Hybrid SiC Power Module with Low Power Loss

Mitsubishi Electric has developed a 1.7 kV hybrid SiC power module consisting of 6th generation Si-IGBT and SiC Schottky Barrier Diode (SBD). Adopting SiC-SBD enables a significant power loss reduction during the diode turn-off and IGBT turn-on. And adopting of 6th generation IGBT enables the reduction of the IGBT turn-off loss. By using the newly developed chip set, high temperature enduring gel and suitable chip layout, the hybrid SiC module can be operated at 150°C junction temperature. 

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Recently, Silicon Carbide (SiC) power devices are investigated for the improvement of the conventional Si devices. We have already reported about the electrical characteristics of prototype of the hybrid SiC power module [1]. We have now developed a 1.7 kV hybrid SiC power module with large current capacity and low power loss consisting of newly developed Si-IGBT and SiC-SBD for free-wheeling-diode.

**SiC-SBD and Si-IGBT**

SiC has a breakdown electric field strength about ten times higher than Si. So the thickness of SiC power chip can be thinner than Si power chip. This enables a significant power loss reduction of the SiC power device in particular for high voltage semiconductors. SiC allows using Schottky Barrier Diodes for high voltage applications, which is not possible with Silicon-SBD due to their high on-state voltage.

SBD is a unipolar device and there is no reverse recovery action during diode turn-off. Since there are no accumulation carriers in a SBD, the conventional reverse recovery loss of the diode is lowered to a negligible level compared with a conventional Si-diode. Moreover, IGBT turn-on switching loss is also reduced because the diode recovery charge is not superimposed to the turn-on current of the IGBT. Figure 1 shows the photo of 1.7 kV SiC-SBD chip (size 6.58 mm x 6.58 mm). The field limiting ring termination structure is adopted which is designed to get the uniform electric field, and more than 1.9 kV blocking voltage is realized at room temperature.

A new (6th) generation 1.7 kV CSTBT™ has been developed by improving the IGBT-cell design and the vertical structure. And the trade-off between the on-state voltage and turn-off switching loss is also improved compared to the conventional N-series Si module.

Figure 5 shows the internal module design. One module consists of four substrates as shown in Figure 6. Each 1.2
kA arm consists of two substrates. One substrate consists of four Si-IGBTs and eight SiC-SBDs. The quantity and size of Si-IGBT is the same as in the conventional Si module, but the size of SiC-SBD is smaller and the quantity is larger than that of Si module. This depends on low yield of large size SiC chip and improvement of the SiC wafer quality is desired. Many SiC-SBD chips are connected in parallel.

**Static and dynamic characteristics**

Figure 7 shows the Si-IGBT on-state voltage curves of the hybrid SiC module measured at Tj=25°C and 150°C. The on-state voltage curve of the SiC-SBD is shown in Figure 8. At Tj=150°C the on-state voltage drop at nominal 1.2 kA current of IGBT is Vces=2.30V, and that one of SiC-SBD is Vce=2.30V. Both Si-IGBT and SiC-SBD have a positive temperature coefficient. This is advantageous for the large current rating module consisting of many chips in parallel.

Figure 9 shows the SiC-SBD turn-off switching waveform measured at nominal condition (I=1.2 kA, Vr=850 V % in spite of higher operation temperature.

Figure 10 shows the Si-IGBT turn-on switching waveform at nominal current (1.2 kA) and Tj=150°C. The free-wheeling SiC-SBD features no reverse recovery charge so the Si-IGBT turn-on loss is also reduced. The IGBT turn-on loss of the same rating conventional Si N-series at nominal current is 0.40 J/pulse at Tj=125°C. The IGBT turn-on loss of the developed hybrid SiC module at nominal current is 0.18 J/pulse at Tj=150°C. Compared to the conventional Si module
conventional Si-module (N-series) the 
VCEsat is about 0.3 V lower while the 
turn-off loss is nearly equal or less. 
Moreover, the operation temperature is 
higher.

Table 1 shows the comparison of 
measured characteristics of the hybrid 
SiC module and the same rating 
conventional Si N-series module. 
Despite the higher operation 
temperature of Tj=150°C of hybrid SiC 
module compared to Tj=125°C of Si- 
module a significant reduction of power 
loss is achieved.

Switching SOA capability
The hybrid SiC module has wide turn-off 
capability. Figure 12 shows the IGBT turn- 
off waveform at large current condition at 
Tj=150°C and DC-link voltage of 1.2 kV. In 
this test, a current of 4.1 kA, which is 
more than three times the nominal 
current, is turned off safely.

Figure 13 shows the short circuit 
capability at Tj=150°C and Vcc=1.2 kV. 
Although the standard gate voltage is 15 
V, the hybrid SiC module has the short 
circuit capability at Vg=18 V.

Conclusion
Adopting SiC-SBD enables a significant 
power loss reduction during the diode 
turn-off and IGBT turn-on. And adopting 
of 6th generation IGBT also enables the 
reduction of the IGBT turn-off loss. By 
using this newly developed chip set, 
high temperature endure gel, and 
suitable chip layout, the newly 
developed hybrid SiC module can be 
operated at 150°C though the maximum 
operation temperature of conventional 
area such as the large current turn-off 
and the short circuit capability. The 
advantage of SiC in a power module 
has been confirmed.

Literature
1. Y.Nakayama, T.Kobayashi, 
R.Nakagawa, K.Hatanaka, 
S.Hasegawa: Railway motor operation 
estimation by inverter with SiC-SBD, 
The 2010 Annual Meeting I.E.E. Japan, 
4-139

<table>
<thead>
<tr>
<th>Item</th>
<th>Si N-series Module</th>
<th>Hybrid SiC Module</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>Tj=125°C</td>
<td>Tj=150°C</td>
</tr>
<tr>
<td>IGBT on-state voltage</td>
<td>2.60V</td>
<td>2.30V</td>
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<tr>
<td>IGBT turn-on loss</td>
<td>0.40J/P</td>
<td>0.18J/P</td>
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<tr>
<td>IGBT turn-off loss</td>
<td>0.37J/P</td>
<td>0.34J/P</td>
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<tr>
<td>Diode on-state voltage</td>
<td>2.30V</td>
<td>2.30V</td>
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<tr>
<td>Diode turn-off loss</td>
<td>0.22J/P</td>
<td>0.01J/P</td>
</tr>
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</table>

Table 1: Comparison of power loss between previous N-Series and Schottky-Barrier Diode power module
Railway Inverter with Hybrid SiC Power Module

A newly by Mitsubishi Electric developed railway inverter contains the latest version of large capacity SiC power module consisting of Si-IGBT and SiC-SBD. However, according to the breakdown for energy consumption of the conventional systems for one of the train lines as an example, the railway inverter power consumption is low percentage-wise in energy consumption of the entire railway inverter systems. This means that the potential of the SiC power device is not utilized enough by replacing Si with SiC in the conventional design of railway inverter systems. Motor and Pneumatic Brake show a large ratio in the power consumption which can be possibly reduced by using SiC power device.

The inverter current and the modulation frequency are restricted by power device loss. Using SiC power devices featuring low-loss, the inverter current and the modulation frequency can be increased. To increase the regenerative brake in the high-speed area, traction motor design requires lower impedance. “Voltage by speed (V/F)” of the SiC inverter system is designed to be lower than that of the conventional system in order to preserve the low impedance motor size. Therefore, the motor current of the SiC inverter system is larger than that of the conventional inverter system so that the required torque is maintained. Moreover, the modulation frequency of the SiC inverter system is designed to be higher than the conventional inverter to reduce harmonic current losses in the traction motors.

As the power loss in SiC power modules is much lower than in Si power modules, the cooling effort is also much lower. The footprint of the SiC power module in the railway inverter box (see Figure) is 26 % smaller than that of the Si power module used in the conventional railway inverter box. As a result of applying the SiC power module and other construction improvements, the volume of the railway inverter box is reduced by 42 %, and the mass is reduced by 37 %.

According to the results obtained from the route performance calculation on one of the train lines as an example, application of high frequency asynchronous modulation to a low-impedance traction motor results in expansion of regenerative brake region, which provides a 30 % of energy saving. Based on this scenario, the stable operation was confirmed by the traction system verification test.

Applying a SiC power module the volume of a railway inverter box is reduced by 42 % and the mass by 37 % compared to a conventional design with Silicon power modules

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- D2Pak without middle pin for higher creepage

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- Input rectification
- High voltage applications

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