Recently, Mitsubishi Electric began the rollout of second generation silicon carbide (SiC) technology in 1200 V and 1700 V class power modules. These new modules, shown in Figure 1, provide greater efficiency and higher power density than previous SiC generations as well as the latest silicon (Si) technology, which enables new capabilities in energy, transportation, and medical applications.

Figure 2 illustrates the dramatic reduction in losses and improvements in efficiency achieved by adopting advanced processing technologies and optimized device structures to power semiconductor devices. This figure also shows the diminishing returns as the fundamental physical properties of Si began to limit the magnitude of improvement that was achievable. For example in the first ten years of IGBT development from the first generation to the fifth Generation, typical inverter losses were cut in half. In the latest ten years from 2010 until today, IGBT losses were only reduced by about 20%. This is one of the main motivations...
for development of SiC technology. This figure shows the
dramatic reduction in losses achieved using SiC. This
improvement is far beyond anything that could be achieved
with a Si IGBT.

These SiC power modules are beginning to replace their
Si counterparts in a variety of application spaces where the
system cost and performance benefits outweigh the higher
initial module cost. Some examples of these applications are:

- Photovoltaic inverters to achieve higher system efficiency and reduced magnetics size/cost
- Railway propulsion inverters to achieve greater regenerative braking capability and therefore lower lifetime operating costs due to reduced mechanical braking
- Traction auxiliary inverters to reduce system magnetics weight and cost
- X-ray and MRI amplifiers to increase system performance thanks to higher frequency operation and smaller cooling systems
- Elevator drives to lower lifetime system operating costs due to increased efficiency
- Automotive propulsion applications to reduce inverter size/weight and increase battery range.

In the spirit of understanding the magnitude of the
improvements offered by this new SiC generation, this
article provides a practical performance comparison of the
latest Si and SiC 300-A/1700-V dual power modules in Table 1.
This detailed comparison covers the chip design technology, experimental results of static and dynamic characteristics, short circuit protection characteristics, and temperature/power loss loss simulations of 3-phase inverters.

![FIG 1 A (a) Si module (top) and a (b) SiC module (bottom).](image)

![FIG 2 Relative inverter losses (typical) by chip technology.](image)

<table>
<thead>
<tr>
<th>Chip Technology</th>
<th>Rated Voltage</th>
<th>Rated Current</th>
<th>Connection Topology</th>
<th>P-N Inductance</th>
<th>Dimensions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mitsubishi Electric 7th Generation CSTBT Si IGBT and RFC Diode</td>
<td>1700 V</td>
<td>300 A</td>
<td>2 in 1</td>
<td>15 nH</td>
<td>W: 62 mm × D: 152 mm × H: 17 mm</td>
</tr>
<tr>
<td>Mitsubishi Electric 2nd Generation SiC MOSFET and Schottky Barrier Diode (SBD)</td>
<td></td>
<td></td>
<td></td>
<td>10 nH</td>
<td>W: 80 mm × D: 122 mm × H: 30 mm</td>
</tr>
</tbody>
</table>
The results of these measurements and simulations are applicable to practicing power systems designers in a variety of fields, especially those investigating SiC implementation.

**Seventh Generation Si Technology**
The Figure 1 Si module is a 300-A/1700-V dual IGBT power module containing seventh generation silicon CSTBT IGBT technology. Per Reference 1, the seventh generation chipset achieves a reduction in turn-off switching losses of 20% over previous IGBT technologies. This reduction in losses is primarily due to the optimization of the CSTBT structure and reduced chip thickness. Typically, short circuit capability is a tradeoff with chip thickness. However, per Reference 2, the short circuit capability was maintained by reducing maximum short circuit current without significantly influencing the $V_{CBO}$, $V_{CE}$, and $E_{oF}$. Thus, the seventh generation IGBT chip achieves an improved tradeoff relationship between $V_{CBO}$ and $E_{oF}$ with sufficient short circuit capability.

**Second Generation SiC Technology**
The Figure 1 SiC module is a 300-A/1700-V dual MOSFET module containing the Figure 3 SiC MOSFETs fabricated using a 6-inch wafer process. Per Reference 3, the $V_{DS(on)}$ and total switching losses of these SiC MOSFETs are among the lowest compared to similarly rated modules with publicly available data. The MOSFET capacitances were optimized for high frequency use. An n-type JFET doping structure was used to reduce on-resistance, which works especially well for high blocking voltage MOSFETs (>1200 V).

For high voltage SiC MOSFETs, body diode degradation is a challenge for long-term module reliability. Continuous conduction of current in the SiC body diode has been shown to cause degradation of $R_{ds(on)}$ over time due to growth of defects in the SiC crystal. Mitigation techniques and raw material improvements may ultimately allow reliable use of the body diode and elimination of the SBD once they have been fully vetted. An existing solution to this problem is incorporating separate SiC Schottky Barrier diodes (SBD) to prevent use of the body diode. The module tested herein includes these SBD to ensure long-term reliability.

**Experimental Results**

**Static Characteristics:** Each module’s static characteristics ($V_{CE}$, $V_{DS(on)}$, $V_{DS(off)}$, $V_{SD(on)}$, $V_{SD(off)}$) were measured on a Keysight B1506A power curve tracer up to 550 A at 125 °C as shown in Figure 4 and Figure 5. A gate bias of 15 V was used for $V_{CE}$, $V_{DS(on)}$ and –15 V for $V_{DS(off)}$. When measuring freewheeling diode characteristics, negative gate bias is used to ensure the IGBT/MOSFET remains off and only diode characteristics are measured.

Figure 6 shows the results of the IGBT/MOSFET static testing. The SiC MOSFET module achieves superior forward characteristics for $V_{CE}$ up to 265 A after which the Si IGBT module is advantageous. At rated current of 300 A, $V_{CE}$ for the Si module is 2.41 V while the SiC module has a $V_{DS(on)}$ of 2.59 V. The SiC $V_{DS(on)}$ is among the lowest values ever reported for similar modules.
Figure 7 shows the results of the diode static testing. The SiC SBD has superior forward voltage characteristics up to the max rated current of 550 A. At 300 A, $V_{EC}$ of the Si diode was measured at 2.98 V while the SiC SBD $V_{SD(off)}$ was measured at 2.75 V. When including the reverse capability of the SiC MOSFET by gating on with +15 V, the $V_{BD(on)}$ measured significantly lower at 1.56 V.

Dynamic Characteristics: Each module’s switching performance was characterized at 1000 Vdc and 125 °C using

![Static characteristic measurement circuit.](image1)

![Dynamic characteristic measurement circuit.](image2)

**FIG 5** Static characteristic measurement circuit.

**FIG 6** $V_{EC}/V_{GS}$ forward voltage characteristics conditions: 125 °C, $V_{sd} = 15$ V.

**FIG 7** $V_{EC}/V_{SD(off)}/V_{SD(on)}$ Diode/MOSFET reverse characteristics conditions: 125 °C, $V_{sd} = -15$ V for $V_{EC}$, $V_{SD(off)}$, $V_{sd} = 15$ V for $V_{SD(on)}$.

**FIG 8** Double pulse test setup.
the double pulse test setup shown physically in Figure 8 and schematically Figure 9. Device current is measured using a low insertion inductance current transformer per Reference 4. The Isahaya Electronics VLA586-01R gate driver was used for both the Si IGBT and SiC MOSFET module. This gate driver provides a gate bias of +15 V–12 V. Gate resistance values of $R_{G(on)}(\text{Si}) = 0 \Omega$, $R_{G(on)}(\text{SiC}) = 3.4 \Omega$, and $R_{G(off)}(\text{SiC}) = 10 \Omega$ were used for the initial switching loss comparison.

Figure 10 shows the results of the turn-on ($E_{on}$), turn-off ($E_{off}$), and reverse recovery ($E_{rr}$) switching losses from 0-550 A. At 300 A, the total switching loss $[E_{sw} = E_{on} + E_{off} + E_{rr}]$ of the Si module is 170.8 mJ. The SiC module measured total switching loss of $E_{sw} = 46.2$ mJ is 73% lower than the comparable Si module. By taking advantage of the SiC module's 73% reduction in $E_{sw}$, larger power electronics systems can make significant increases in operating frequency, performance, and/or overall efficiency.

Figure 11 shows the turn-on and turn-off switching waveforms of the Si IGBT and SiC MOSFET modules. Due to the SiC MOSFET characteristics, switching speed is increased and loss is greatly reduced compared to the Si IGBT module. At the conditions shown in Figure 11(b), the maximum $dv/dt$ at turn-off is $7.9 \text{kV/s}$ for the Si module while the SiC module has a maximum $dv/dt$ of $15.4 \text{kV/s}$. The peak surge voltage of the Si module reached 1174 V while the SiC module had a peak surge voltage of 1258 V. To take advantage of the fast switching speed of the SiC module, proper gate drive, a low inductance decoupling capacitor on the module terminals, and a low inductance DC link is required. With the proper external hardware, even faster switching speeds are possible with the SiC module.

$R_G$ Controllability: Double pulse tests were completed with several gate resistor values ranging from datasheet minimum to maximum values for both the Si and...
SiC modules. The maximum turn-off dv/dt and turn-off switching energy were recorded at rated current of 300 A. As shown in Figure 12, the SiC module has a larger range of controllability with a possibility of 90% lower E_{off}. When the Si and SiC module turn-off dv/dt are both adjusted to 8 kV/μs, the SiC module is still capable of 45% lower E_{off}.

The maximum reverse recovery dv/dt and turn-on switching energy were also recorded at various gate resistance values. As shown in Figure 13, the SiC module has a larger range of controllability with a possibility of 90% lower E_{off}.

When the Si and SiC module reverse recovery dv/dt are both adjusted to 8 kV/μs, the SiC module is still capable of 45% lower E_{off}. Additionally, the SiC module has approximately 96% lower Err as shown in Figure 10 which further contributes to reduced power losses in the module.

During development, the designer must consider the EMI noise generated from dv/dt, di/dt, and ringing of the voltage/current waveforms at switching. EMI/ringing can be reduced by switching slower (increasing Rg) but that will cause increased switching losses. Therefore, the designer must determine the acceptable trade-off between switching losses and EMI for their specific application.

**Simulations:** Using the data measured above, loss/temperature simulations were performed to characterize each module’s performance. The simulations below are for a 3-phase inverter using conventional sinusoidal modulation with a modulation ratio of 1. A dc bus voltage of 1000 V was selected which is typical for 1700 V rated power modules. A fixed heatsink temperature of 80 °C was selected which is typical for air-cooled heatsink applications. The output power factor was selected to be 0.9. Additionally, gate resistance values of R_{G(on)}(Si) = 3.4 Ω, R_{G(off)}(SiC) = 10 Ω were selected after considering the trade-offs between switching losses, dv/dt, and surge voltage.

The Figure 14 simulation results show the overall module output current capability at carrier frequencies (f_c) up to 50 kHz. The plot represents the maximum output current capability allowed versus f_c until T_j reaches 150 °C maximum. At all carrier frequencies, the SiC module provides greater output current capability. At 10 kHz, the Si module can support up to 175 A_{rms} while the SiC module is capable of 275 A_{rms}, a 57% increase. At 160 A_{rms} the Si module is capable of a carrier frequency up to 11 kHz while the SiC module is capable of 50 kHz, 4.5 times higher f_c.

Figure 15 shows the total power module losses versus carrier frequency at a set sinusoidal output current of 200 A_{rms}. The other simulation conditions are the same as...
listed previously. At typical operating conditions of 5 kHz and 200 A<sub>rms</sub>, the Si module has a total power loss of 930 W while the SiC module has only 440 W, a 53% reduction. Comparing at a higher f<sub>c</sub> of 8 kHz, the Si module has total power losses of 1260 W while the SiC module has only 500 W loss, a 60% reduction. At 200 Arms, the SiC module is able to operate at up to 31 kHz before reaching the same losses as the Si module operating at 5 kHz.

As shown in the Figure 14 and Figure 15 simulation results, the new SiC modules provide significantly greater efficiency and higher possible carrier frequencies than the latest Si technology. These significant performance improvements allow reduction of magnetics/heatsinking size and weight and enable new performance capabilities for the end application.

**Short Circuit Protection:** Many applications require the module to survive a low impedance short circuit event. The Si module tested herein is capable of surviving a short circuit event of 8 μs, which is more than adequate for implementing robust short circuit protection. On the other hand, many SiC modules on the market today do not specify any guarantee for short circuit capability. Additionally, an inverse tradeoff between short circuit capability and on-resistance exists. As a result, it can be extremely difficult to reliably protect SiC MOSFET devices from low impedance short circuit events.

In order to provide reliable short circuit protection, the SiC module tested herein contains a dedicated current limiting circuit called Real Time Control (RTC). As shown in Figure 16 the RTC circuit limits the short circuit current by reducing the gate voltage when high current is detected. The RTC is made possible by fabricating the MOSFET with an on-chip current mirror. Proper use of the RTC circuit enables the SiC module to have robust short circuit withstanding capability similar to that of the conventional Si module without having to trade off on-resistance performance or develop expensive/complex external circuits.

**Lineup Plan:** Table 2 shows the initial second generation SiC power module lineup plan for 1200 V and 1700 V modules. The lineup includes dual modules and full
bridge modules both with and without the incorporated RTC circuit. The 1200 V modules in this line-up utilize the same Mitsubishi second generation SiC MOSFET with JFET doping technology. Therefore the static and dynamic characteristics will tend follow a performance profile similar to that which has been presented here for the 1700 V devices.

**Conclusions**

This article introduces practicing engineers to a new commercially available SiC MOSFET module that achieves both static and dynamic performance that is among the best of any similar modules reported before. Additionally, the SiC module presented herein provides a simple way to achieve short circuit capability similar to that of industry standard Si modules. Per Table 3, these new SiC modules provide greater efficiency and higher power density than the latest silicon technology, which enables new capabilities in energy, transportation, and medical applications.

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**References**


