Hybrid Si-SiC Modules for High Frequency Industrial Applications

Abstract

This presentation introduces a new family of 1200V IGBT modules that combine high switching frequency optimized silicon IGBTs with SiC SBD (Schottky Barrier Diode) free wheel diodes to provide dramatically reduced losses in hard switched applications. The performance of these new modules will be compared to currently available standard speed and high frequency optimized IGBT modules.

Introduction

Standard industrial IGBT modules are usually optimized for motor drive applications in which the carrier frequency is typically less than 5kHz. For these applications conduction losses tend to dominate so the IGBT chip is optimized primarily for low $V_{CE(SAT)}$. As a result these "standard" devices typically have a rather large turn-off switching loss. Likewise at turn-on the free wheel diode is optimized for a "soft" recovery characteristic that has well controlled dv/dt and is free of oscillations and surge voltages. Often these characteristics come with a corresponding increase in recovery losses.

Despite these optimizations standard industrial modules are increasingly being used in applications such as medical, laser, induction heating, and welding power supplies where higher operating frequencies are desired to improve performance and reduce the size of magnetic components. Higher frequency operation is also desirable to reduce the filter size in grid connected inverters for alternative energy applications and active rectification for recovery of mechanical energy in motor drives.

The latest generations of modules [1] having both lower $V_{CE(SAT)}$ and lower turn-off losses offer improved performance in high frequency applications but are still seriously limited by their relatively high turn-off and free wheel diode recovery losses.

This paper introduces for the first time a standard line-up of industrial modules that utilize both high frequency optimized IGBTs and SiC SBD free wheel diodes to provide dramatically reduced losses in high frequency hard switched applications.

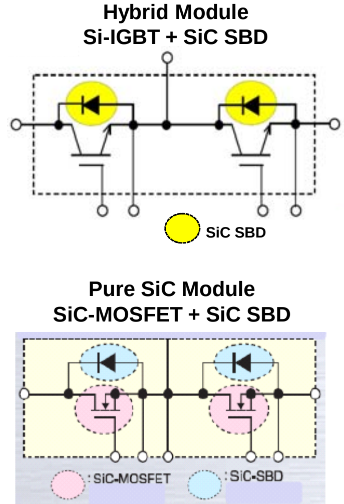


Figure 1: Hybrid and Full SiC Modules

Rational for Hybrid Configuration

The advantages of SiC as a material for power semiconductor devices is well known [2]. The main drawbacks are the relatively high cost of SiC compared to Silicon and lingering concerns about the long term reliability of SiC devices. One approach to at least partially mitigate these concerns in the near term is to make hybrid modules consisting of Silicon IGBTs and SiC Schottky free wheel diodes as shown in figure 1. This combination of the more mature SiC SBD technology with a well-established high frequency optimized silicon IGBT provides both lower cost and greater reliability confidence.

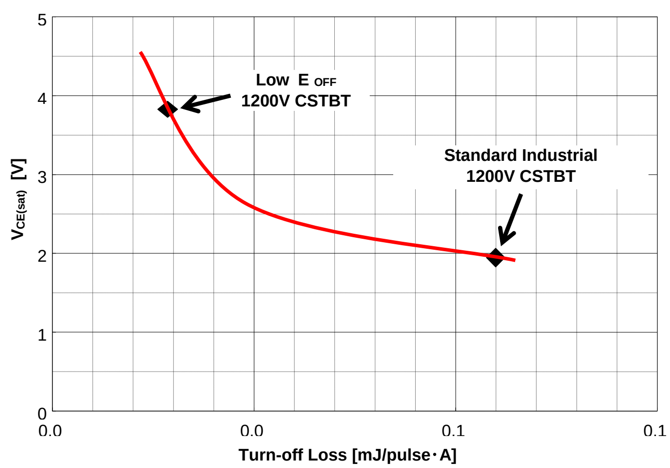


Figure 2: Low Eoff CSTBT Optimization

1200V Low E_{OFF} CSTBT Chip

Silicon IGBTs optimized for low turn off losses (Eoff) have been commercially available for more than a decade [3]. In the design of an IGBT chip it is possible to trade $V_{CE(SAT)}$ for lower switching losses by adjusting the minority carrier lifetime. Fig. 2. shows the trade-off curve of saturation voltage versus turn-off switching losses obtained for a 5th generation 1200V CSTBT chip [3]. For the target high frequency industrial applications an optimum point was selected at a $V_{CE(SAT)}$ of 3.8V and an Eoff of 0.028mJ/pulse•A. Fig. 3 shows example switching waveforms comparing the high speed CSTBT to a standard IGBT. These waveforms clearly show the dramatic reduction in turn-off losses and almost complete elimination of the “tail” current. Unfortunately this technology does not improve the hard switched turn-on losses (Eon) which depend mainly on the free wheel diode recovery characteristics. As a result conventional high frequency optimized IGBT modules offer a large performance improvement in applications having a soft turn-on but only a modest improvement in applications like PWM inverters with a hard turn-on switching.

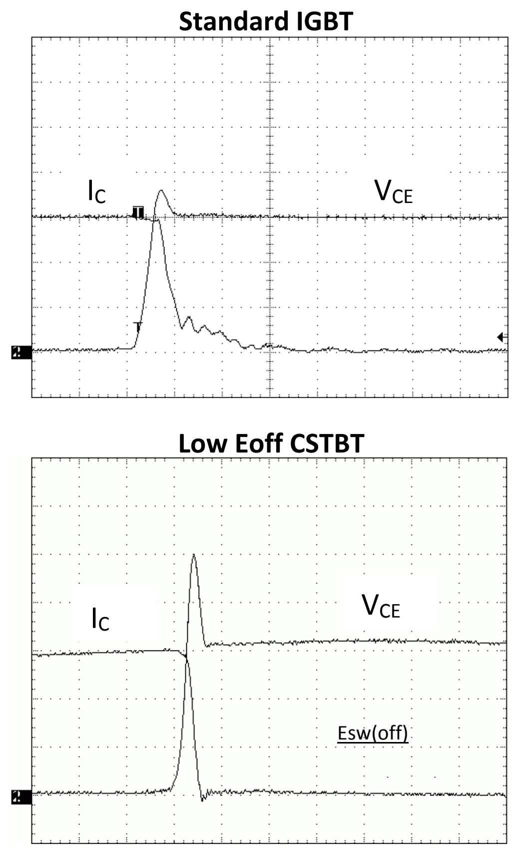


Fig. 3 Turn-Off Switching Waveform

Hybrid Module Characteristics

The advantage of using an SiC Schottky diode instead of a conventional silicon PIN diode is illustrated in Fig. 4. The SiC Schottky almost completely eliminates the reverse recovery loss. In addition, for applications such as PWM inverters that have a hard switched turn-on there is also a significant reduction in turn-on losses due the dramatic reduction in free wheel diode recovery current. Fig. 5 shows the turn-on current waveforms for 600A, 1200V modules. The dramatic reduction of reverse recovery current in the hybrid module is readily apparent.

Application Performance

Figure 6 shows a comparison of the performance of a standard 6th generation industrial IGBT module, a conventional high frequency optimized IGBT module, and the new hybrid SiC module in a hard switched

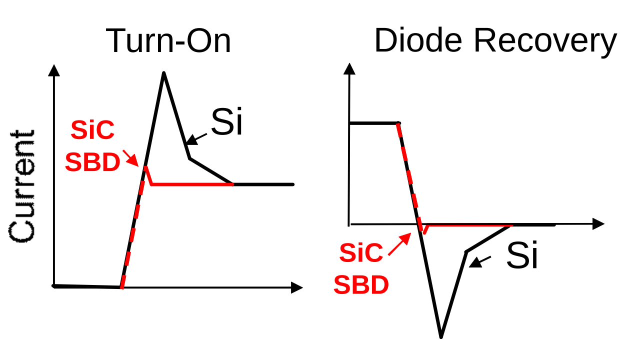


Figure 4: Hybrid Module Hard Turn-On Waveform

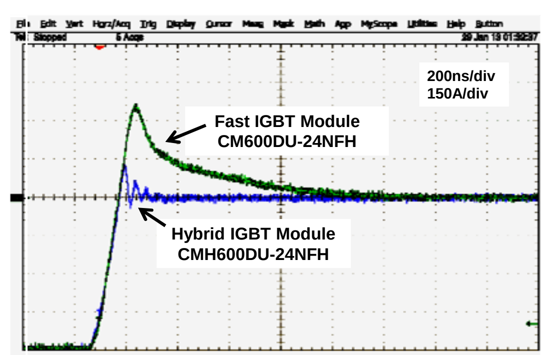


Figure 5: Hard Turn-On Comparison

sinusoidal output inverter. At low PWM frequencies which are common in many industrial drives the standard speed module still has the lowest losses. For the modules in this comparison the practical power dissipation limit in a typical air cooled application is around 600W per module. At this power level the standard speed module is limited to about 12KHz, the high frequency optimized all silicon device gives a modest improvement to about 17KHz but the hybrid module is usable up to 50KHz.

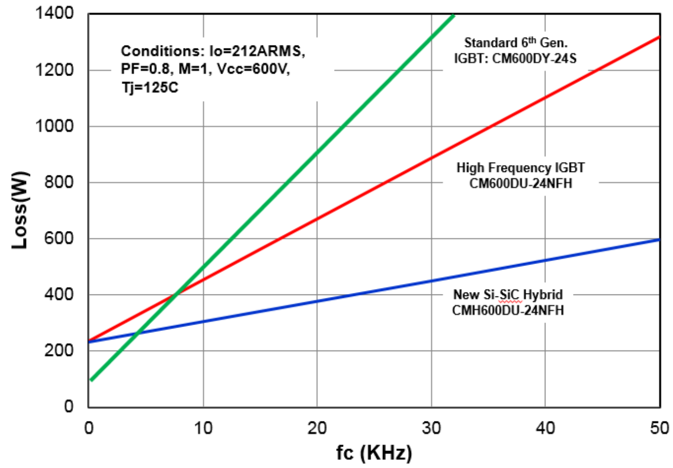


Figure 6: Sinusoidal output hard switched PWM inverter loss comparison

Module Line-Up

A new line-up of 1200V SiC hybrid modules has been developed as shown in Table II. All modules have a dual (half bridge) configuration and are available with nominal current ratings ranging from 100A to 600A. In order to take full advantage of the increased switching speed the modules utilize the same low inductance packaging that was developed for the conventional high frequency devices [5].

TABLE II: New Hybrid IGBT Module Line-Up

Ratings Ic/Vces	Part Number	Package
100A/1200V	CMH100DY-24NFH	48mm X 94mm 
150A/1200V	CMH150DY-24NFH	
200A/1200V	CMH200DU-24NFH	62mm X 108mm 
300A/1200V	CMH300DU-24NFH	
400A/1200V	CMH400DU-24NFH	80mm X 110mm 
600A/1200V	CMH600DU-24NFH	

Conclusions and Future Work

This presentation introduces for the first time a new family of standard 1200V IGBT modules that combine high switching frequency optimized silicon IGBTs with SiC SBD (Schottky Barrier Diode) free wheel diodes to provide dramatically reduced losses in hard switched applications. It has been shown that these new devices enable dramatically higher modulation frequencies in high power hard switched inverters.

References

[1] T. Nishiyama, et al., "The IGBT Module with 6th Generation IGBT" Proceedings PCIM 2009

[2] T. Kobayashi, et al., "Energy Saving Operation for Railway Inverter Systems with SiC Power Module" PCIM Europe 2012

[3] Junji Yamada,et al. "Low Turn-off Switching Energy 1200V IGBT Module", IEEE IAS Conference 2002

[4] Takahashi, et al., "Carrier Stored Trench-Gate Bipolar Transistor (CSTBT) - A Novel Power Device for High Voltage Application", The 8th International Symposium on Power Semiconductor Devices and ICs 1996

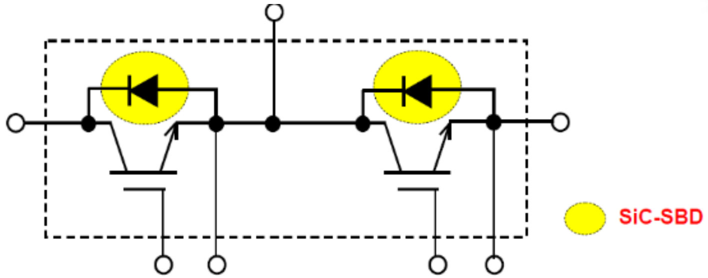
[5] E. R. Motto, "A New Low Inductance IGBT Module Package", PCIM Conference 1996

Speaker Biography:

Eric R. Motto is principal application engineer with Powerex. He is a senior member of IEEE and holds a BSEE from Pennsylvania State University. Since 1990 Eric has been with Powerex Inc. in Youngwood PA. providing technical support for users of power semiconductor devices. Eric has written and presented more than fifty technical papers at industry conferences and published numerous application notes and magazine articles related to the design and application of high power IGBTs, Intelligent Power Modules and SiC power devices.

Hybrid Si – SiC High Power Modules

For cost effective high voltage, high current, high frequency switching



INTRODUCTION
High Power Module Status & Outlook

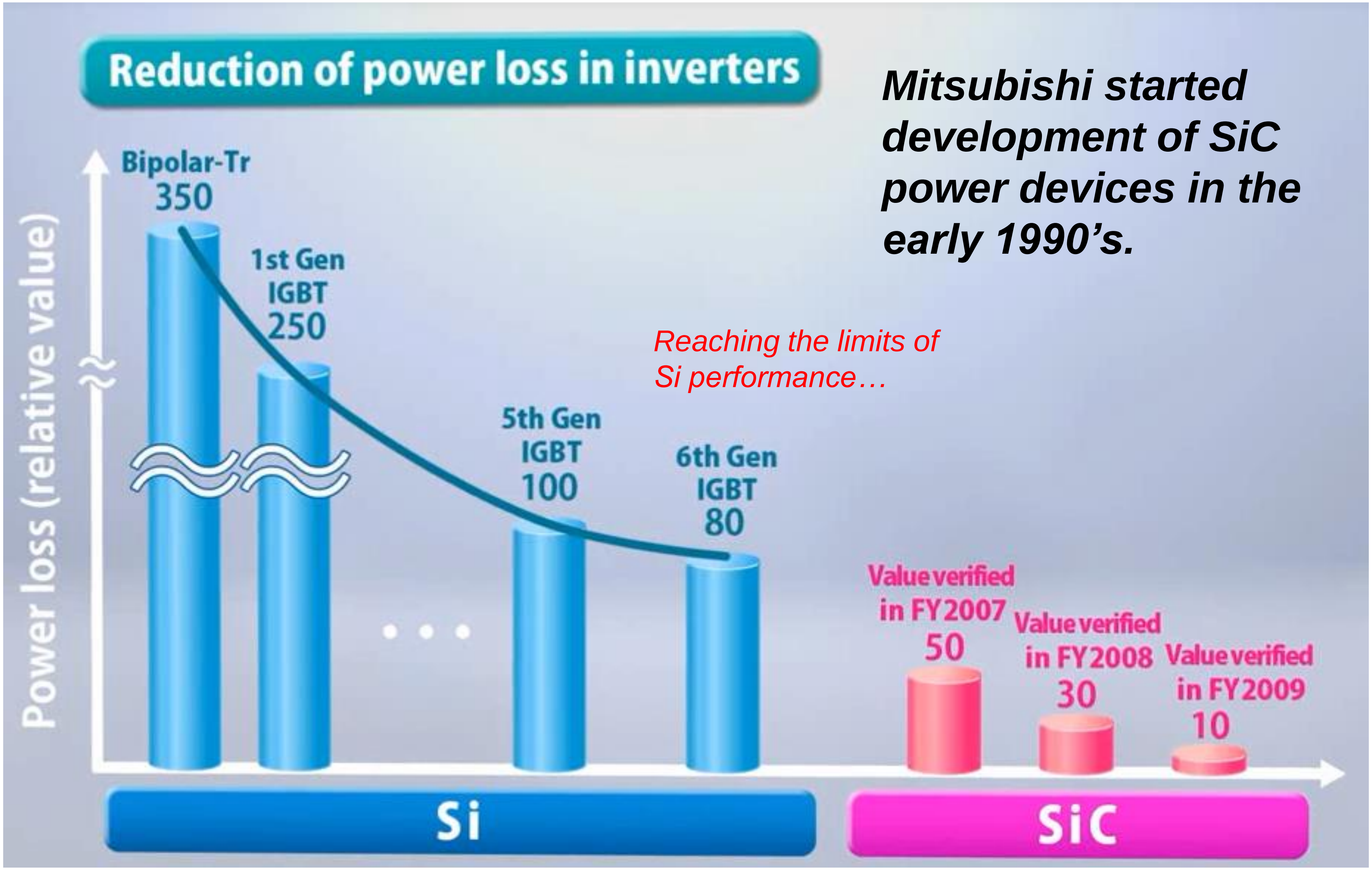
Use of SiC is on the rise

- More than 20 module types using SiC chips are in various stages of development and production.
- The cost premium of SiC versus silicon requires applications where significant performance improvements yield high value. These are primarily high frequency (20KHz+), high voltage (1200V+) hard switching applications.
- Hybrid devices consisting of SiC Schottky in combination with a silicon IGBT provide a good compromise between cost and performance for many industrial applications.
- Current SiC module offerings are utilizing standard IGBT module packaging and manufacturing processes. Therefore, the maximum operating temperature is limited to 150C-175C.

Silicon is not dead yet

- The Silicon IGBT is expected to continue as the most cost effective power device for most industrial applications for the next five to ten years
- Currently a new 7th generation family of silicon IGBT modules is being introduced.
- Support for three level topologies using silicon devices is being expanded for applications requiring increased efficiency at higher voltages

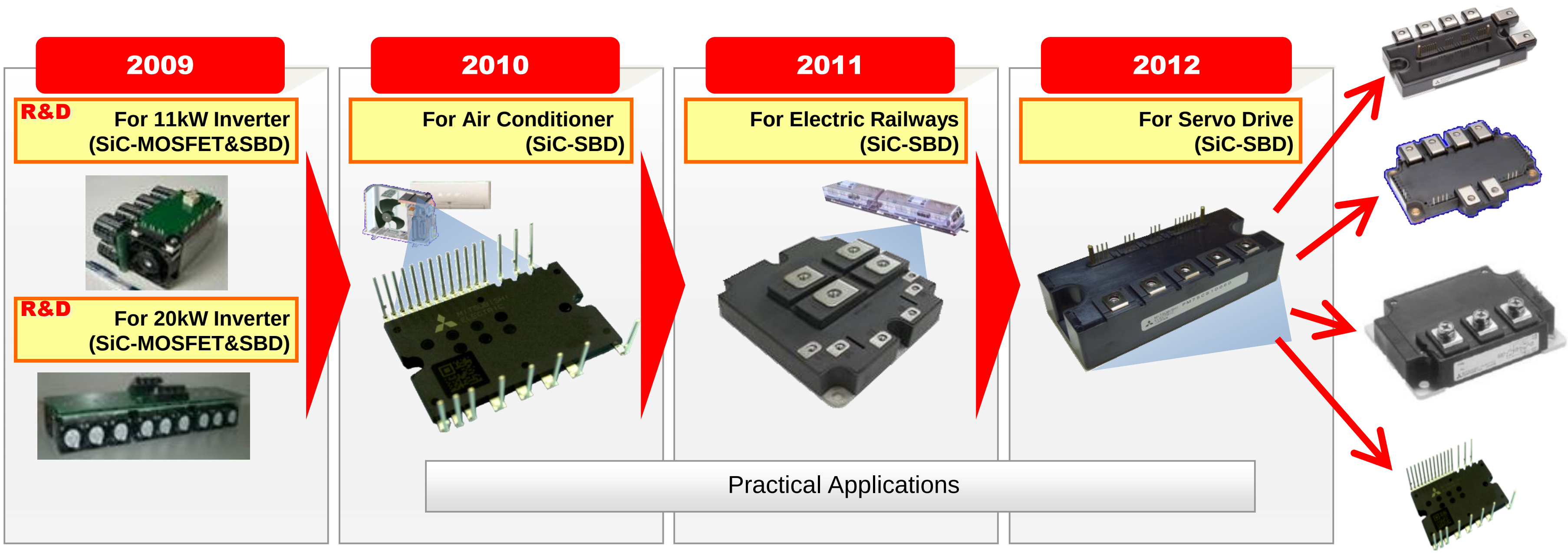
Power Device Technology Trend



Reaching the limits of Si performance…

Mitsubishi started development of SiC power devices in the early 1990's.

Commercialization of Mitsubishi SiC Power Modules



- Mitsubishi Electric started research and development of SiC devices in the early 1990's and has gained knowledge and experience to cost effectively produce high power devices.
- Schottky Barrier Diode (SBD) and Power MOSFET are the two key chip technologies currently emphasized for power module product applications.
- Mitsubishi Electric has released several module types to production since 2012.

Why SiC?

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.

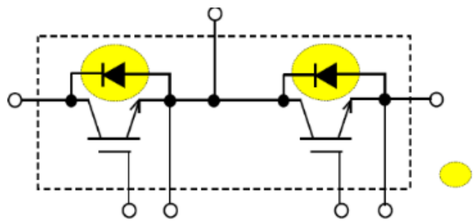
High field break down means that a thinner blocking junction can be used for a given voltage. The thinner junction provides reduced switching and conduction losses especially at higher voltages

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

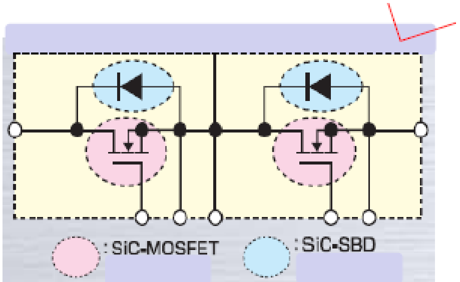
Also, IGBT structure has no significant benefit until about 5000V

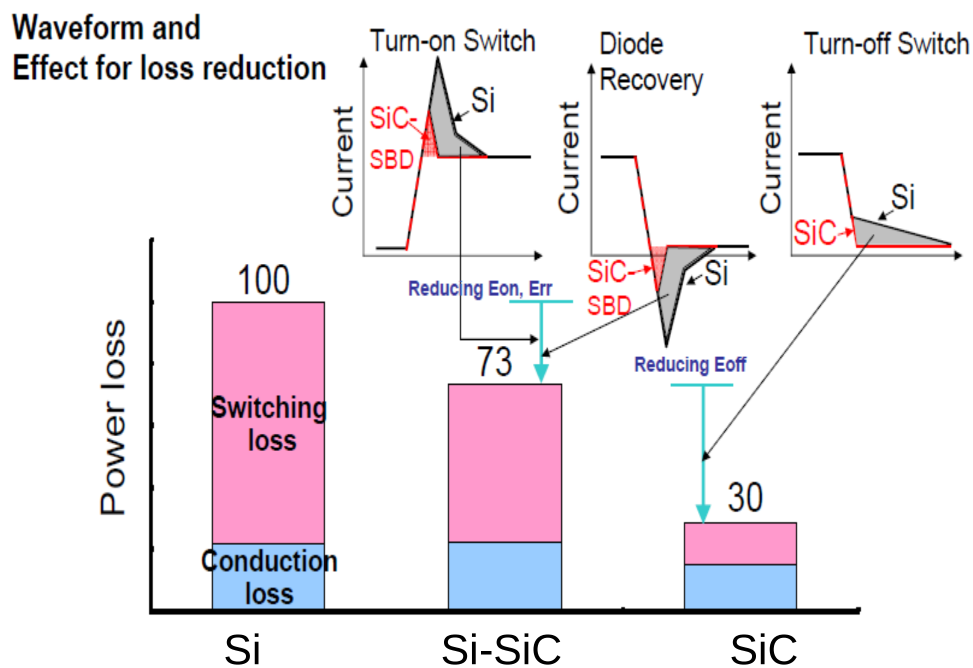
Hybrid versus Pure SiC

Hybrid
Si-IGBT + SiC SBD



Pure SiC
SiC-MOSFET + SiC SBD

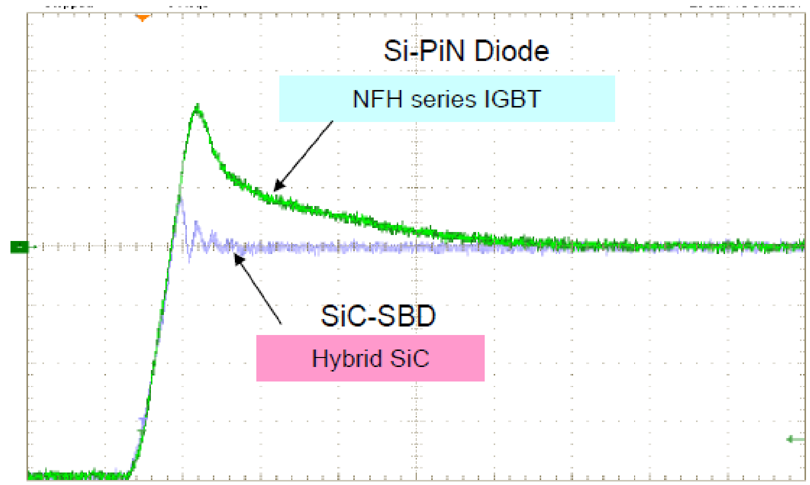


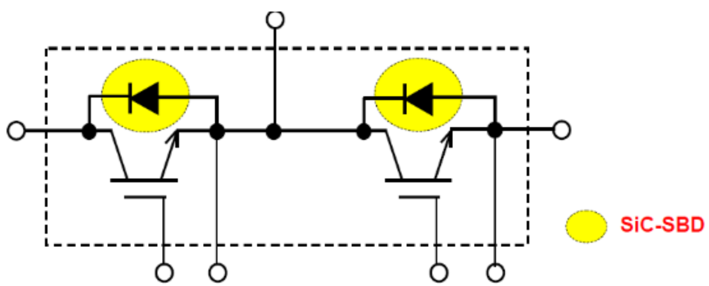


Module Type	Advantages	Disadvantages
Hybrid Si-SiC Module	➢ SiC SBD technology considered more mature ➢ Lower Cost than Pure SiC	➢ Si-IGBT has higher turn-off loss and/or On-state voltage drop. ➢ Frequency of operation limited by Si-IGBT speed ➢ Operating temperature limited by Si-IGBT
Pure SiC Module	➢ 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 Industrial Applications

- Product Range 1200V, 100A-600A
- Package: Same as existing NFH-Series
- Power Chips: NFH Si IGBT, SiC SBD
- Cost: Today ~1.5X all silicon device

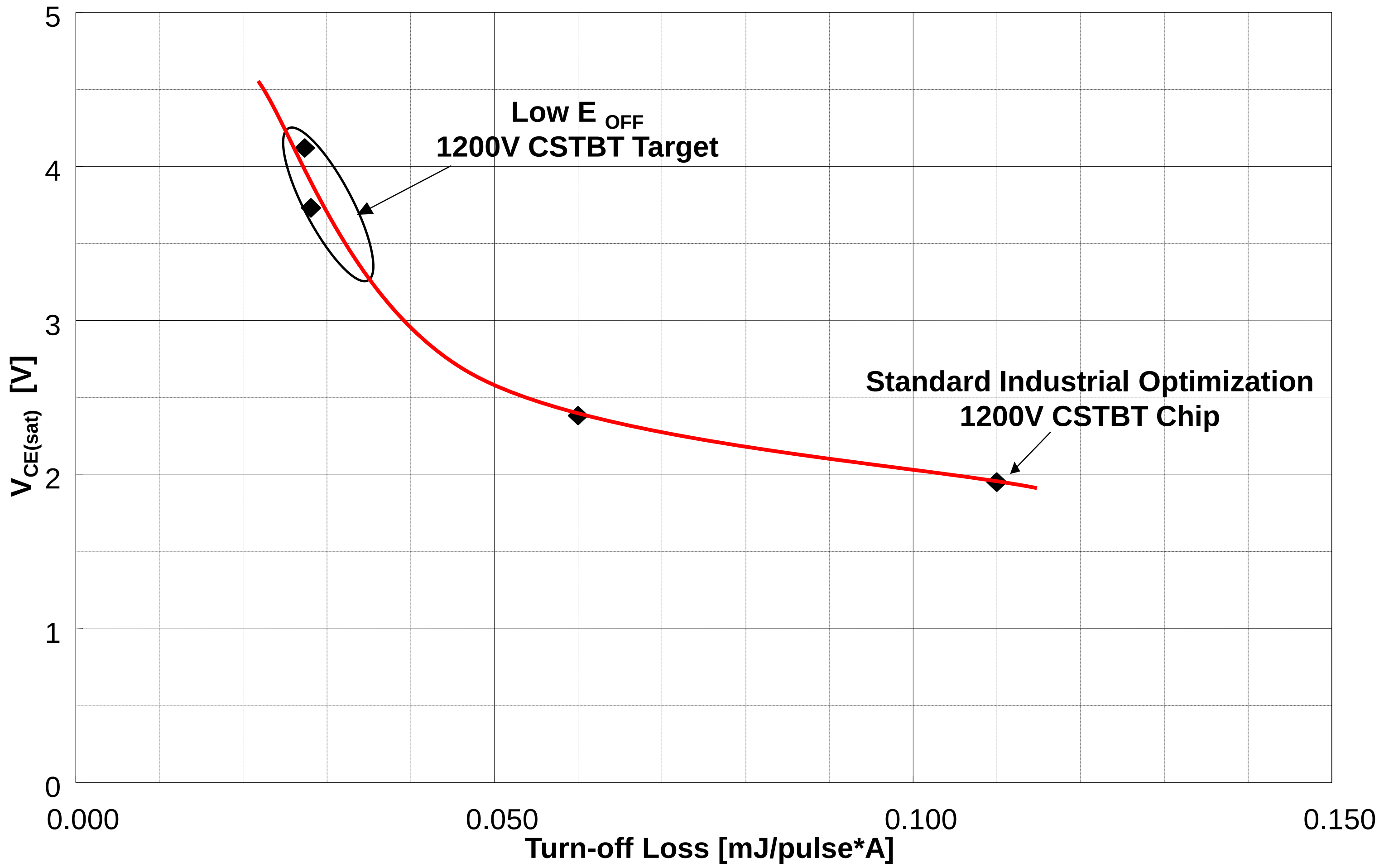




NFH Series IGBT Chip Development Concept

- Start with CSTBT for best $V_{CE(sat)}$ versus E_{off} trade-off
- Adjust the carrier lifetime to trade $V_{CE(sat)}$ for increased switching speed

IGBT E_{SW} Versus $V_{CE(sat)}$ Trade-Off



How do we make the 1200V CSTBT faster ?

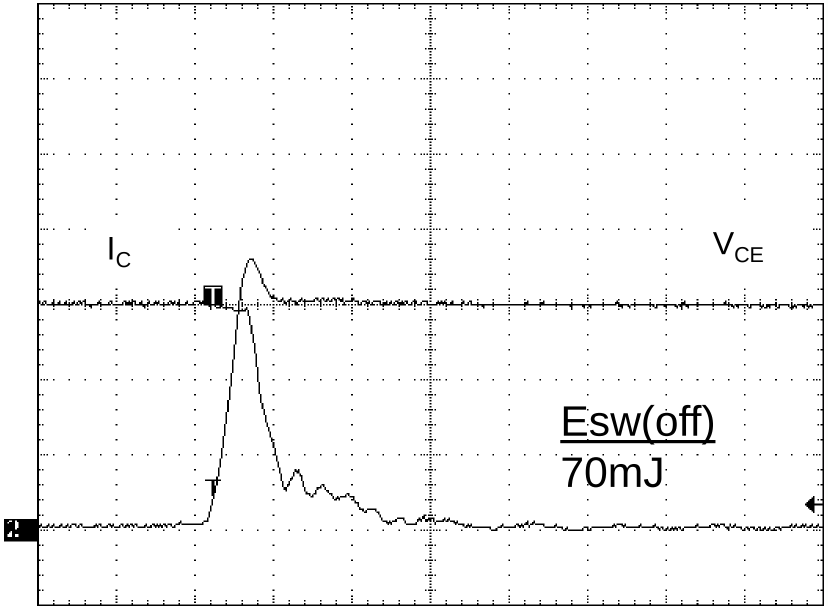
Optimize buried layer

Optimize n- carrier lifetime and concentration

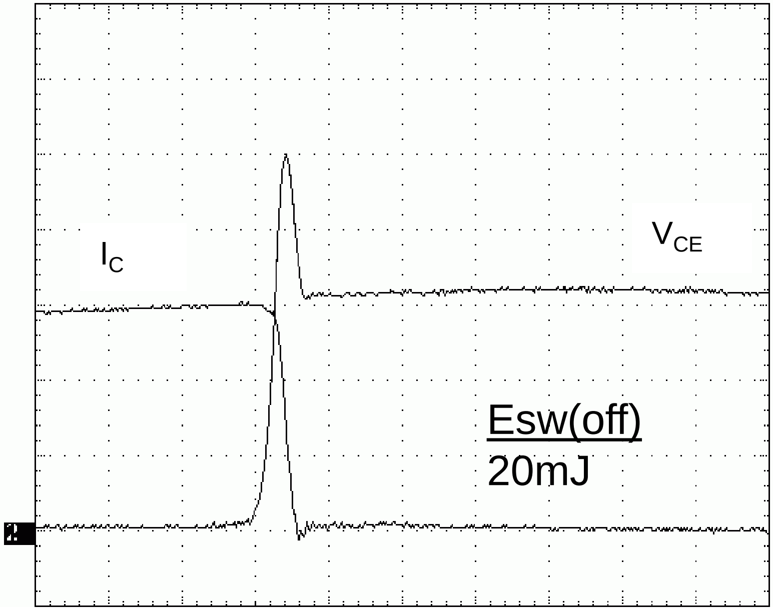
Optimize n backside layer and collector

IGBT Turn-Off Switching Waveform Comparison

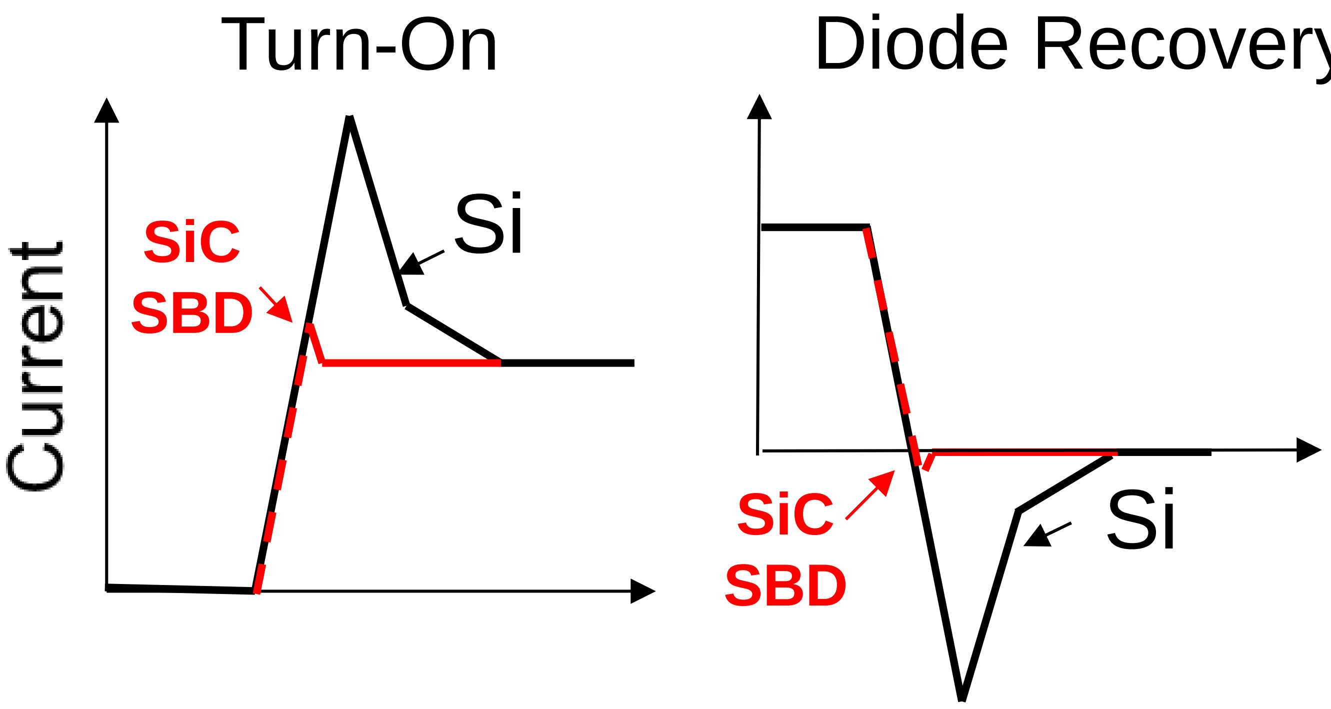
Standard IGBT
Turn-Off Waveform Tj=125C,
Vcc=600V, Ic=300A, t:200ns/div



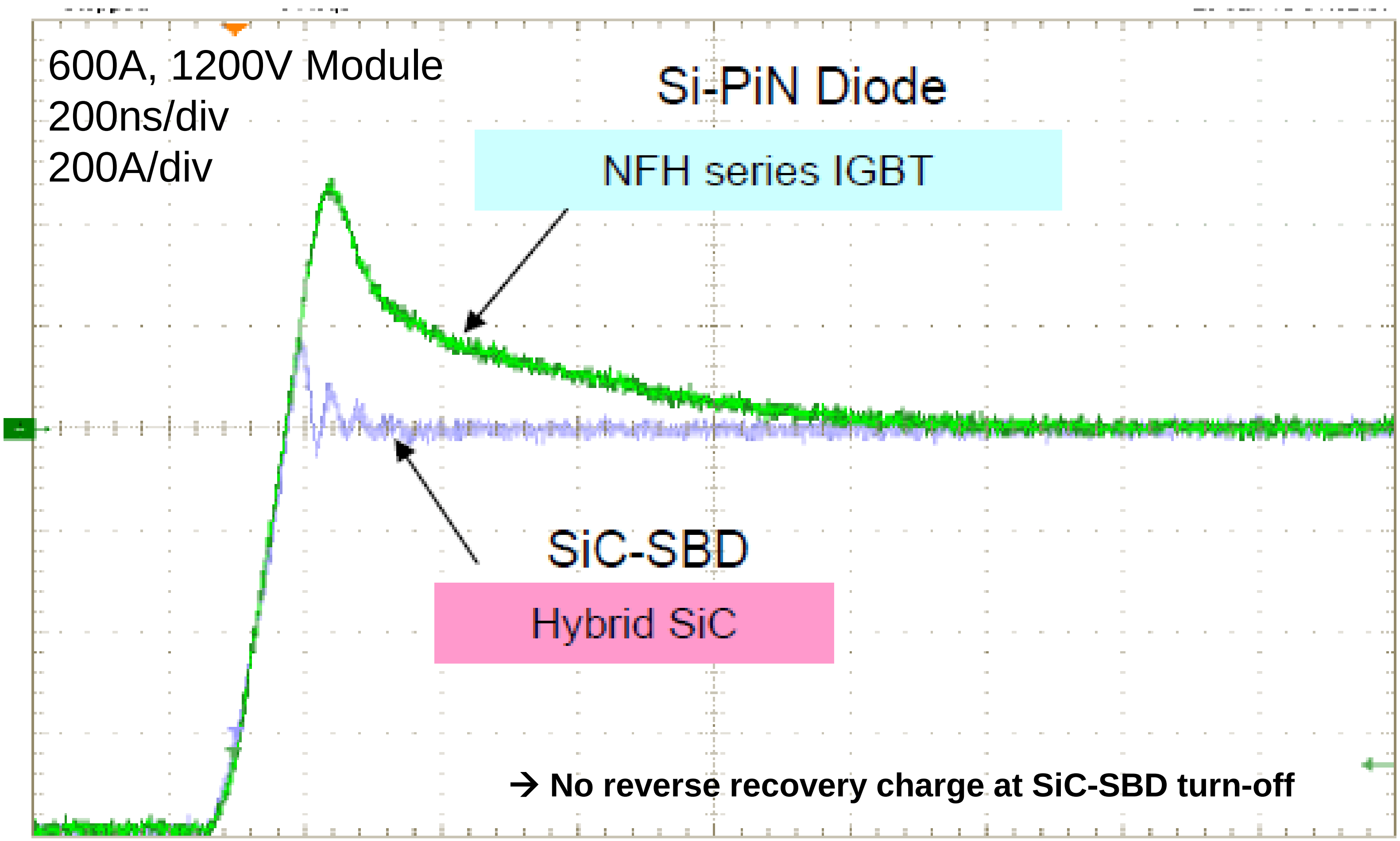
High speed NFH IGBT
Turn-Off Waveform Tj=125C,
Vcc=600V, Ic=300A, t:200ns/div



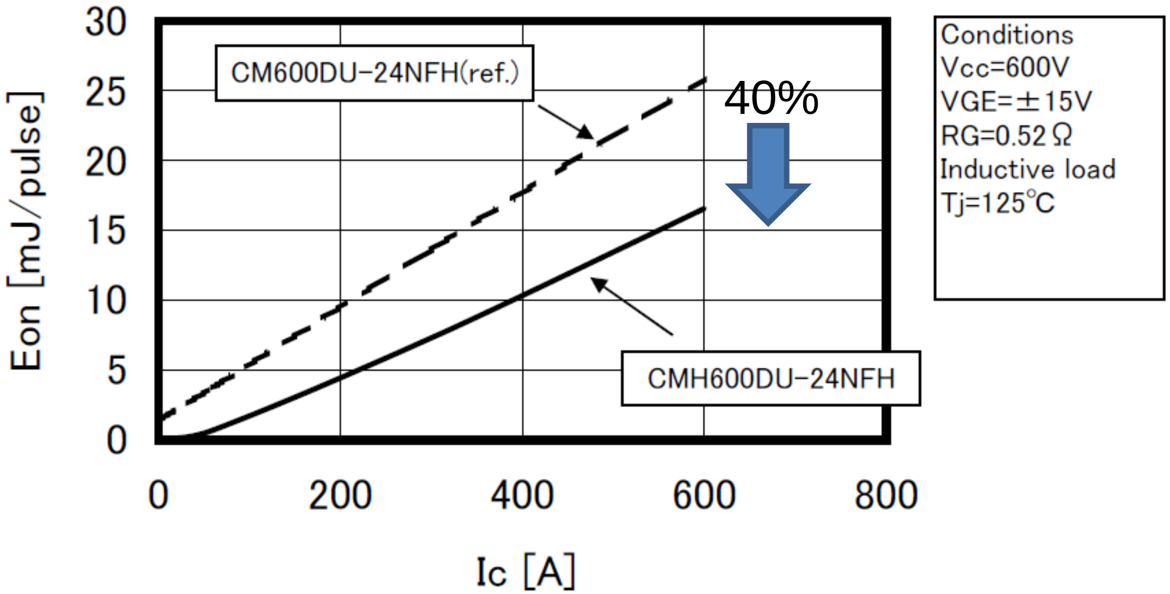
Hybrid versus Standard module Turn-On Switching and Diode Reverse Recovery Loss

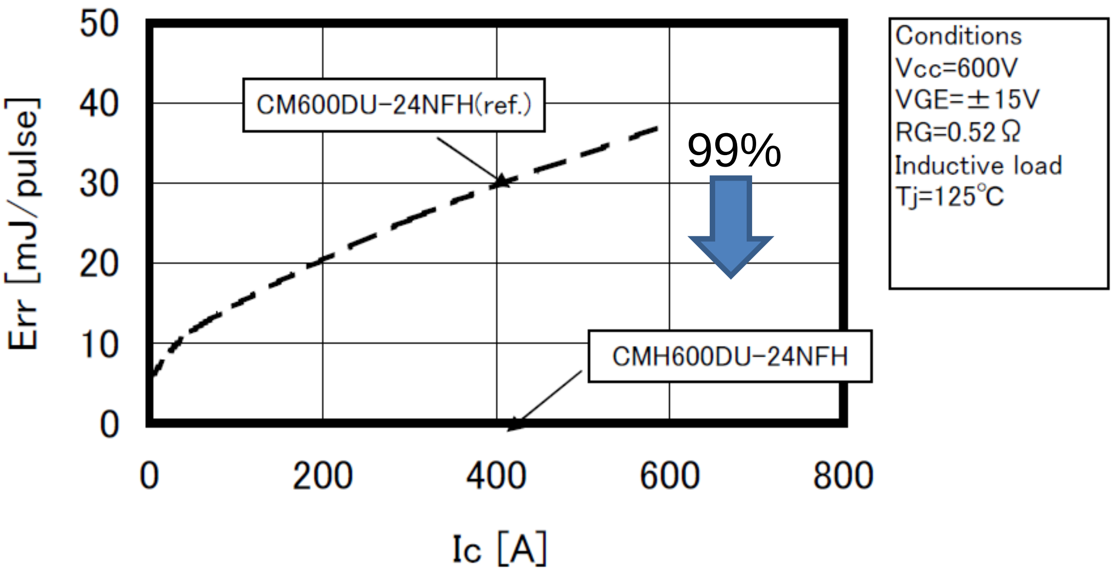


Hybrid versus Standard module Turn-On Switching Waveform

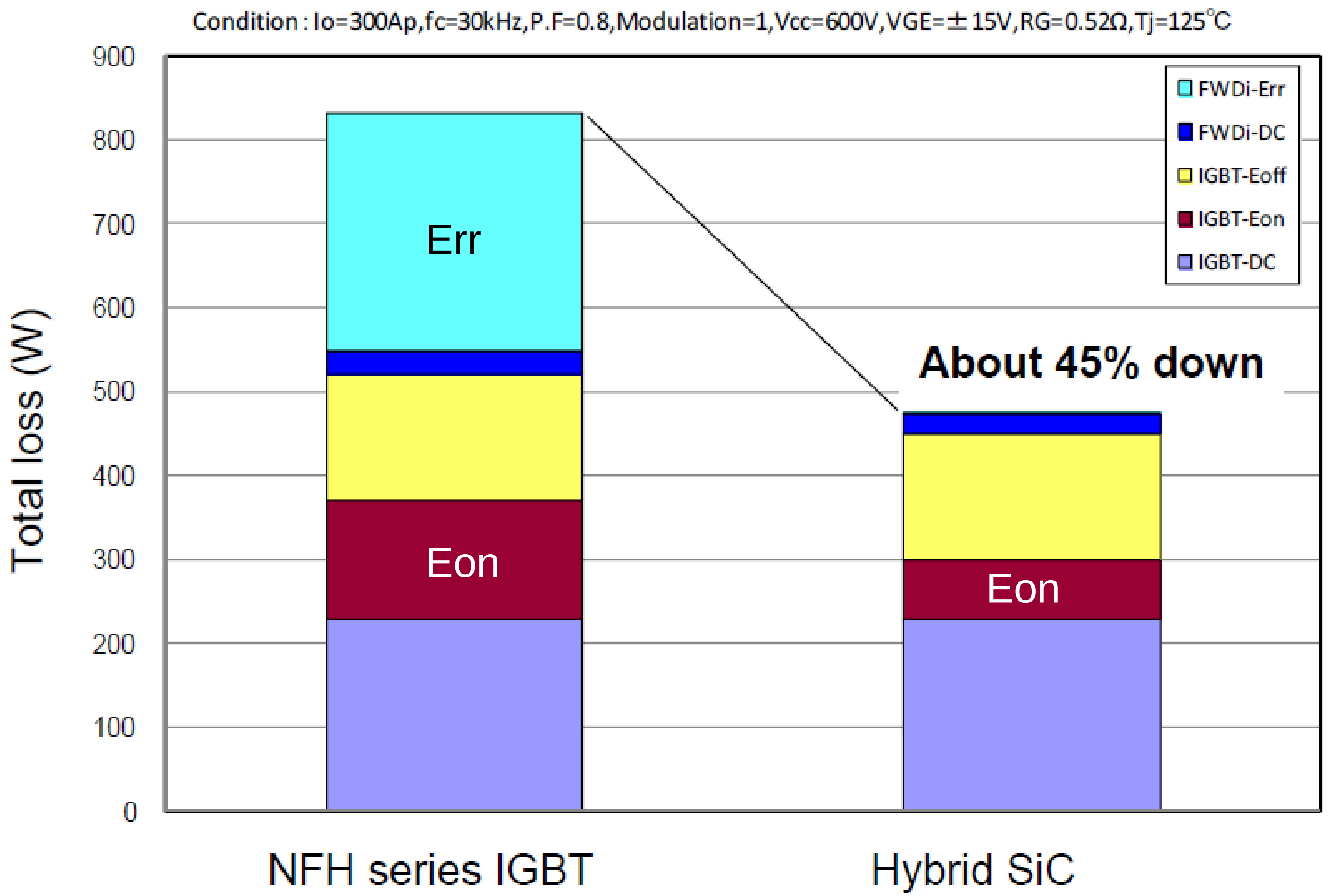


CMH600DU-24NFH Performance

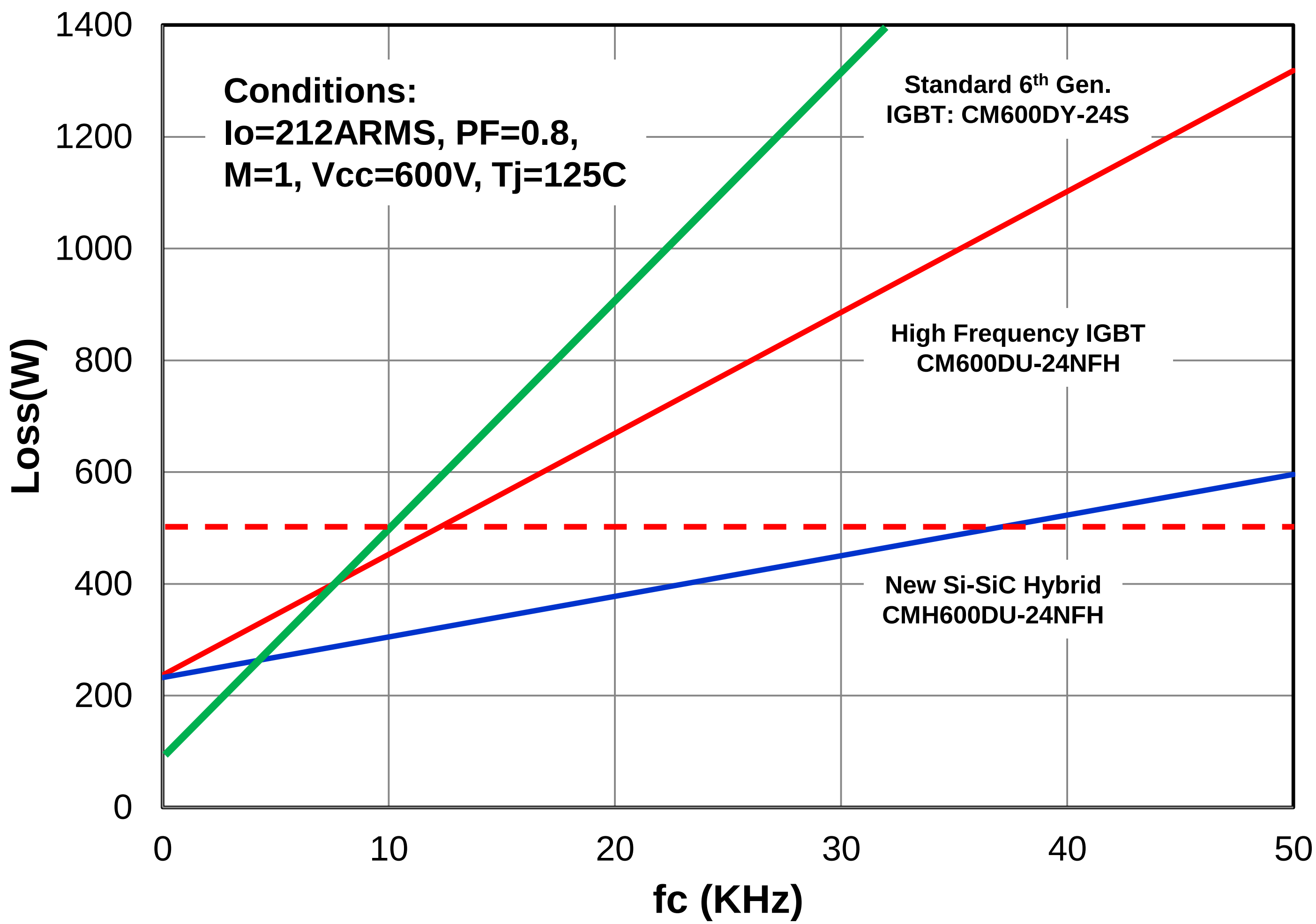




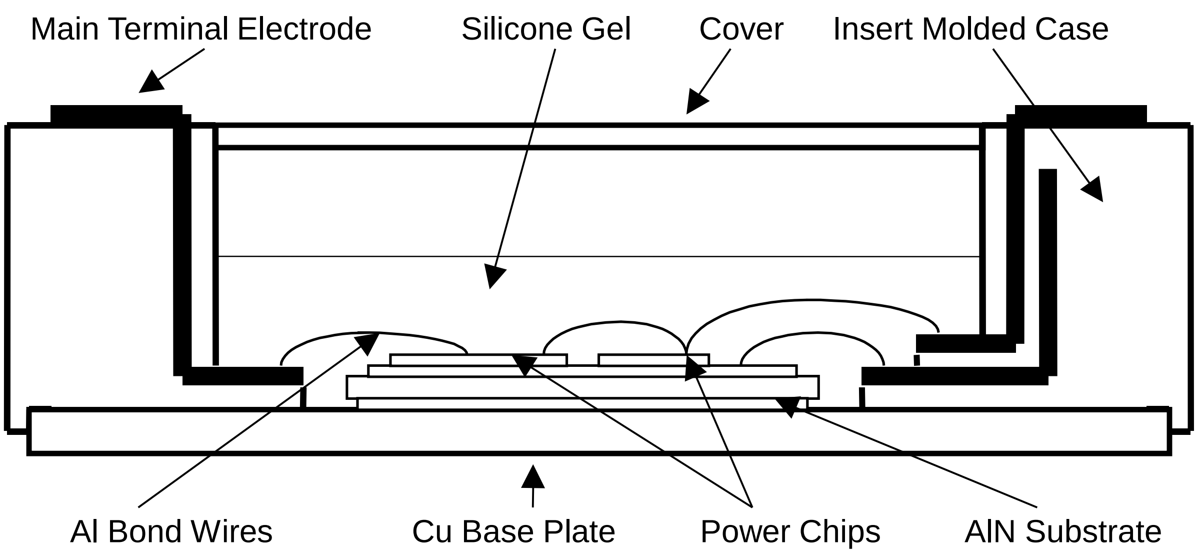
Hybrid versus Standard Module Inverter Loss Comparison

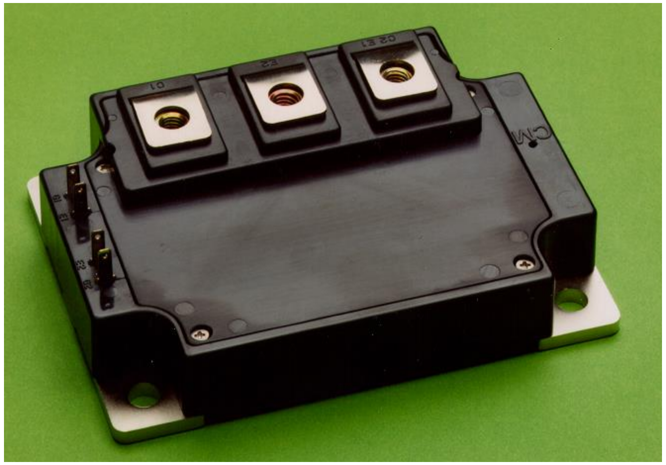


Hard Switched Sinusoidal Output Inverter Loss Vs. Switching frequency 600A, 1200V Modules



Low Inductance Package





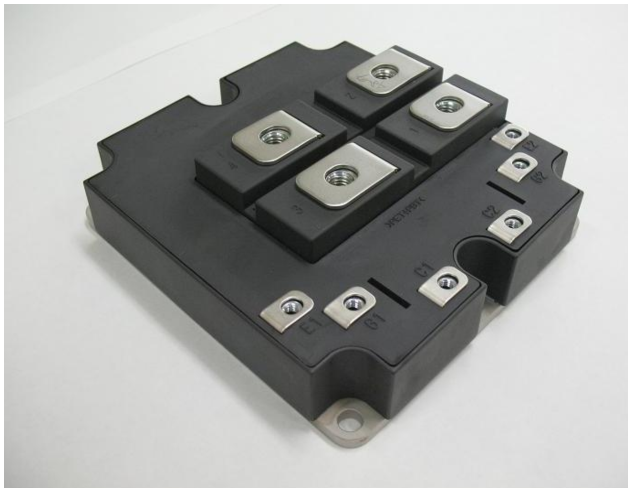
SiC – NFH Hybrid IGBT Module Line-Up

Ratings Ic/Vces	Part Number	Package
100A/1200V	CMH100DY-24NFH	48mm X 94mm 
150A/1200V	CMH150DY-24NFH	
200A/1200V	CMH200DU-24NFH	62mm X 108mm 
300A/1200V	CMH300DU-24NFH	
400A/1200V	CMH400DU-24NFH	80mm X 110mm 
600A/1200V	CMH600DU-24NFH	

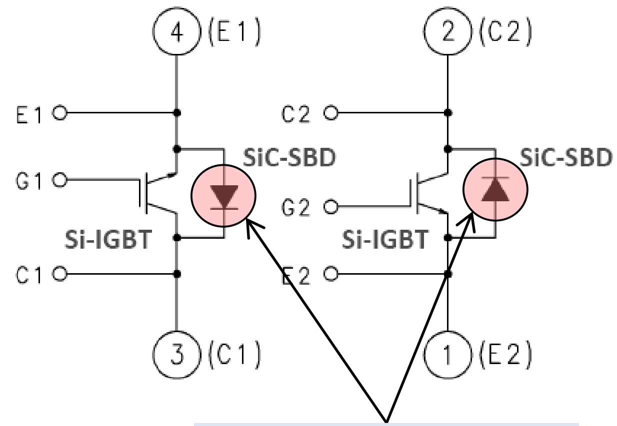
1200A/1700V hybrid SiC 2in1 HVIGBT

■ Type name: CMH1200DC-34S

■ Outline



■ Internal Circuit



Using SiC-SBD

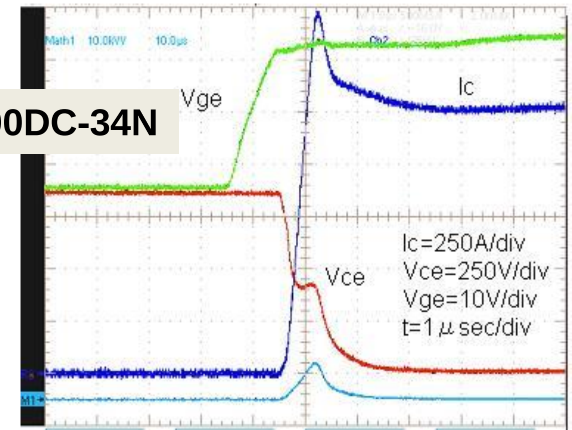
■ Performance comparison

Item	CM1200DC-34N (Si-IGBT,Si-diode)	CMH1200DC-34S (Si-IGBT,SiC-SBD)	
	Tj=125°C	Tj=125°C	Tj=150°C
IGBT on-state voltage	2.40V	2.25V	2.30V
IGBT turn-on loss	0.40J/P	0.14J/P	0.14J/P
IGBT turn-off loss	0.38J/P	0.37J/P	0.39J/P
Diode on-state voltage	2.30V	2.20V	2.30V
Diode turn-off loss	0.24J/P	0.01J/P	0.01J/P

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

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

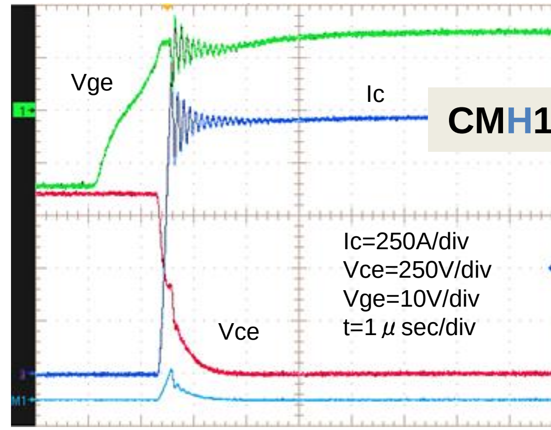
CM1200DC-34N



Eon=0. 40J/pulse

68% Reduction

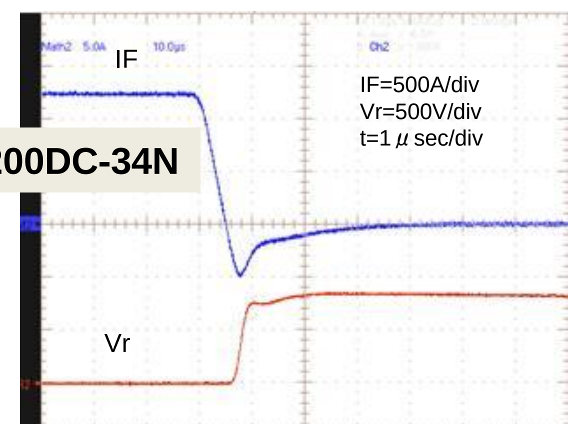
CMH1200DC-34S



Eon=0.18J/pulse

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

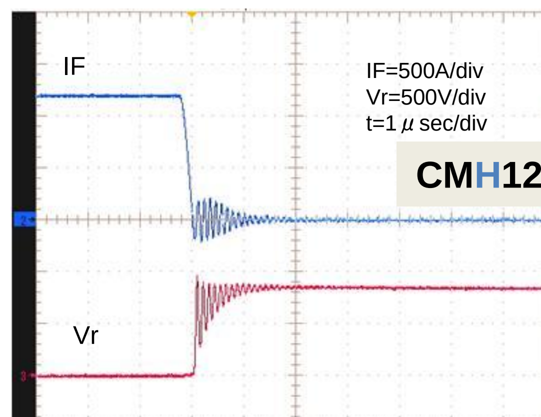
CM1200DC-34N



Erec=0.22J/pulse

95% Reduction

CMH1200DC-34S



Erec=0.01J/pulse

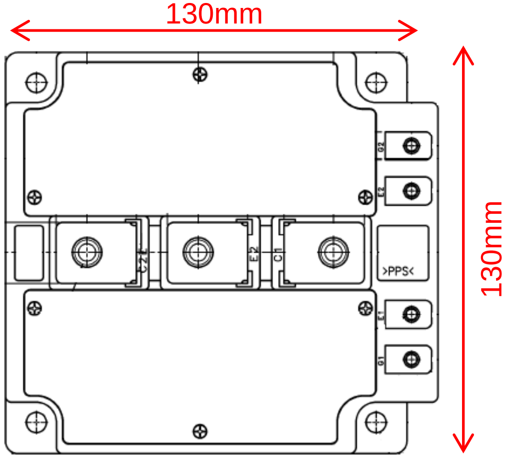
800A/1200V Full-SiC 2in1 Module

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

Mounting area
- Small mounting area (56% off)

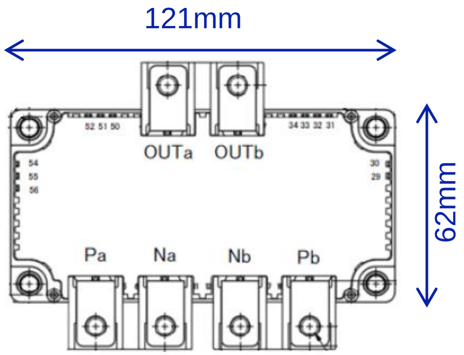
Package outline

16900mm2

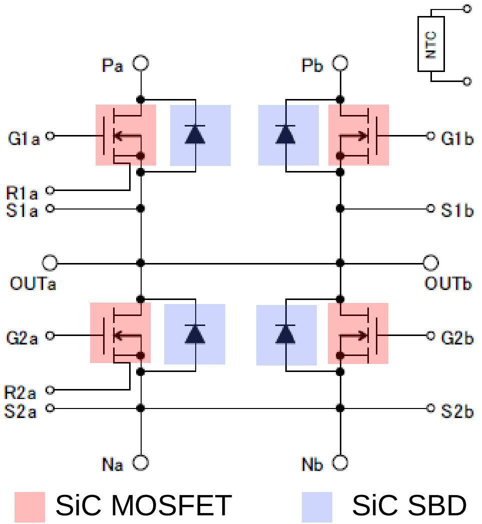


CM800DY-24S (Si)

7502mm2

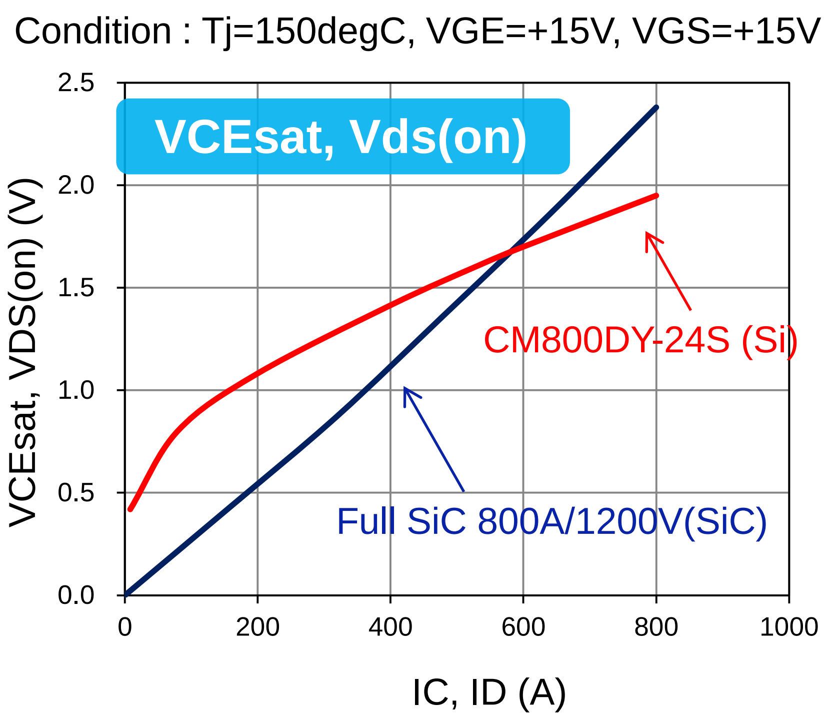


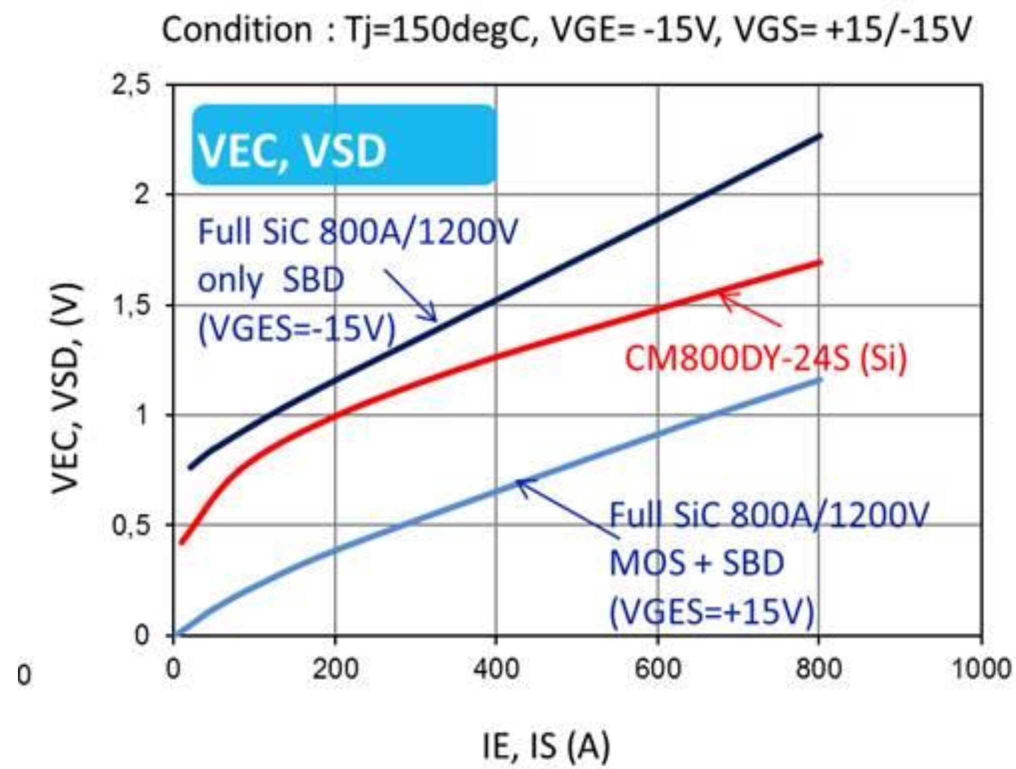
Full SiC 800A/1200V(SiC)



Internal connection

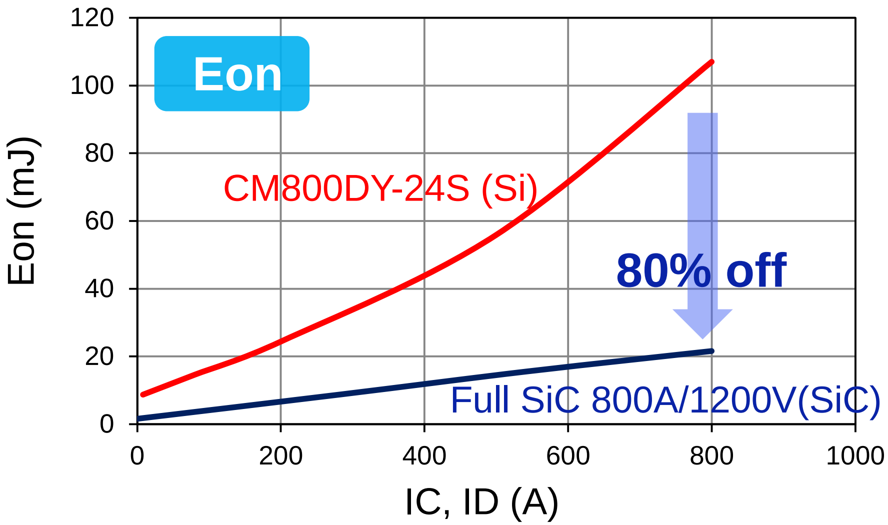
Static Performance Comparison 800A/1200V Full-SiC 2in1 Module

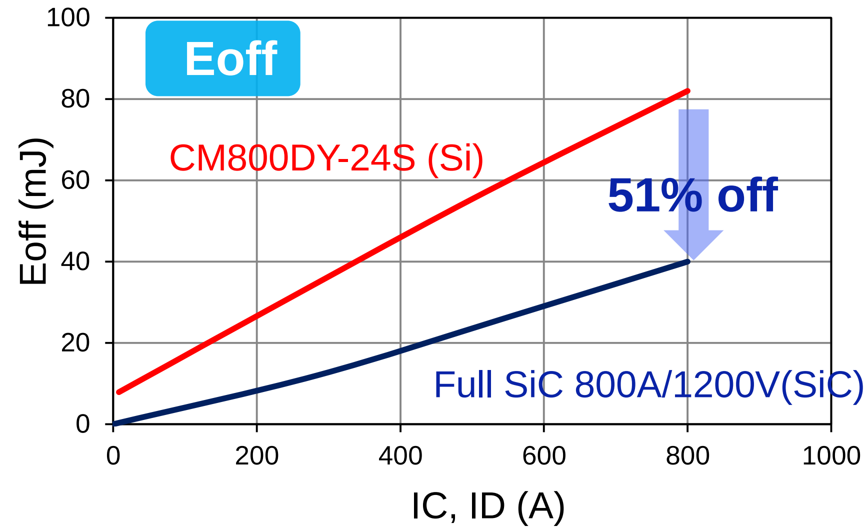


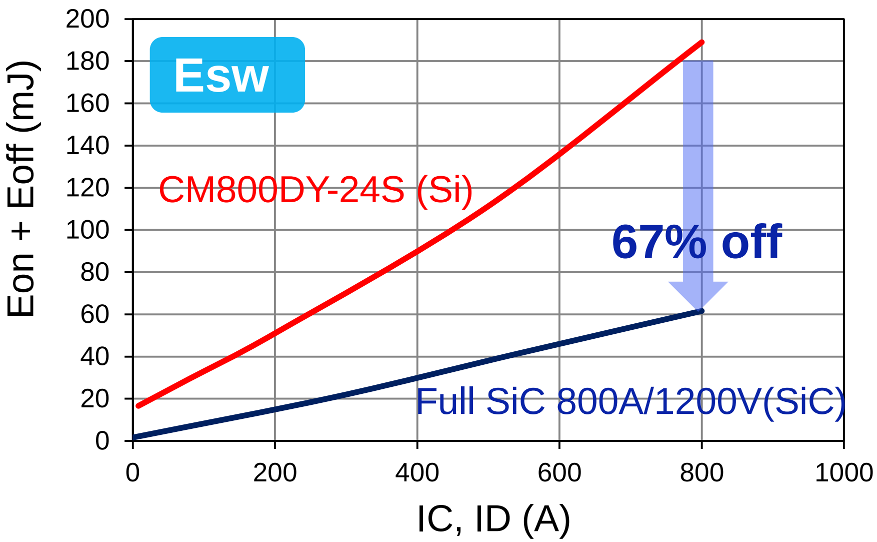


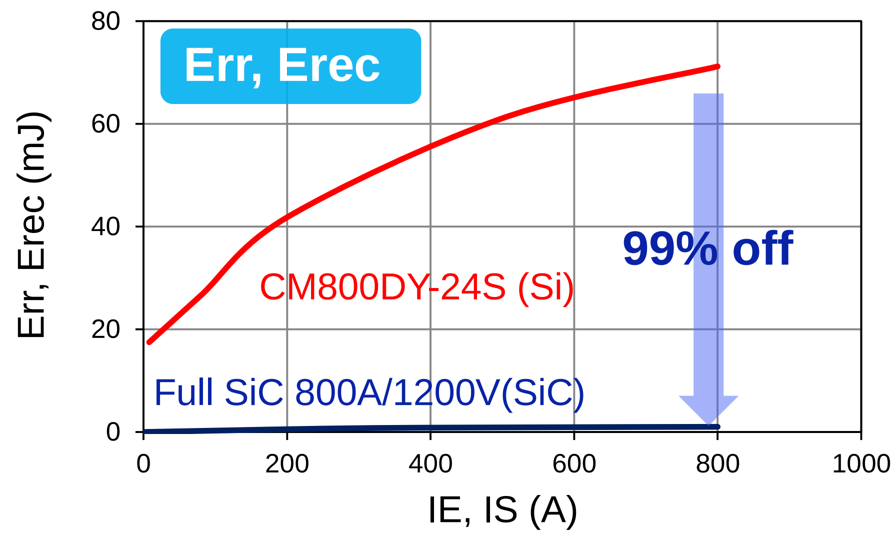
Dynamic Performance Comparison 800A/1200V Full-SiC 2in1 Module

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



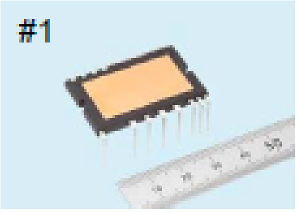






SiC Commercial Module Line-Up

Vces (V)	Ic (A)	Module type	Hybrid / Full SiC	Type name	Package
600	20	DIPPFC	Hybrid	PSH20L91A6-A	#1
600	20	DIPPFC	Full SiC	PSF20L91A6-A	#1
600	200	6in1 IPM	Hybrid	PMH200CS1D060	#2
1200	75	6in1 IPM	Hybrid	PMH75-12-S002	#3
1200	75	6in1 IPM	Full SiC	PMF75-12-S002	#3
1200	800	2in1	Full SiC	CMF800-24-S001 (*) NEW	#4
1200	1200	2in1	Full SiC	FMF1200DX1-24A NEW	#5
1200	100	2in1	Hybrid	CMH100DY-24NFH NEW	#6
1200	150	2in1	Hybrid	CMH150DY-24NFH NEW	#6
1200	200	2in1	Hybrid	CMH200DU-24NFH NEW	#7
1200	300	2in1	Hybrid	CMH300DU-24NFH NEW	#7
1200	400	2in1	Hybrid	CMH400DU-24NFH NEW	#8
1200	600	2in1	Hybrid	CMH600DU-24NFH NEW	#8
1200	400	1in1	Hybrid	CMH400HC6-24NFH	NN
1700	1200	2in1	Hybrid	CMH1200DC-34S	#9



Thank You For Your Attention……

Questions?