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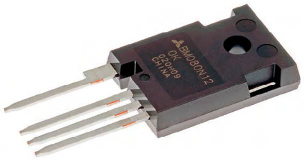
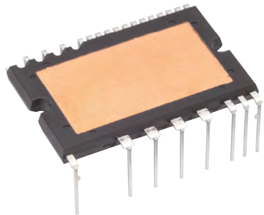


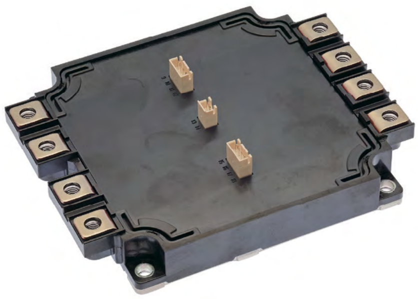
22mΩ / 1200V
SiC MOSFET



25A / 600V
SiC Super-Mini DIPIPM

400A / 1200V
Full-SiC 4-in-1 Module

800A / 1200V
Full-SiC Dual Module



1200A / 1200V
Full-SiC Dual Module

750A / 3300V
Full-SiC Dual Module

Towards a Greener Future: Highly Efficient SiC Power Devices for Wide Application Range

In various applications, SiC devices are used today to achieve highly efficient and compact converters. Applications range all power ratings, from air conditioners, to battery chargers, to industrial drives and even railway propulsion.
This article discusses the demands from different applications, highlights the MITSUBISHI ELECTRIC SiC power devices available in different voltage and power classes and gives insights in latest developments.

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Introduction
The reduction of carbon dioxide and the responsible use of electric energy are main drivers for a more sustainable future society. Silicon Carbide (SiC) and its superior physical properties shall save even more electric energy and make power-electronic converters more compact, which reduces the consumption of valuable materials and resources.

The main difference between SiC semiconductors and classical silicon is the higher band gap. This allows 10-times higher critical field strength in the SiC material. Consequently, for the same blocking-voltage capability, SiC chips can be made thinner. Hence, electrical resistance and power losses are decreased.

Furthermore, due to the higher band gap, SiC MOSFETs or SiC Schottky Barrier Diodes can be produced even for higher blocking voltages (e.g. 3300 V or 6500 V). Due to high switching speed, these unipolar devices have low switching losses and enable high switching frequencies. In many applications, the higher switching frequencies yields power-density increase of other system components, like filters, transformers or motors. Hence, the power-electronic converter becomes more compact and saves material and related costs.

Since the 1990s, Mitsubishi Electric has gained comprehensive experience about the production and application of SiC devices and power modules. SiC power semiconductors have successfully completed the technology hype cycle and Mitsubishi Electric SiC products are widely available. Today, we find SiC products in various applications: from chargers for electric vehicles, to air conditioners, to uninterruptable power supplies, to industrial drives and even railway traction drives. These different applications result different requirements to the SiC device. This article demonstrates the variety of demands and the according SiC solution.

The Core of our SiC Devices: Next Generation of SiC chips
The newest SiC devices feature Mitsubishi Electric's 2nd generation of SiC chips. These chips are manufactured on the new 6-inch SiC wafer line. As shown in Figure 1, the 2nd generation has an enhanced planar MOSFET structure. The special JFET doping profile enables improvement of the specific electric resistance $R_{on,sp}$ while reducing the MOSFET cell width as demonstrated in Figure 2. The excellent electric resistance of this enhanced planar MOSFET technology is highly competitive against other trench gate structures as shown in Figure 3. Moreover, the JFET doping lowers the reverse transfer

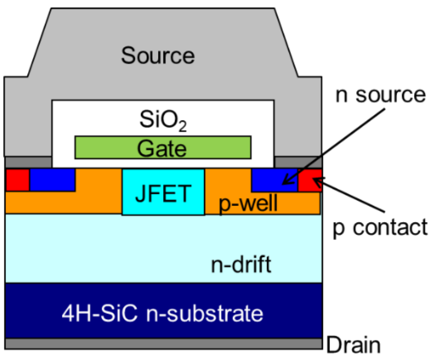


Figure 1: Structure of 2nd Generation SiC MOSFET Chip

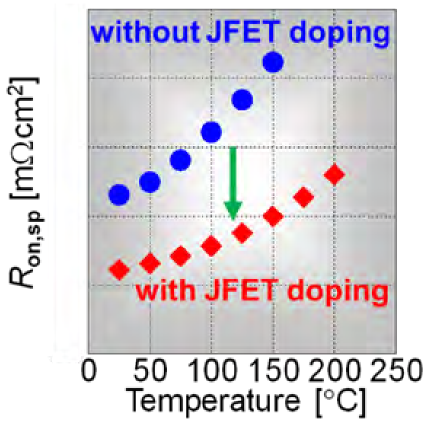


Figure 2: Unique JFET doping improves $R_{on,sp}$

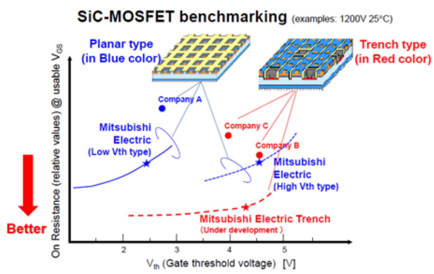


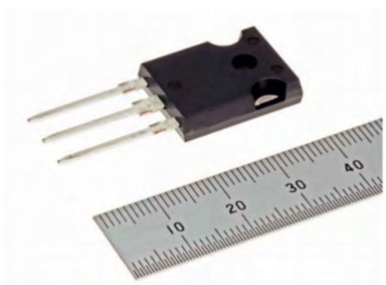
Figure 3: Comparison between different Planar- and Trench-Gate SiC MOSFET technologies

capacitance C_{rss}. This capacitance affects the switching speed of the SiC device. The smaller C_{rss} allows higher switching speeds and improves robustness against parasitic turn-on as explained further below.

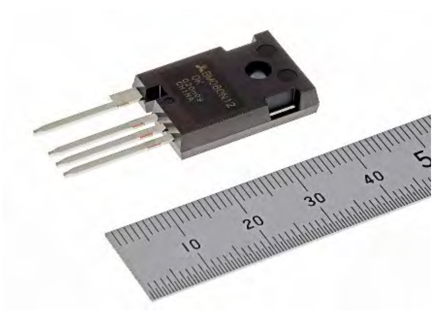
SiC Discrete Devices for Automotive Battery Chargers, Air Conditioners or Heat Pumps

Applications like battery chargers, air conditioners or heat pumps demand high-volume production capacity, a compatible package among different suppliers and current ratings of up to 100 A.

For such applications, our solution is Mitsubishi Electric's N-Series 1200 V 2nd generation SiC discrete power devices in the industry standard TO-247 package [1] [2]. This type of devices is still the preferred choice in many low- to medium-power applications, due to their flexibility: Discrete devices consist of only a single MOSFET switch, making it possible to build any type of converter topology. Due to the simpler package (cf. Figure 4) and high volume production, they can offer a cost effective introduction of the SiC technology. Besides the 3-terminal package, Mitsubishi Electric also offers a 4-terminal version of TO-247. It has further improved switching characteristics and achieves 30% less switching loss [3]. Table 1 shows the line-up of the N-Series SiC MOSFET devices. All are tested according to Mitsubishi high quality standards, fulfilling the requirements of industrial applications. Additionally, all discrete devices are available in a version qualified according to the standard AEQ-Q101 for the use in automotive applications.



(a) N-Series with 3 terminal package (TO-247-3)



(b) N-Series with 4 terminal package (TO-247-4)

Figure 4: N-Series 1200 V SiC-MOSFET

Model	BM080N120S(J)	BM040N120S(J)	BM022N120S(J)
V_{DS}	1200 V		
$R_{DS(on)}$	80 mΩ	40 mΩ	22 mΩ
$I_{D,max@25}$	38 A	68 A	102 A
Package	TO-247-3		
Size	15.9 × 41.0 × 5.0mm		

Table 1: Line-Up of Mitsubishi Electric's N-Series

Due to their low losses, the industrial N-Series SiC MOSFETs are ideally suited for example to improve the efficiency of residential solar inverters and reduce the size of bulky and costly passive components. In fast battery chargers the SiC technology enables more compact and at the same time efficient systems.

In electric vehicles, the AEQ-Q101 qualified SiC MOSFETs can reduce the size and weight of auxiliary components such as on-board battery chargers or DC-DC converters.

Besides those examples, Mitsubishi Electric's discrete SiC devices can be used also in various other applications.

Key Features:

The N-Series SiC MOSFETs use Mitsubishi Electric's 2nd generation of planar SiC technology with JFET doping. This technology offers several advantages as compared to previous generations of SiC technologies.

The high breakdown field strength of SiC material has enabled power MOSFETs in the 1200 V class with a low drift layer resistance (R_{drift}). But another significant part of the specific on resistance is caused by the parasitic JFET between the p-wells of the MOSFET structure. With the introduction of the JFET doping in the 2nd generation SiC technology, the specific on resistance is improved making smaller MOSFET cells possible.

An important factor for the MOSFET switching behavior is the ratio between the input capacitance (C_{iss}) and the reverse transfer capacitance (C_{rss}). The fast switching transients of discrete SiC power MOSFETs can cause a parasitic turn-on of a MOSFET and in worst-case could lead to a catastrophic arm shoot through failure. By reducing C_{rss}, a figure of merit of 1450 mΩ·nC is achieved, which is defined as the product of the on-resistance and the gate-drain charge. As visualized in Figure 5, this improves the robustness against parasitic self-turn-on by around 14 times as compared to conventional devices and therefore enables high switching speeds and reduced switching losses [1].

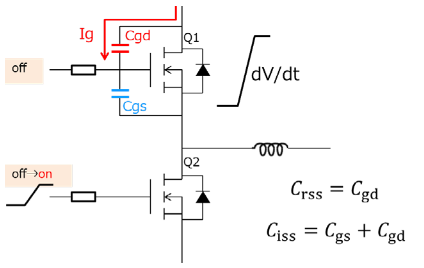


Figure 5: Parasitic turn-on effect – The turn-on of the low side MOSFET Q2 causes a dV/dt at the high side MOSFET Q1. As a result, the gate current I_g flows via the reverse transfer capacitance C_{rss} of Q1 into the gate. If this current causes a sufficient voltage drop at the gate resistor to exceed the gate threshold voltage $V_{gs(th)}$, MOSFET Q1 is turned-on parasitically. The current I_g is proportional to C_{rss} and dV/dt.

Discrete SiC MOSFETs are typically specified and initially compared by the $R_{DS(on)}$ resistance measured at T_j = 25 °C. However, under real application conditions with typically T_j = 100 °C and above, the $R_{DS(on)}$ of power MOSFETs increases. Mitsubishi Electric's N-Series power MOSFETs show comparably low $R_{DS(on)}$ increase of only about 10 % at T_j = 100 °C. This reduces the conduction losses in the application and allows converter designs for higher output power than with comparable devices specified with the same $R_{DS(on)}$.

In addition to the discrete N-Series SiC MOSFETs, Mitsubishi Electric also offers a line-up of matching SiC Schottky-Barrier Diodes (SBD). SBD typically offer lower forward voltage V_F drop than bipolar diodes. However, a trade-off exists between low V_F and high forward surge current capability. To optimize both, Mitsubishi Electric developed the so called Junction Barrier Schottky Diode structure, where in addition to the Schottky contact a pn-junction is integrated in parallel for handling high surge currents as demonstrated in Figure 6 and Figure 7. The line-up consists of 600 V and 1200 V diodes with current ratings of 10 A and 20 A in different discrete package variants (TO-247, TO-220FP-2, TO-263S) [4].

Integrated SiC DIPIPM power module solutions increasing the efficiency of air conditioners

For the lower power inverters, Mitsubishi Electric introduced SiC DIPIPM power devices with blocking voltage capability of 600 V and two different current ratings: 15 A and 25 A. This class of intelligent power modules contains the relevant components such as six switches and gate driver ICs to build compact inverters (cf. Figure 9). The intelligence of these products are the integrated protection functions, such as short-circuit protection, under-voltage lockout or over-temperature protection. As shown in Figure 8, the modules are manufactured using transfer molded technology, which allows to secure high productivity and robustness against influence of aggressive environments. Especially applications running almost 24 hours per day, such as air conditioners or pumps, can benefit from the increase of efficiency by applying SiC. Figure 10 shows a comparison to conventional silicon device and how 70% of converter power loss can be saved under regarded operating conditions.

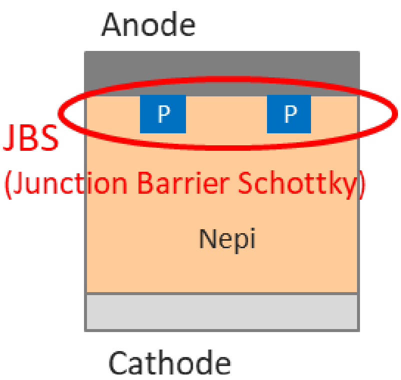


Figure 6: Structure of Mitsubishi Electric's Junction Barrier Schottky Diode

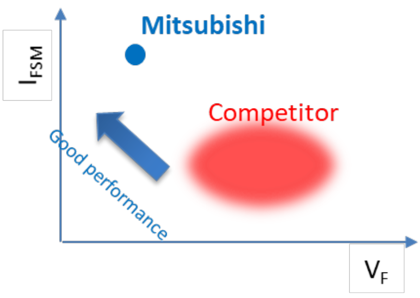


Figure 7: Diode Trade-off comparison (V_F vs. I_{FSM})

SiC Power Modules for Uninterruptable Power Supplies, Fast Chargers and Efficient Feed-In of Renewables

Applications like uninterruptable power supplies, fast chargers or the feed-in of renewable energy sources usually require much higher current ratings than discussed before. Therefore, Mitsubishi Electric has developed SiC power modules, that also feature the 2nd generation chip technology [5]. These modules offer the benefits of SiC technology to industrial applications requiring high currents, beyond the capability of discrete devices. Available are voltage classes of 1200 V and 1700 V and a wide line-up of current ratings

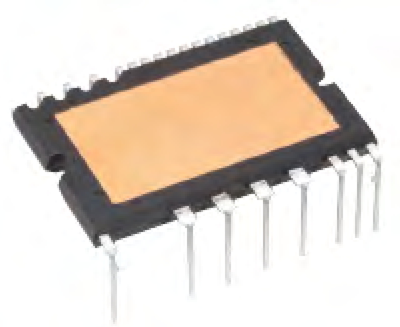


Figure 8: Super Mini Full SiC DIPIPM

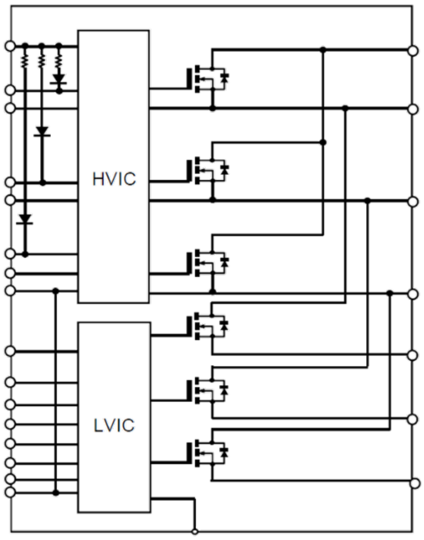


Figure 9: SiC DIPIPM internal block diagram

up to 1200 A. As shown in Figure 11, the 2nd generation power modules are package-compatible to the 1st generation, allowing our customers an easier development based on their existing designs.

Key Features:

With 122 x 79.6 mm², the footprint of the modules is the same as Mitsubishi Electric's NX-series power modules. However, to reduce the parasitic loop inductance of the package significantly, the terminals were re-arranged, allowing a better utilization of the benefits of the SiC technology. Additionally, the design of the baseplate and the

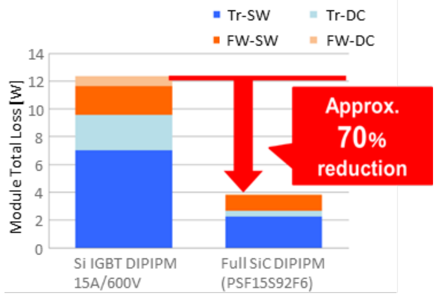


Figure 10: SiC DIPIPM benchmark (V_{cc}=300V, V_D=18V(SiC) /15V(Si), f_c=15kHz, PF=0.95, M=0.8, I_o=1.5Arms, T_j=125°)

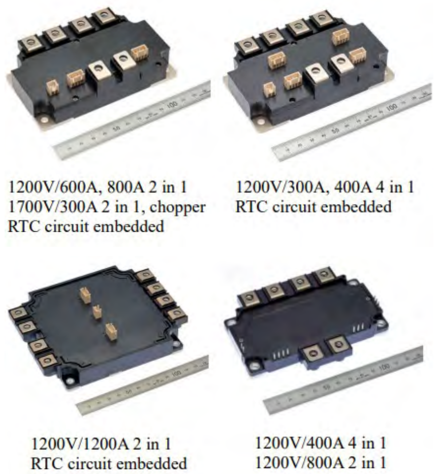


Figure 11: Industrial SiC power modules' line up

Model	Rated Voltage	Rated Current	Circuit Structure	RTC circuit	Size
FMF400BX-24B	1200 V	400 A	4 in 1	No	121.7 x 92.3
FMF800DX-24B		800 A	2 in 1	No	
FMF300BXZ-24B		300 A	4 in 1	Yes	122 x 79.6
FMF400BXZ-24B		400 A		Yes	
FMF600DXZ-24B		600 A	2 in 1	Yes	
FMF800DXZ-24B		800 A		Yes	
FMF1200DXZ-24B		1200 A		Yes	122 x 152
FMF300DXZ-34B	1700 V	300 A	2 in 1	Yes	122 x 79.6
FMF300E3XZ-34B		300 A	Chopper	Yes	

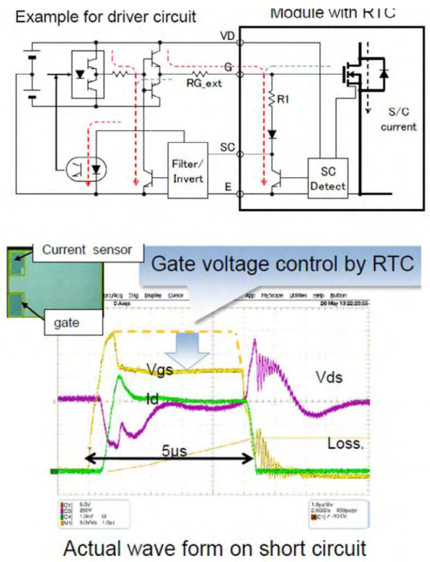


Figure 12: Efficient short circuit detection by RTC function

Figure 13: 3.3 kV Full-SiC power module in LV100 package with 6 kV insulation voltage

Circuit	Circuit Diagram	Package Type	3300 V
2-in-1	or	LV100 V_{iso} = 6 kV	750 A (Full SiC)
			375 A (Full SiC)
			600 A (Hybrid SiC)
			600 A (Silicon)
			450 A (Silicon)

Figure 14: Lineup of 3.3 kV SiC and Si power modules in LV100 package

placement of the SiC-MOSFET and SiC-SBD chips was optimized to improve the heat spreading inside the package

The 2nd generation with the previously described JFET doping technology offers lowest overall losses. Compared to the 1st generation, both, the conduction and the switching losses were further reduced [6].

Mitsubishi Electric's Real-Time Control (RTC) function eases the design of short circuit protection. The design of short-circuit protection is a challenge when changing from IGBTs to SiC MOSFETs, as methods such as desaturation detection cannot be applied in the same way. To overcome these constraints, the RTC function detects a short circuit using current sensors integrated into the MOSFETs. When a short circuit is detected, the gate voltage is automatically reduced to limit the current and increase the short-circuit withstand time. This gives enough time to the driver circuit to react on the short circuit signal from the RTC function.

High-Voltage SiC Modules for Railway and Grid Applications

In this bullet train operation, SiC power modules allow a more efficient and more compact traction system. As an example, SiC power modules have enabled 20% weight savings in the Shinkansen drive train, leading to a more flexible railroad car designed. The volume of the traction inverter itself was reduced by 50% which was enabled by the lower losses of SiC devices leading to a simpler cooling system [7].

Besides traction inverters, auxiliary converters, railway battery chargers and dc-dc converters especially benefit from the switching frequency increase enabled by SiC power modules. The increasing switching frequency typically allows the size reduction of passive components (like transformers, inductors or capacitors). Moreover, the higher switching frequency might allow the use of different soft-magnetic core materials. It gives the potential for efficiency increase and cost reduction [8] [9].

With increasing voltage and power ratings, railway and grid applications demand for best performance and highest reliability. Mitsubishi Electric offers commercial high-power SiC modules for voltages up to 3.3 kV for high-reliability application. Already in 2015, Mitsubishi Electric has applied 3.3 kV Full-SiC semiconductor modules in high-speed bullet trains [10]. Hence, the robustness of these devices has been demonstrated under real conditions by several years of field operation.

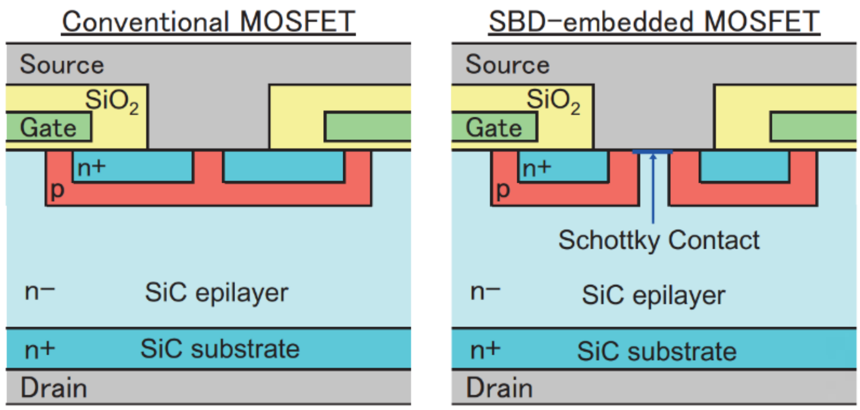


Figure 16: Structure of a conventional MOSFET and one with embedded SBD [12]

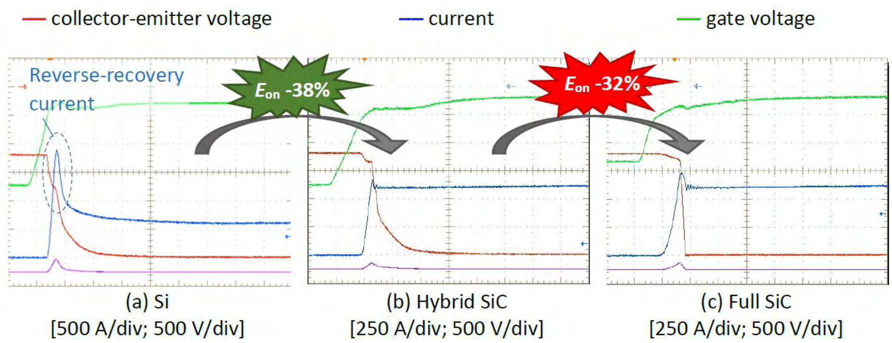


Figure 15: Comparison of turn-on waveforms between silicon (Si), hybrid SiC and Full-SiC (V_{cc} = 1800 V, I_C = 600A, T_j = 150 °C, L_s = 65 nH)

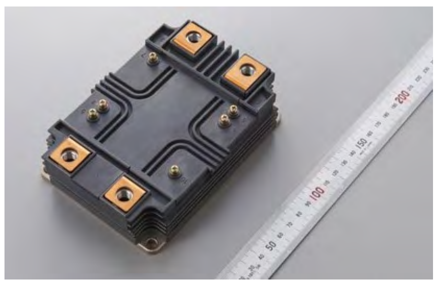


Figure 17: 6.5 kV Full-SiC power module in HV100 package with 10.2 kV insulation voltage

Mitsubishi Electric offers its 3.3 kV SiC power modules in the LV100 package as depicted in Figure 13. As shown in Figure 14, two different Full-SiC products are available with current ratings of 375 A and 750 A.

Additionally to Full-SiC Power Modules, Mitsubishi Electric also offers Hybrid-SiC modules. In the same LV100 package, a 600 A Hybrid-SiC module for 3.3 kV is available. This device combines an silicon High-Voltage IGBT of the latest X-Series generation with a SiC diode. Compared to the Si diode, the SiC diode is reverse-recovery free. Hence, the switching losses in the diode are much smaller. Moreover, the losses in the IGBT are reduced as well due to the absence of the reverse recovery current. As shown in Figure 15, IGBT turn-on losses are 38% lower. This makes the hybrid SiC power module the ideal candidate for relatively high switching frequencies (e.g. around 2 kHz). If higher switching frequency and lower losses are required, then Full-SiC power modules are the perfect choice.

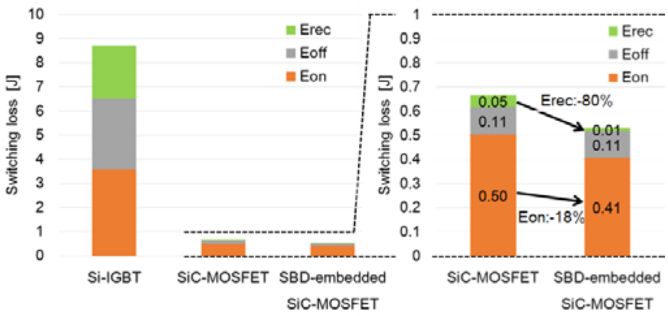


Figure 18: Comparison of switching loss between Si-IGBT at 150°C, SiC-MOSFET and SBD-embedded SiC-MOSFET at 175°C [13]

Beyond existing SiC products, Mitsubishi Electric is further developing SiC technology to become even more competitive in future. One research topic is related to the integration of the SiC SBD diode in the MOSFET structure. Generally, the SBD diode is required to avoid bipolar current flow through the body diode of the MOSFET. Hence, degradation effects like stacking faults are suppressed. To achieve this in today's SiC power modules, dedicated SBD diode chips are connected in parallel to the MOSFET chips. In future, the SBD structure is integrated into the MOSFET chip as shown in Figure 16. Additional benefits, besides avoidance of stacking fault, are lower switching losses and the omission of dedicated diode chips [11] [12].

The technology of embedding the SBD is also utilized in the 6.5 kV Full-SiC prototype [13]. This prototype utilizes the HV100 package as show in Figure 17 and is rated for 400 A. As shown in Figure 18, the switching losses of this device are less than 1/10 compared to a Si IGBT. This gives 6.5 kV SiC devices enormous potential for high-switching frequency applications.

Conclusion

This article has shown that today many applications benefit from the advantages of SiC devices, which result in more efficient and more compact power converters. All these different applications make different demands on the SiC devices. It has been shown that Mitsubishi Electric offers particular SiC products for nearly every application.

Acknowledgement

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