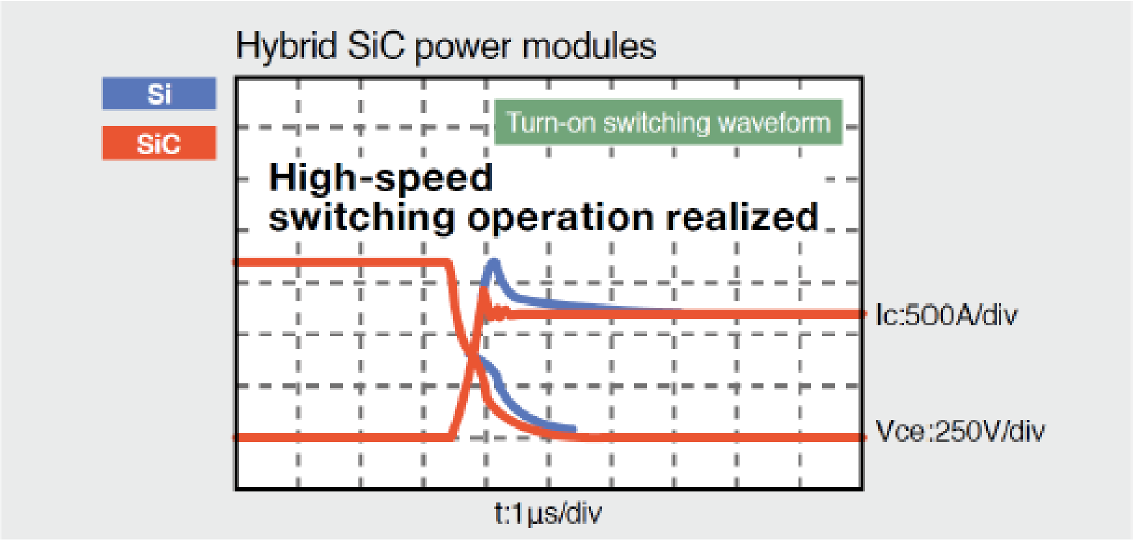
Power loss reduced

SiC has approximately 10 times the critical breakdown strength of silicon. Furthermore, the drift layer that is a main cause of electrical resistance is one-tenth of the thickness. This allows a large reduction in electrical resistance and, in turn, reduces power loss. This SiC characteristic enables dramatic reductions in conductivity loss and switching loss in power devices.

High-temperature operation

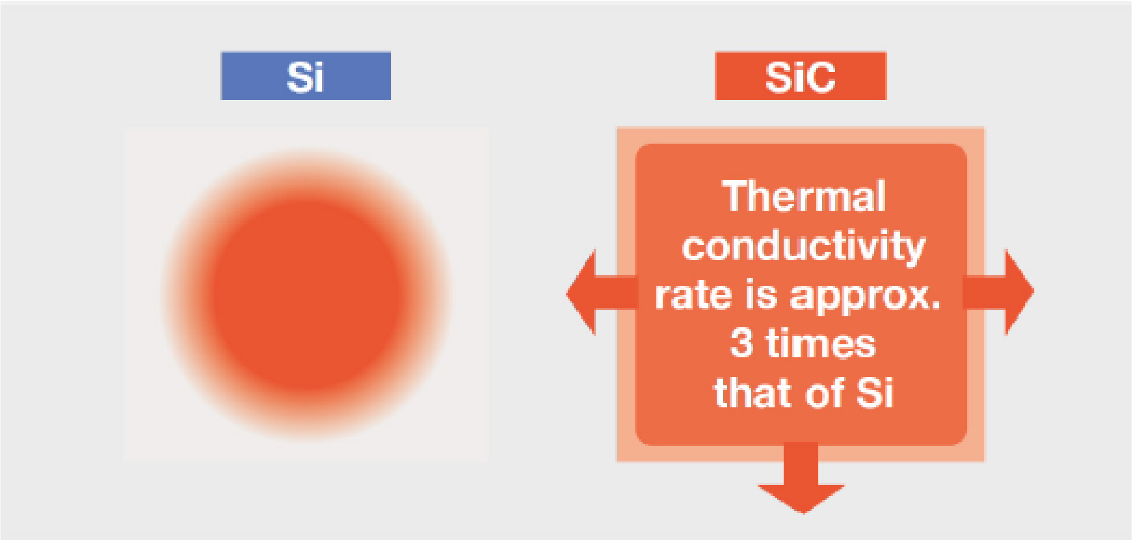
When the temperature increases, electrons are exited to the conduction band and the leakage current increases.
At times, this results in abnormal operation.
However, SiC has three times the band gap width of silicon, preventing the flow of leakage current and enabling operation at high temperatures.

Additional Benefits of SiC



High-speed switching operation

With SiC, owing to the high dielectric breakdown, power loss is reduced and high-voltage is easier to achieve, it is possible to use Schottky Barrier Diodes (SBDs), which cannot be used with Si. BSDs can realize high-speed switching motion because they don't have accumulation carriers. As a result, high-speed switching can be realized.



Heat dissipation

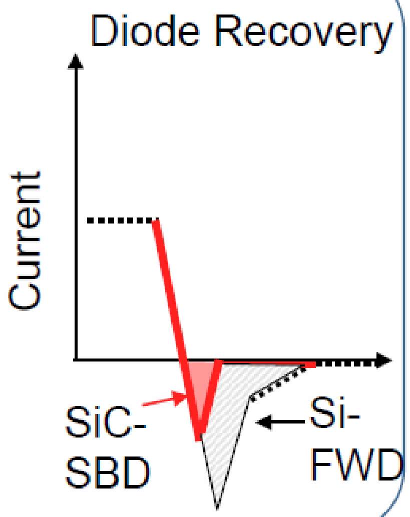
SiC has three times the heat conductivity of silicon, which improves heat dissipation.

Advantages of Mitsubishi SiC Chip Technology

■ **Diode**

- ➢ No accumulation carriers enables SiC-SBD to realize high-speed switching operation.
- ➢ With JBS (Junction Barrier Schottky) structure, durability against forward surge current can be improved.

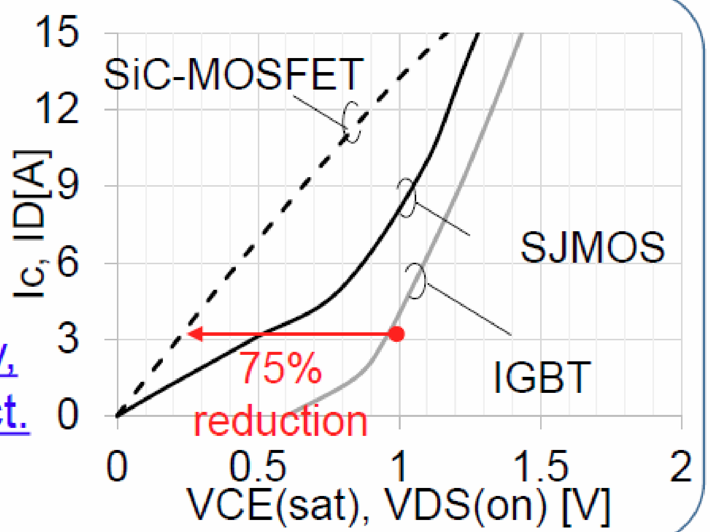
<u>Realize much improvement in power loss with SBD & JBS structure supplement durability against forward surge current.</u>



■ **MOSFET**

- ➢ SiC-MOSFET achieves reduction in ON resistance (high output) with our original high Vth SiC-MOSFET technology.

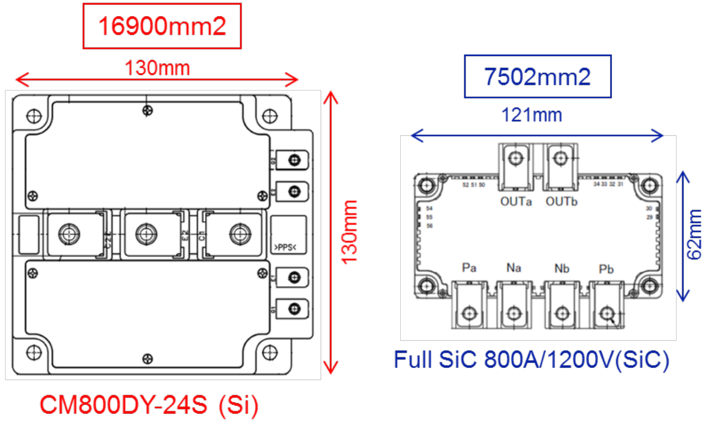
<u>Negative voltage for gate drive circuit is unnecessary, so can continue to use conventional driver IC product.</u>



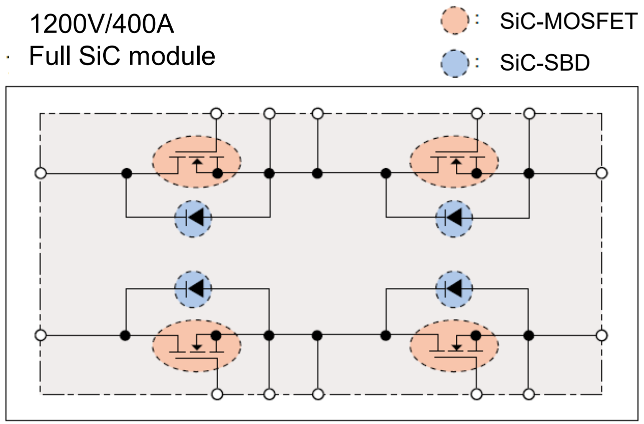
800A/1200V Full-SiC Dual Module
400A/1200V Full SiC H-Bridge

- Power loss reduced by approximately 70%, compared to Si products
  ⇒ High efficiency
- Reduction of package size
  ⇒ Miniaturization and weight reduction
- High switching frequency
  ⇒ Smaller magnetics and peripheral components

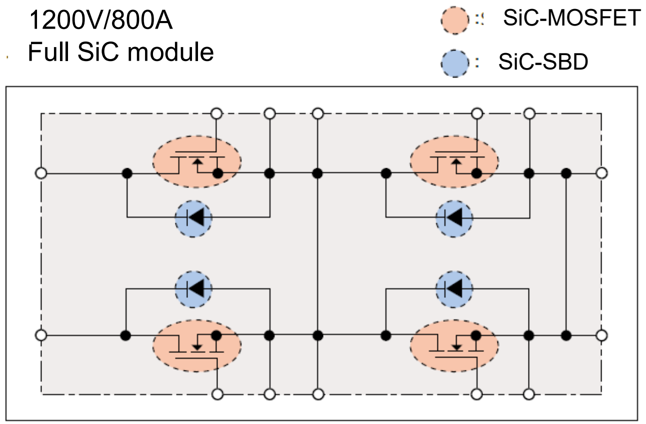
Package outline



Module Size Comparison



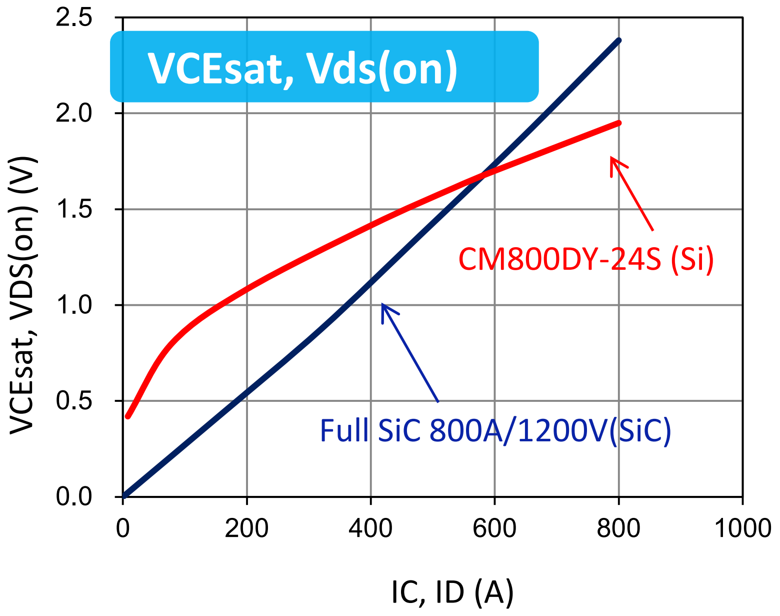
FMF400BX-24A



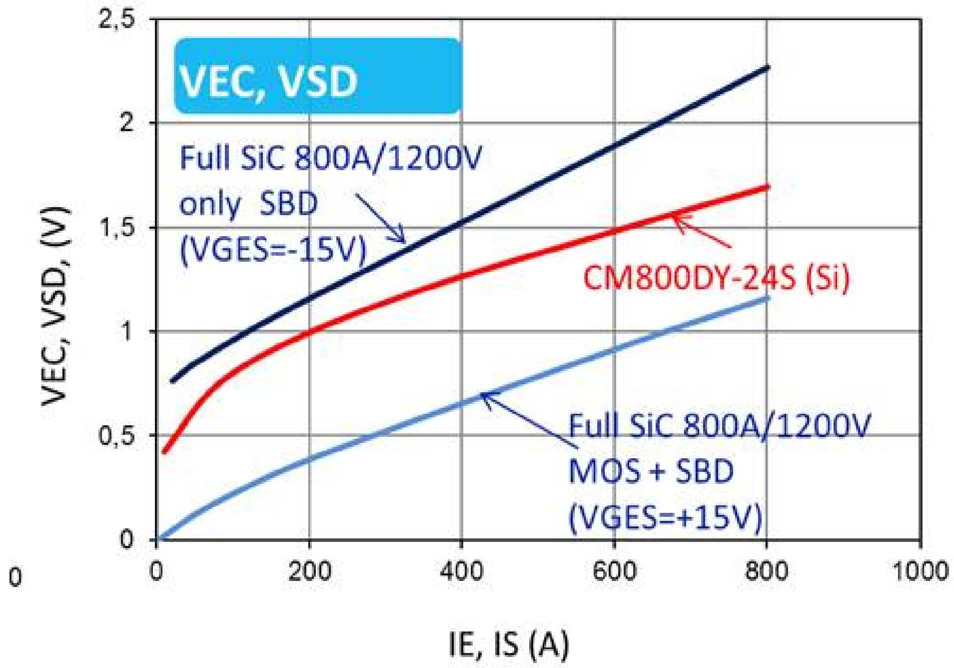
FMF800DX-24A

Static Performance Comparison 800A/1200V
Full-SiC 2in1 Module

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



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



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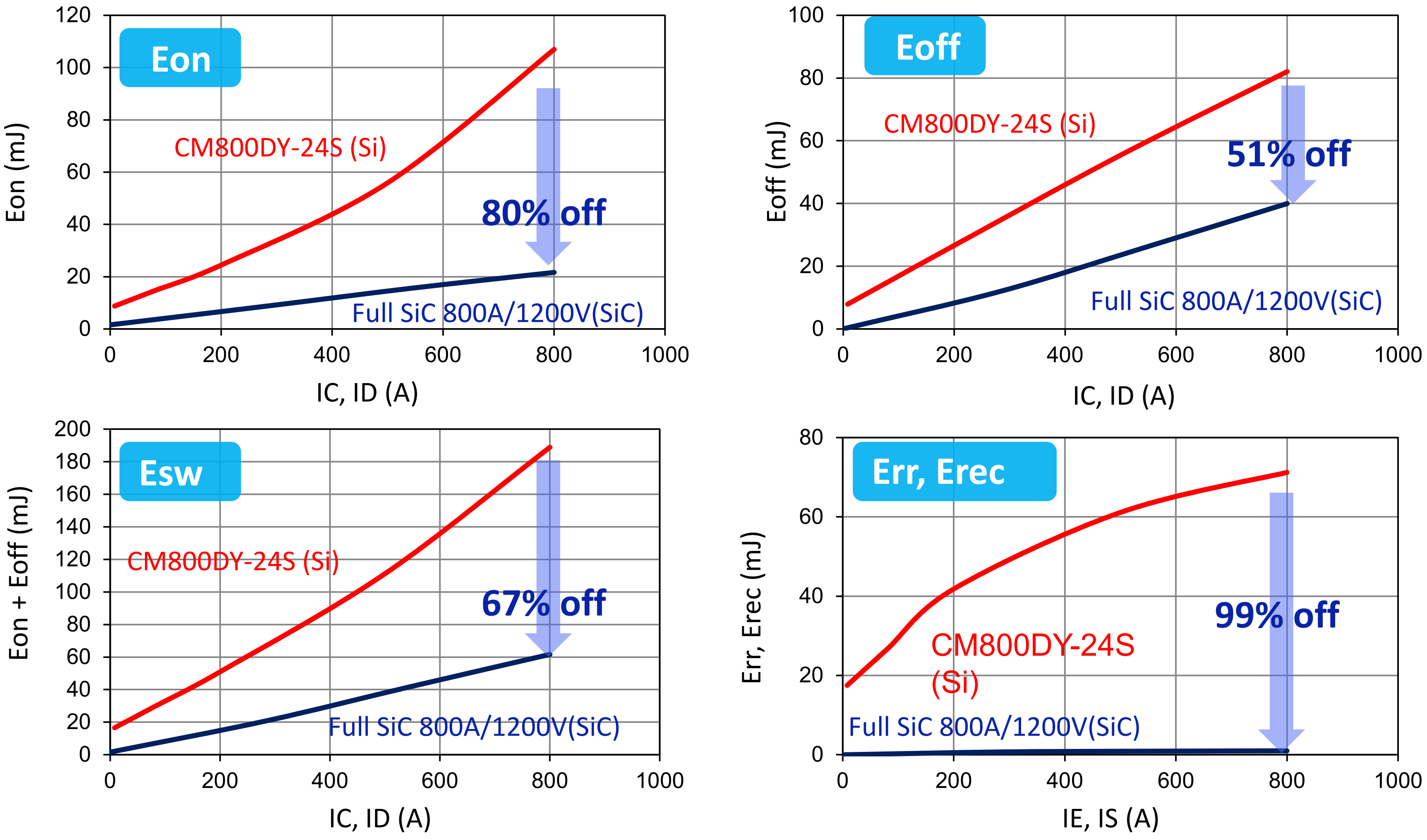
Changes for the Better

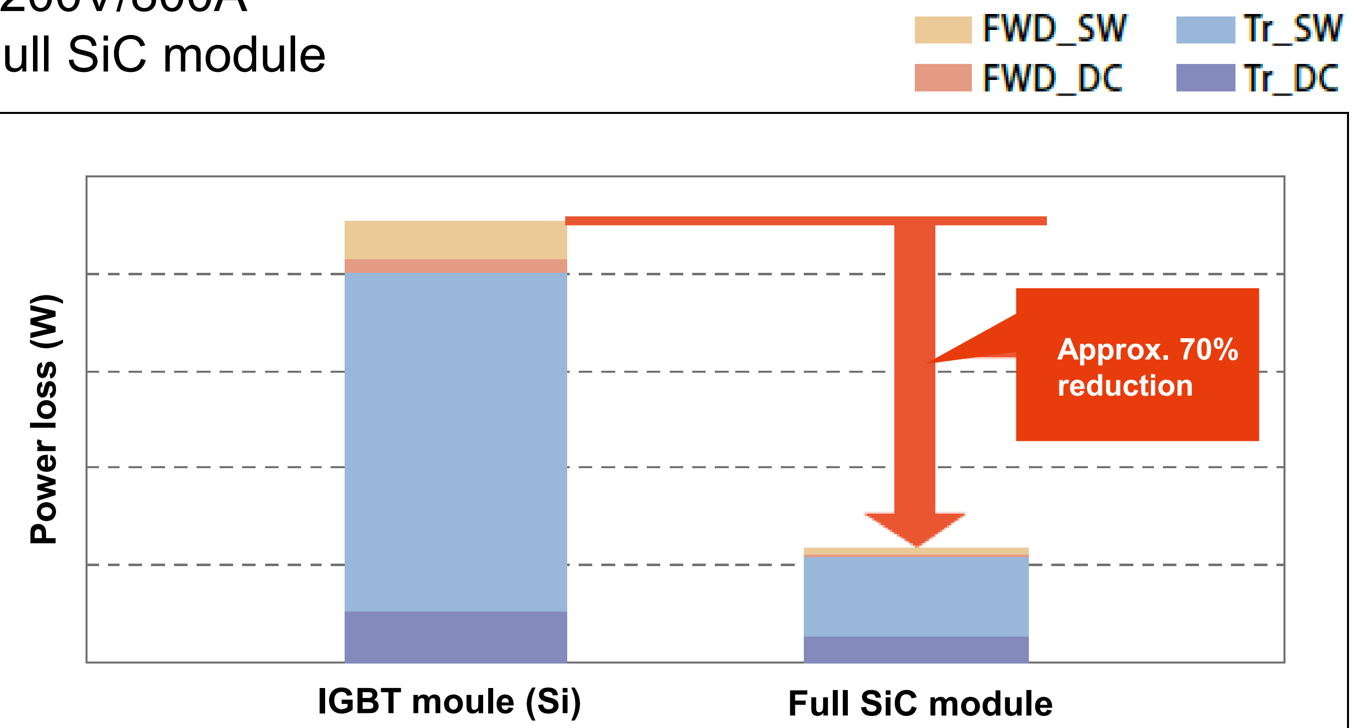
Dynamic Performance Comparison 800A/1200V Full-SiC 2in1 Module

Condition : Tj=150degC, VGE=15V, Vcc=600V, Rg=0ohm(Si), Rg=2.2ohm(SiC)



FMF800DX-24A 800A/1200V Full-SiC Dual Module Power Loss Comparison

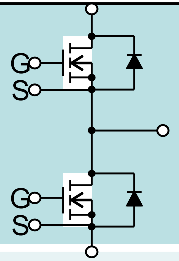
1200V/800A
Full SiC module

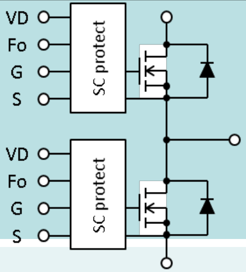


Conditions: Vcc=600V, Io=222Arms(110kW inverter), fc=15kHz, P.F=0.8, Modulation ratio=1, Sinusoidal modulation, Tj=125℃

MITSUBISHI ELECTRIC
Changes for the Better

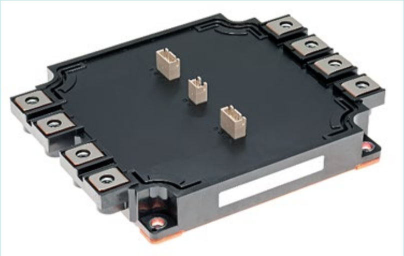
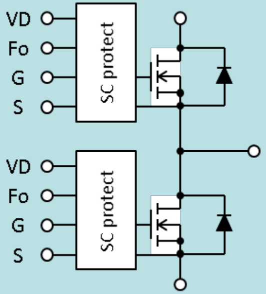
2nd Generation SiC Development Plan





RTC	-		✓	
Generation	**1st**	**2nd**	**1st**	**2nd**
Inch Size	**4-inch**	**6-inch**	**4-inch**	**6-inch**
1200V300A 4in1				FMF300BXZ-24B
1200V400A 4in1	FMF400BX-24A	FMF400BX-24B		FMF400BXZ-24B
1200V600A 2in1			FMF600DX2-24A	FMF600DXZ-24B
1200V800A 2in1	FMF800DX-24A	FMF800DX-24B	FMF800DX2-24A	FMF800DXZ-24B
1700V300A 2in1				FMF300DXZ-34B
1700V400A 2in1				（FMF400DXZ-34B）

2nd Generation SiC Development Plan

		
RTC	✓	
Generation	**1st gen**	**2nd gen**
Inch Size	**4-inch**	**6-inch**
1200V1200A 2in1	FMF1200DX1-24A	FMF1200DXZ-24B

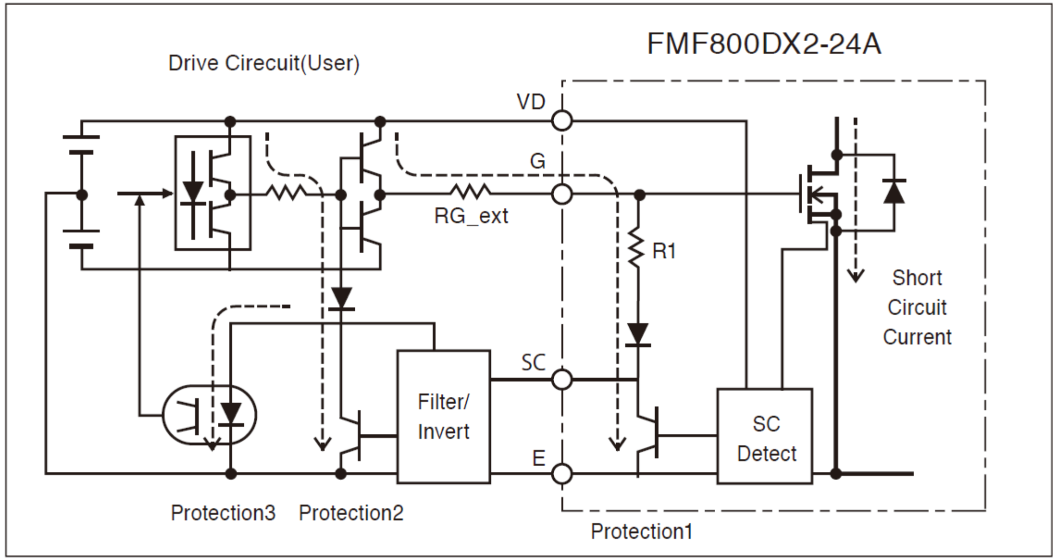
NEW: FMF600DXZ-24B, FMF800DXZ-24B

600A, 800A 1200V SiC MOSFET Modules with RTC

Features

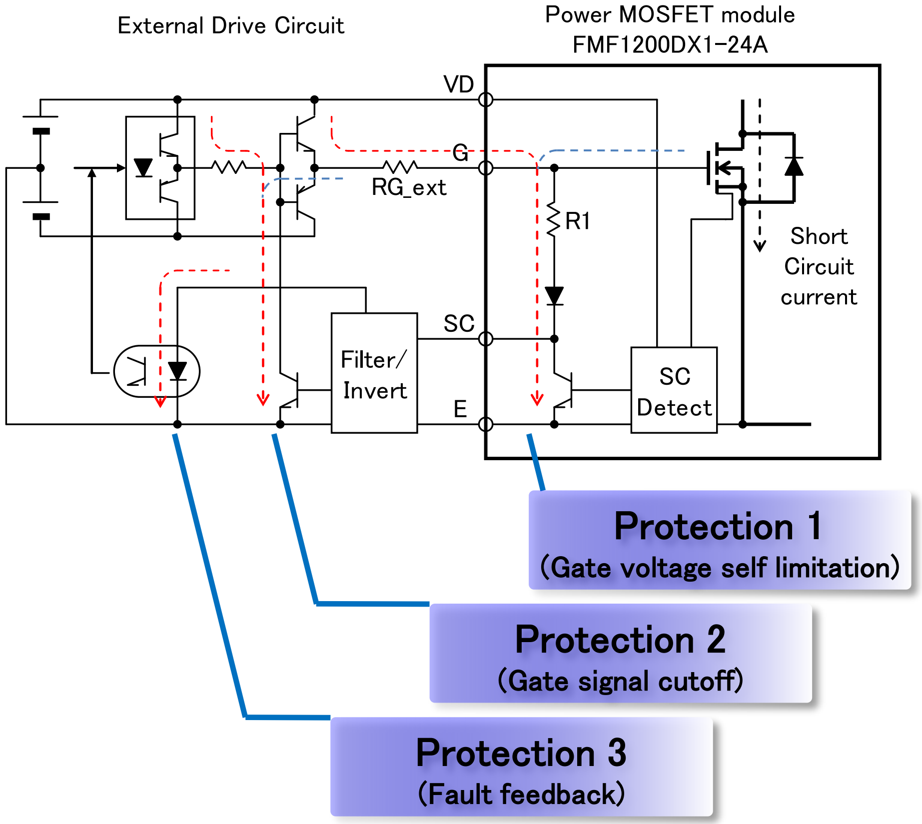
- By using short circuit monitoring circuit in the module it is possible to transfer a short circuit detection signal to the system side
- Power loss reduced approx.70% compared to the conventional product*
- Low- inductance package adopted to deliver full SiC performance

Protection circuit diagram

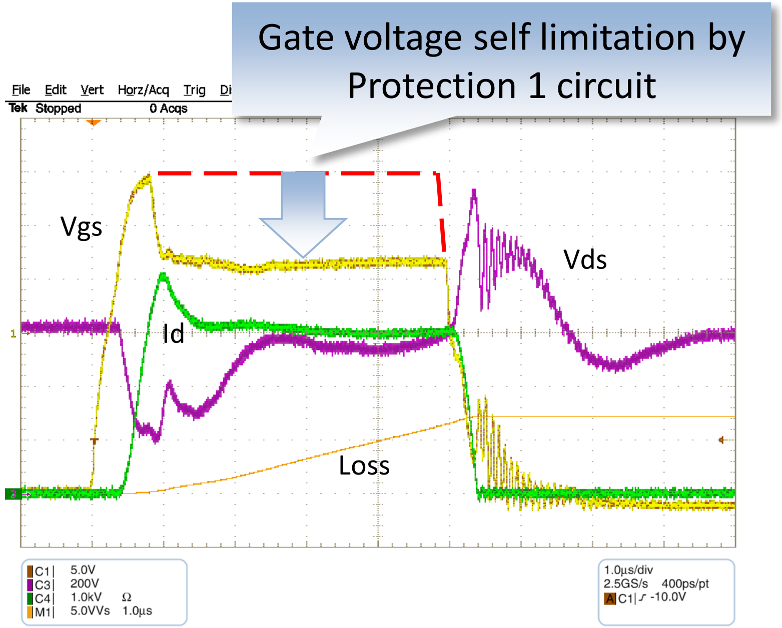


Short Circuit Protection for 1200A/1200V Full-SiC 2in1 Module

■ Example of drive circuit



■ Short Circuit waveform



Vgs : 5V/div.、Vds : 200V/div.

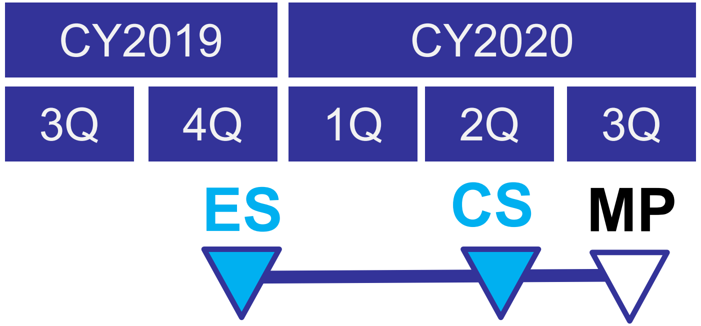
Id : 1kA/div.、Time : 1µs/div.

Under Development: FMF300DXZ-34B

300A, 1700V SiC MOSFET Modules with RTC

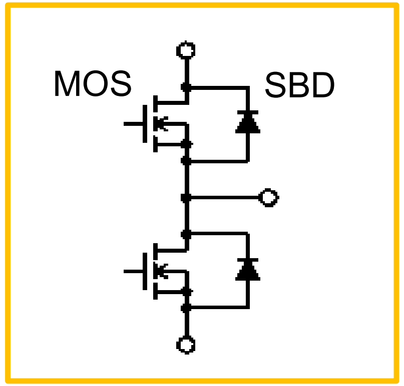
1700V300A
Full SiC

Base size
122 × 62mm

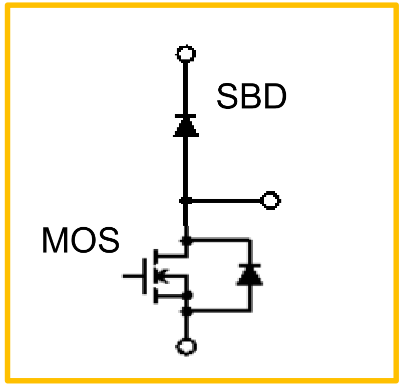


FEATURES

- ✔Low loss：Ron 6.7mΩ(25℃)
- ✔Short circuit detection with RTC
- ✔Type A/B circuits available



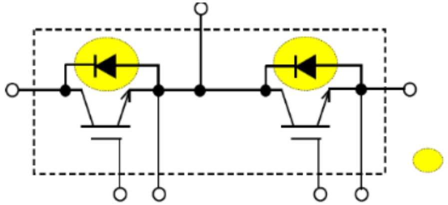
Type A
(Half-Bridge Type)



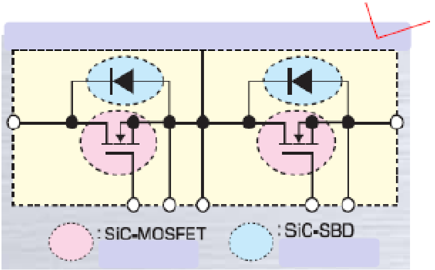
Type B
(Chopper Type)

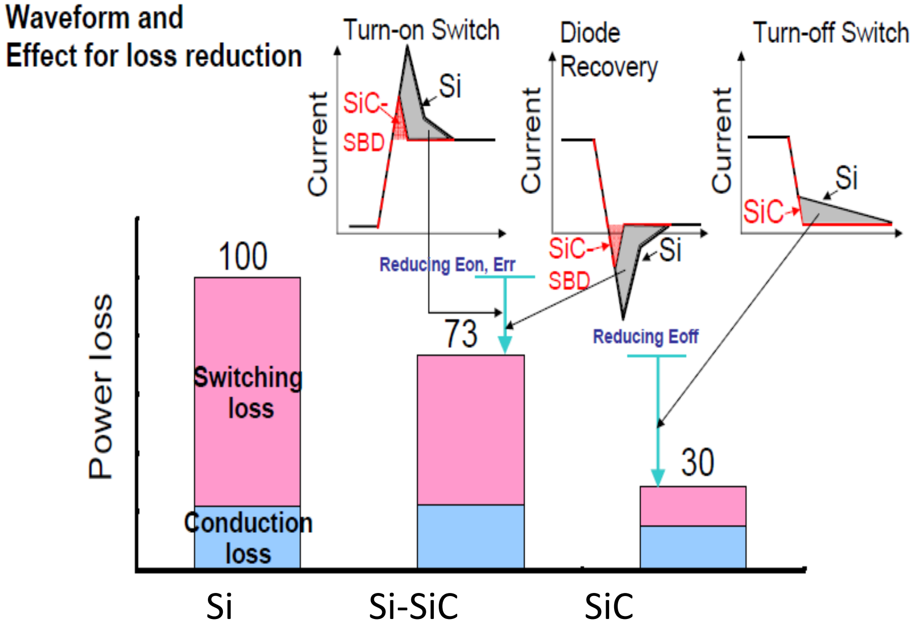
Hybrid versus Pure SiC

Hybrid
Si-IGBT + SiC SBD



Pure SiC
SiC-MOSFET + SiC SBD





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

Hybrid Si-SiC Modules for High Frequency Applications

Features

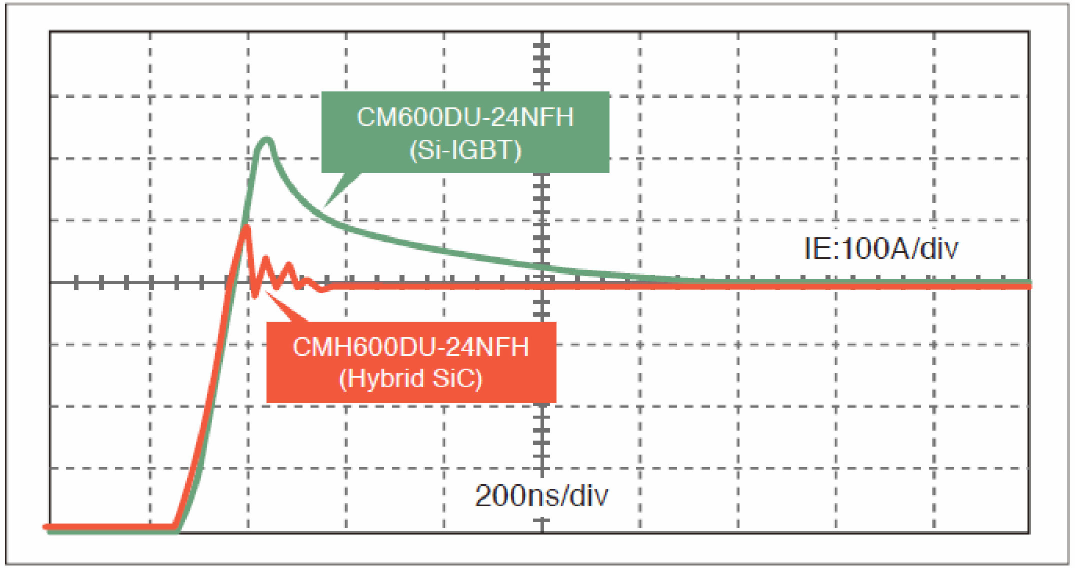
- Power loss reduction of approx. 40% contributes to higher efficiency, smaller size and weight reduction of total system
- Suppresses surge voltage by reducing internal inductance
- Package compatible with the conventional product*

* Conventional product: Mitsubishi Electric NFH Series IGBT Modules

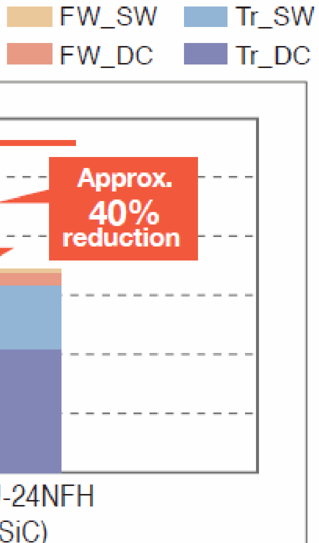
Product lineup

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

Recovery waveform (FWD)

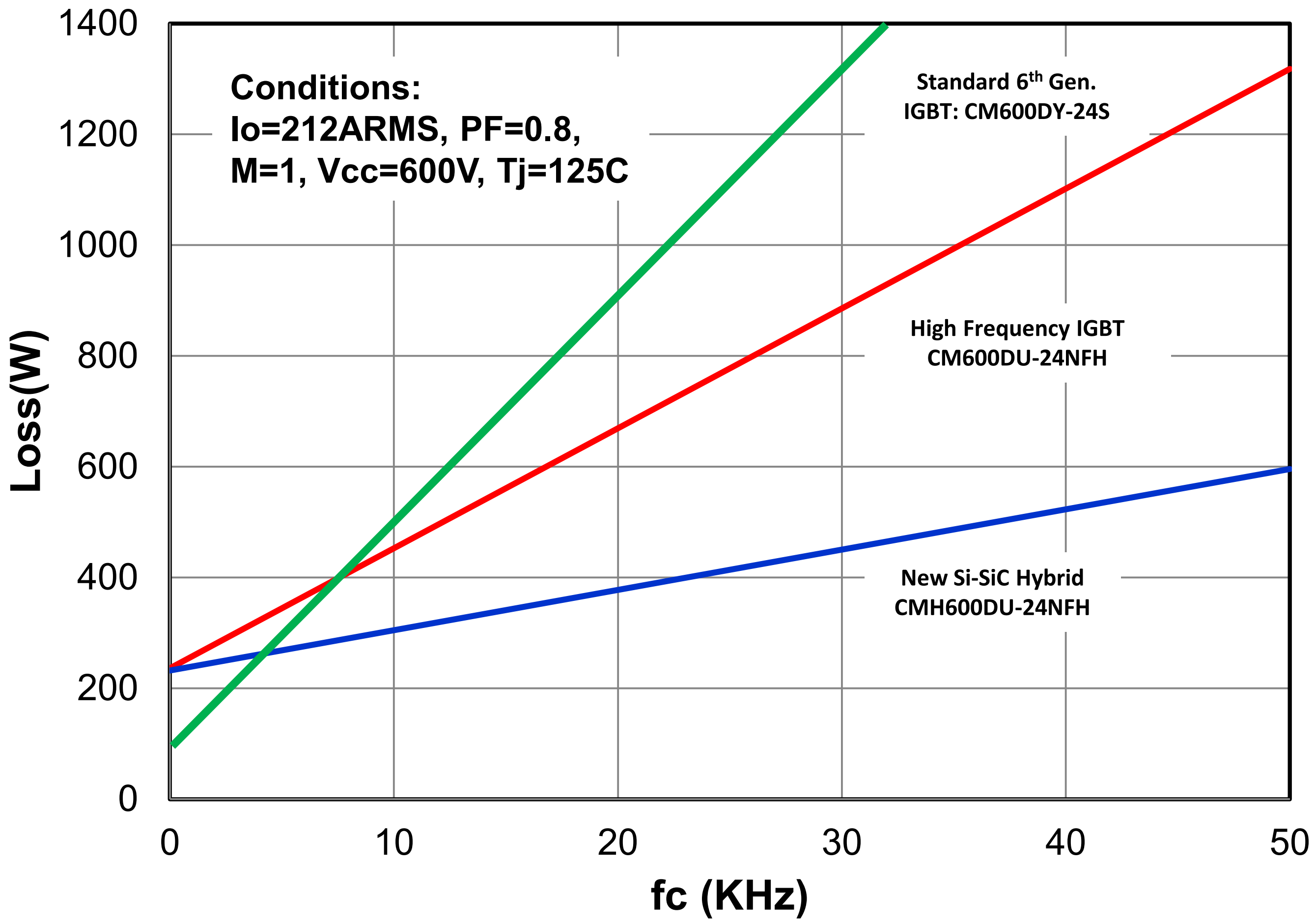


Power loss comparison



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

Hard Switched Sinusoidal Output Inverter Loss Vs. Switching frequency 600A, 1200V Modules



1200A/1700V Hybrid SiC 2in1 HVIGBT

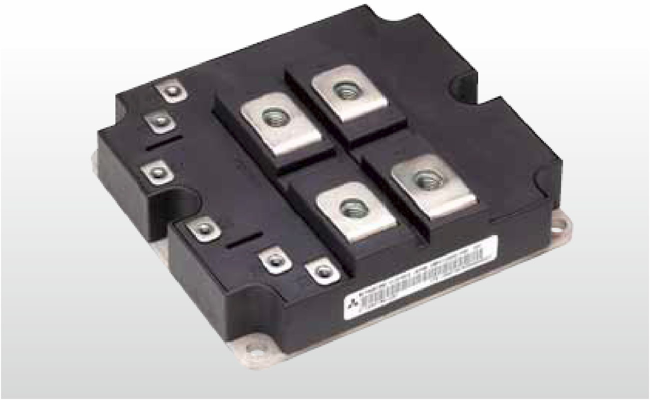
Features

- Power loss reduced approximately 30% compared to the conventional product*
- Highly reliable design appropriate for use in traction
- Package compatible with the conventional product*

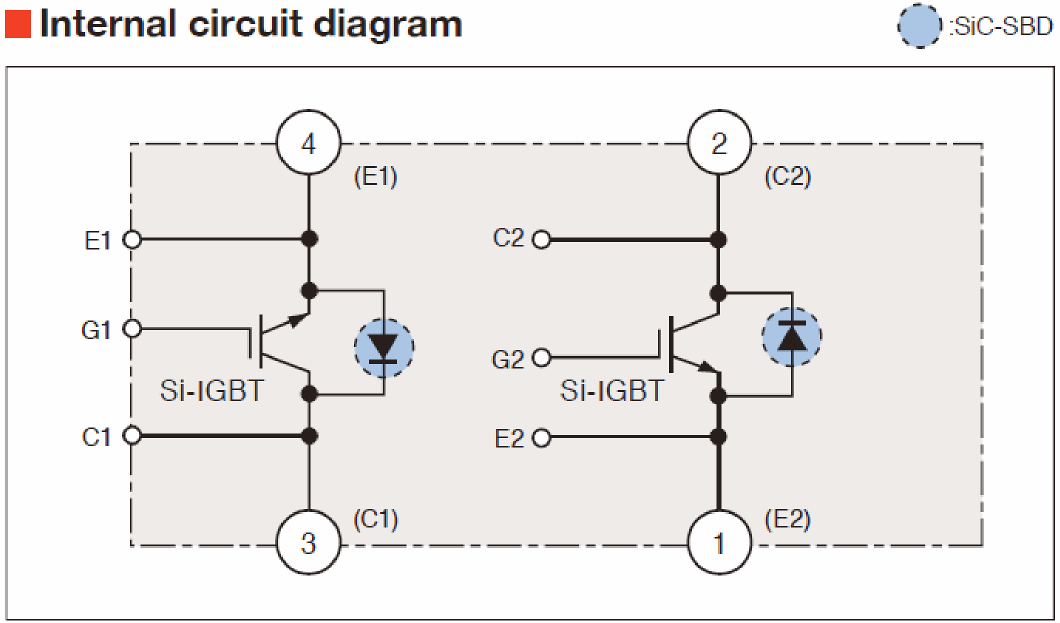
* Conventional product: Mitsubishi Electric Power Module CM1200DC-34N

Main specifications

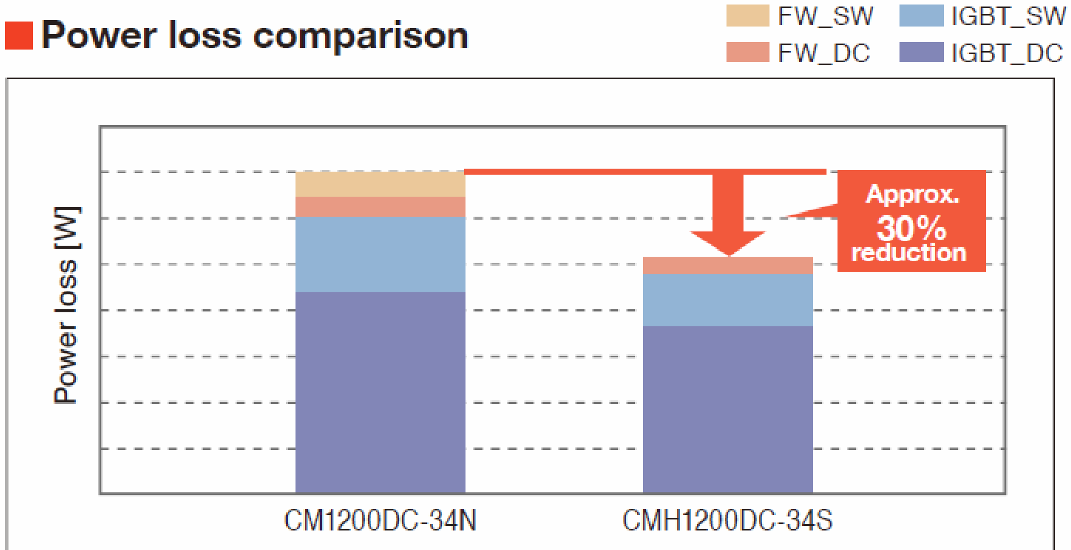
Module	Max.operating temperature		150˚C
	Isolation voltage		4000Vrms
Si-IGBT @150˚C	Collector-emitter saturation voltage		2.3V
	Switching loss 850V/1200V	turn-on	140mJ
		turn-off	390mJ
SiC-SBD @150˚C	Emitter-collector voltage		2.3V
	Capacitive charge		9.0μC



Internal circuit diagram



Power loss comparison

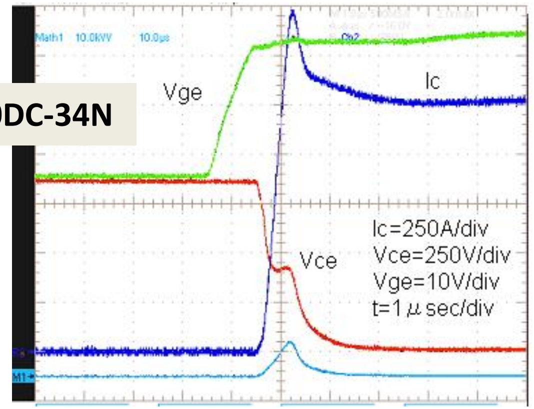


Condition:Vcc=850V, Io=600Arms, fc=1kHz, P.F=1, Modulation=1, Three-phase modulation, Tj=125˚C

1200A/1700V hybrid SiC 2in1 HVIGBT Dynamic Performance

■ **IGBT turn-on waveforms at nominal conditions Vcc=850V; Ic=1200A; inductive load**

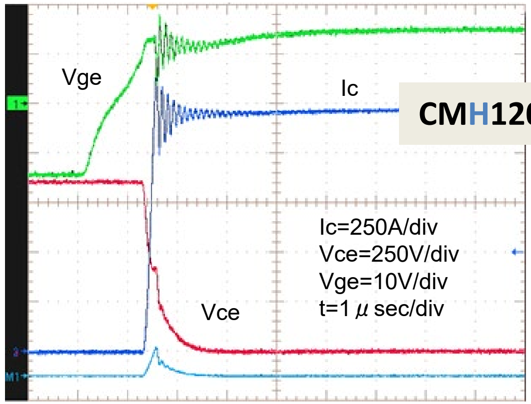
CM1200DC-34N



Eon=0. 40J/pulse

68% Reduction →

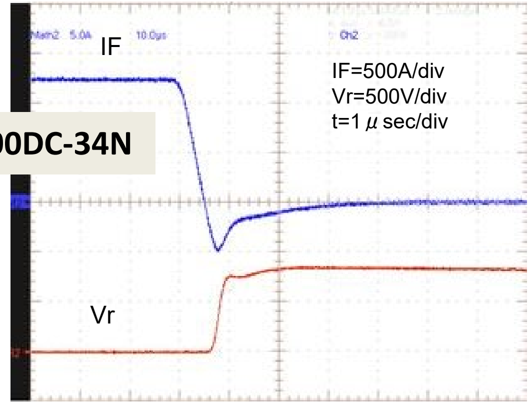
CMH1200DC-34S



Eon=0.18J/pulse

■ **SiC SBD turn-off waveforms at nominal conditions Vcc=850V; IF=1200A; inductive load**

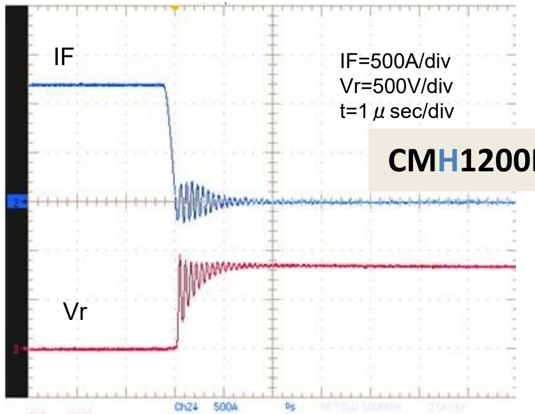
CM1200DC-34N



Erec=0.22J/pulse

95% Reduction →

CMH1200DC-34S



Erec=0.01J/pulse

1200A/1700V hybrid SiC 2in1 HVIGBT Application

■ **Auxiliary Power supply system for Railcars**

Tokyo Metro Ginza Line's new Type 1000 railcars

SiC auxiliary power supply systems for railcars

❑ **Main specifications**

Rated voltage DC 600V

Main power circuit 2 level, voltage-type PWM inverter

Output voltage 140kVA (AC200V, AC100V, DC100V and DC24V)

Air Cooled

❑ **Achievements** (vs. existing Mitsubishi system with Si based power modules)

→ Power loss reduced by 30%

→ 20% smaller

→ 15% lighter

→ Transformer noise reduction by 4dB

→ 35% less distortion in output voltage wafevform

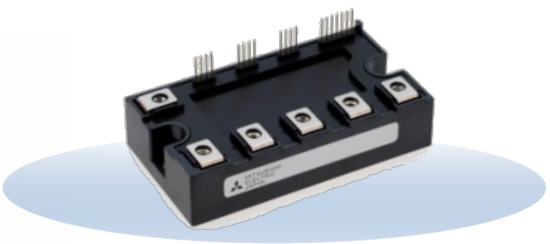
2nd generation SiC IPM

2nd gen. SiC-IPM is under development as a solution for high efficiency and frequency modules suitable for PV, ESS-PCS and fast EV chargers, etc.

*** 1st gen. SiC-IPM was released for evaluation only, and will not be mass produced.**

Development concept of 2nd gen. SiC IPM

1) Apply 2nd gen. SiC chip (6-inch)
2) High Vth enables 15V drive and same interface as Si–IPM
3) Integrated protection functions(SC, UV, OT, Fo identifiable) equivalent with G1 series IPM
4) Using Compact G-series A-PKG



A-Pkg. screw-type (50x90x22mm)

Line-up and schedule

Hybrid-SiC-IPM: 50A/1200V, 6in1
CY20/1Q:ES, CY20/2Q:CS

Full-SiC-IPM: 75A/1200V, 6in1
CY20/3Q:ES, CY20/4Q:CS

Chip	gen	25A	50A	75A	100A	150A	200A
SiC (Hybrid)	1st		L1-series small-pkg		Sample only		
	2nd	G-series A-PKG			Mass production model		
SiC (Full)	1st		L1-series (Small-PKG)		Sample only		
	2nd		G-series A-PKG		Mass production model		

Full SiC Super Mini-DIPIPM

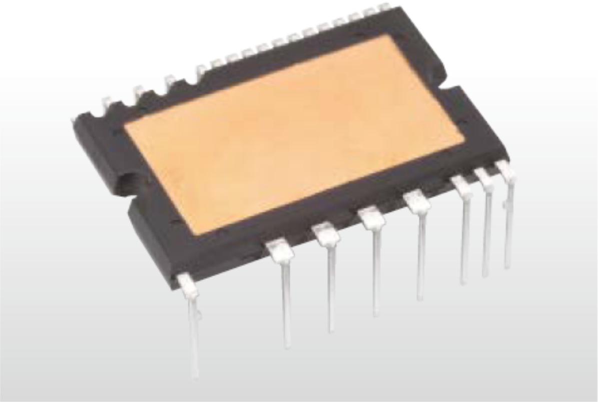
Part No.	Ratings
PSF15S92F6	15A/600V
PSF25S92F6	25A/600V

Contributes to extremely high power-efficiency in air conditioners, and easily applicable to industrial equipment

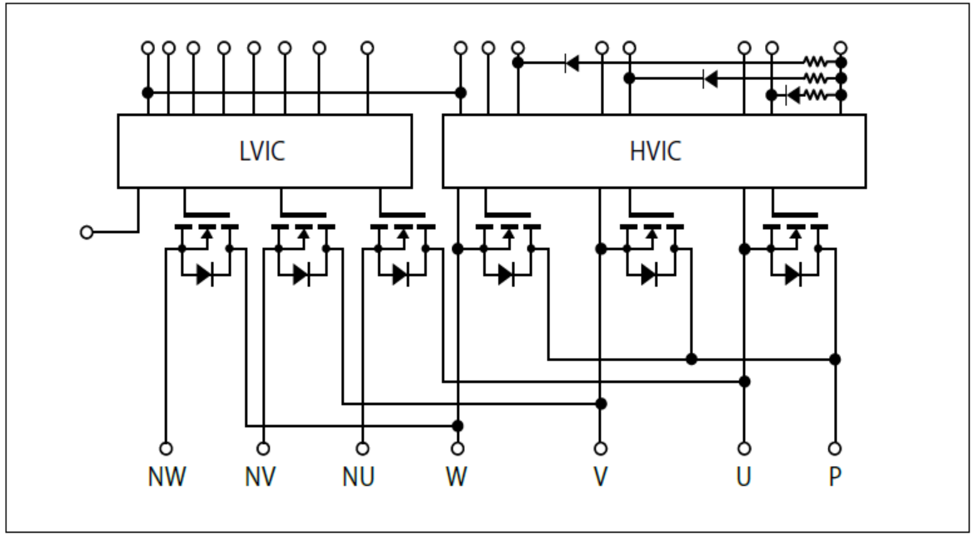
Features

- SiC-MOSFET achieves reduction in ON resistance, power loss reduced approx. 70% compared to conventional product*
- Construct low-noise system by reducing recovery current
- Numerous built-in functions: Bootstrap diode for power supply to drive P-side, temperature information output, etc.
- Unnecessary minus-bias gate drive circuit using original high Vth SiC-MOSFET technology
- As package and pin layout compatibility with conventional products* is ensured, simply replace with this product to improve performance

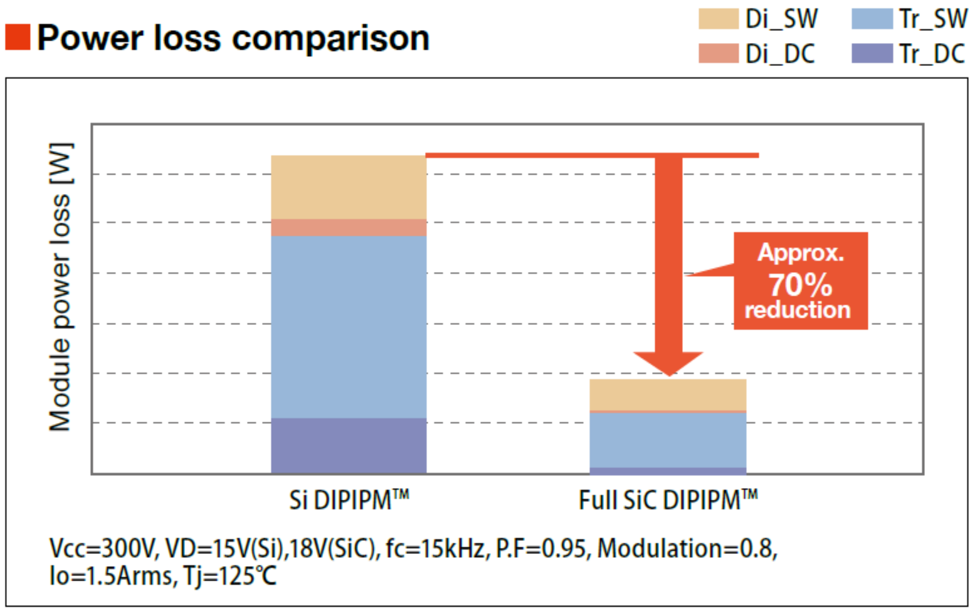
*Conventional product: Mitsubishi Electric Super-mini DIPIPM™ Series



Internal block diagram



Power loss comparison



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Changes for the Better

3.3-kV Full-SiC Module Reliability in Real-World Use

3.3-kV All-SiC Power Module for Traction System Use

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Abstract

High voltage power modules in a railcar traction system are required to reduce power loss and system size and increase system reliability. To satisfy these requirements, Mitsubishi has developed the first 3.3-kV all-SiC (silicon carbide) power module composed of SiC-MOSFET (Metal-Oxide Semiconductor Field-Effect Transistor) and SiC-SBD (Schottky Barrier Diode) for practical use in a railcar traction system [1] [2].

The new 3.3-kV all-SiC power module has about 80% lower total power loss than a conventional Si power module. In addition, we have developed technologies that achieve sufficiently high reliability for actual use.

1. Introduction

Around 20 years have passed since Si-based IGBTs (Insulated Gate Bipolar Transistors) were first applied as power modules to railcar traction systems. From then until today, the performance of railcar traction systems has been improved by making many improvements to semiconductor chips for power modules such as reducing loss and

A railcar traction system requires not only loss to be reduced but also reliability to be increased by improved semiconductor chip and package technology.

This paper presents the loss and durability performances for a new 3.3-kV all-SiC power module that is already in use in actual railcar traction systems for 1500-V DC catenaries [3] compared with a conventional Si power module.

2. Characteristics of new 3.3-kV all-SiC power module

2.1. Advantages of SiC

For Si power modules, minority carrier devices such as bipolar devices and IGBTs have been mainly used to increase the on-resistance accompanying high withstand voltage. However, minority carrier devices have large switching loss, and the heat generated by the switching loss limits high frequency operation.

Because SiC has about 10 times higher breakdown electric field strength than Si, it can be

- The First 3.3-kV Full-SiC power module with a performance suitable for a railcar traction system using SiC MOSFET and SiC SBD technology.
- The new Full-SiC power module has ~80% lower switching loss than a conventional Si power module.
- More details can be found in the paper published at PCIM2017.

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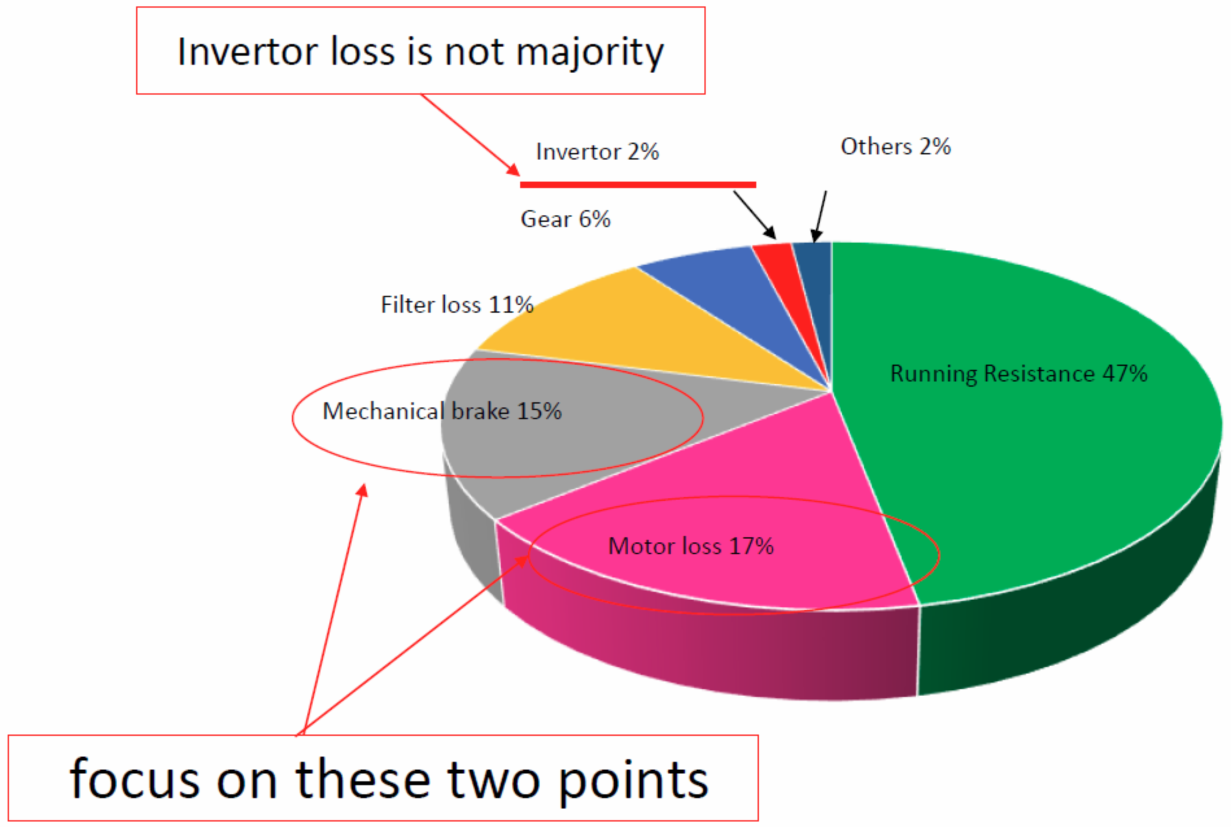
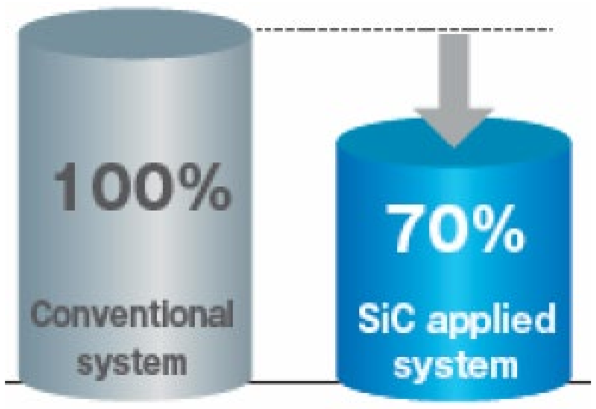
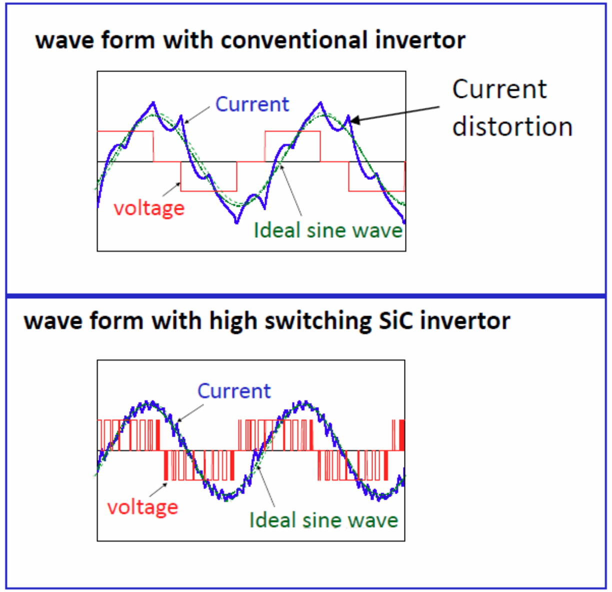
Benefits of SiC in Traction Application







- ➢ 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

Summary & Outlook

1) After 20+ years of basic research and system/device performance and reliability varification Mitsubishi started commercialization of SiC power devices in 2010 for a wide range of applications.
2) Today we launching 2nd generation SiC mosfets produced on a newly comissiones 6 inch wafer fab.
3) For new designs we are focused on applications where SiC technology is offering substantial system benefits versus today‘s Si-based power modules:
   - System cost reduction
   - System performance improvement
   - Reduced system size & weight
4) Mitsubishi is ready to support new SiC design projects with evaluation samples and comprehensive application engineering assistance.

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