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. **Shigeru Hasegawa et al, Mitsubishi Electric Corporation, Japan, and Eugen Stumpf, Mitsubishi Electric Europe B.V., Ratingen, Germany**

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

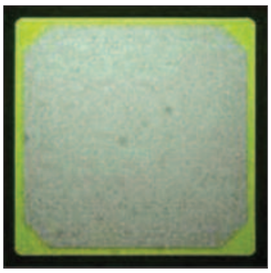


Figure 1: SiC Schottky-Barrier diode chip

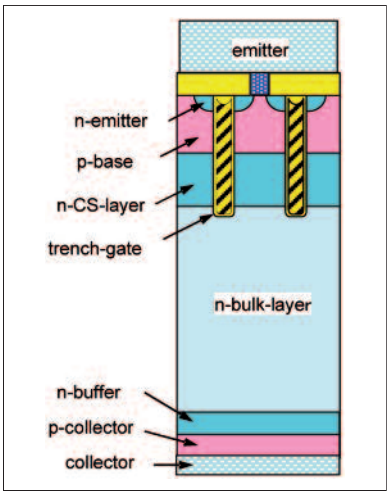


Figure 2: Sixth generation IGBT cell structure

Figure 3: 1.7 kV hybrid power module outline

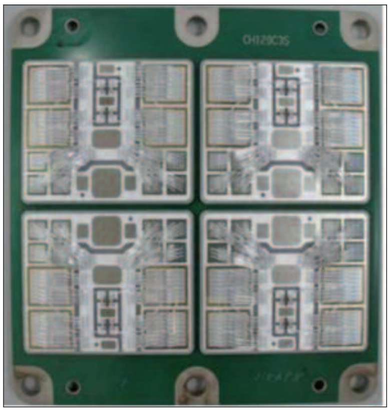
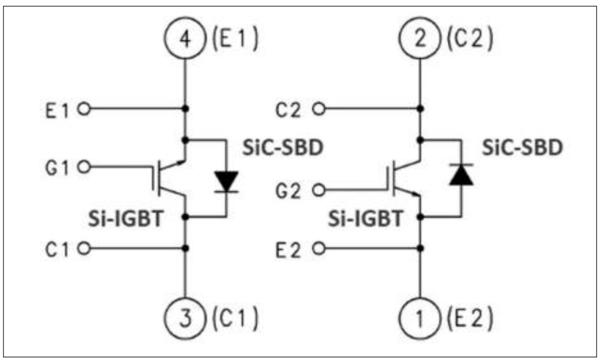


Figure 5: Internal power module design7



RIGHT Figure 4: 1.7 kV hybrid power module circuit diagram

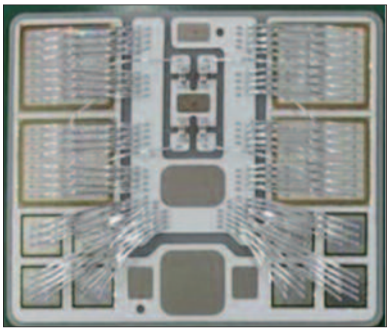


Figure 6: Substrates for the 1.7 kV hybrid power module

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 T_j=25°C and 150°C. The on-state voltage curve of the SiC-SBD is shown in Figure 8. At T_j=150°C the on-state voltage drop at nominal 1.2 kA current of IGBT is V_{CEsat}=2.30V, and that one of SiC-SBD is V_{ec}=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_F=1.2 kA, Vr=850 V and T_j=150°C). The conventional Si diode is a bipolar device, and there is a reverse recovery charge during the diode turn-off. The SiC-SBD is unipolar device and there is no reverse recovery charge and there is only ringing due to charging the junction capacitance. The Si diode turn-off loss (reverse recovery loss) of the same rating conventional Si N-series at nominal current is 0.22 J/pulse at T_j=125°C, the diode turn-off loss of the developed hybrid SiC module at nominal current is 0.01 J/pulse at T_j=150°C. Compared to the conventional Si module the diode turn-off loss is reduced by 95 % in spite of higher operation temperature.

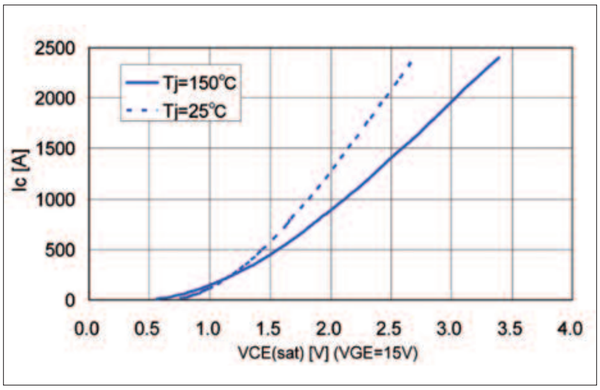


Figure 7: IGBT on-state voltage curve

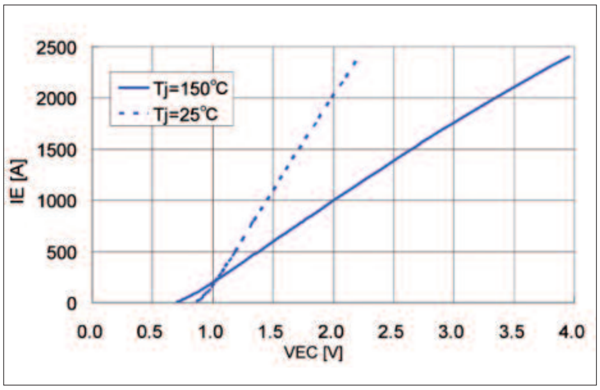


Figure 8: SiC-SBD on-state voltage curve

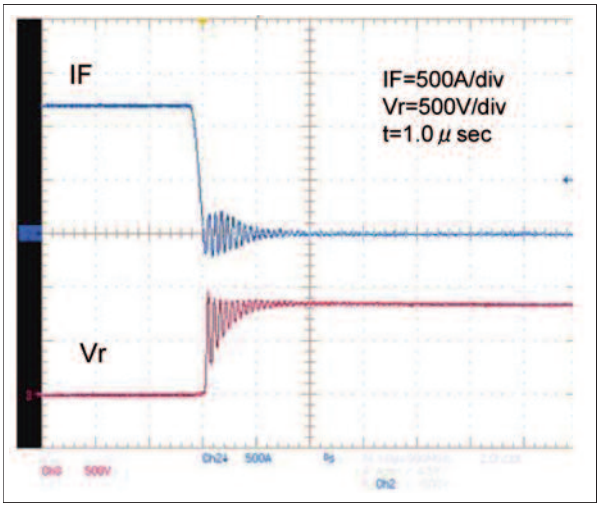


Figure 9: SiC-SBD turn-off

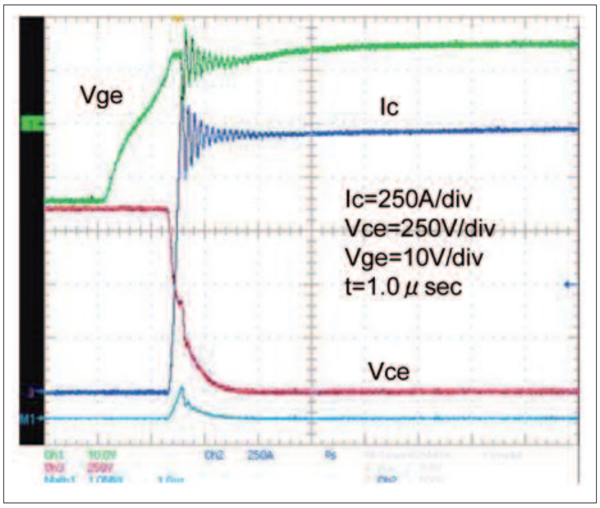


Figure 10: IGBT turn-on

Figure 10 shows the Si-IGBT turn-on switching waveform at nominal current (1.2 kA) and T_j=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 T_j=125°C. The IGBT turn-on loss of the developed hybrid SiC module at nominal current is 0.18 J/pulse at T_j=150°C. Compared to the conventional Si module the IGBT turn-on loss of the hybrid SiC module is reduced by 55% in spite of higher operation temperature.

Figure 11 shows the turn-off switching waveform of the 6th generation Si-IGBT at nominal current (1.2 kA) and T_j=150°C. The on-state voltage V_{CEsat} is 2.30 V and turn-off loss is 0.34 J/pulse at T_j=150°C. In the case of the conventional Si module, V_{CEsat} is 2.60V and turn-off loss is 0.37 J/pulse at T_j=125°C. Generally on-state voltage and IGBT turn-off loss have a trade-off relationship. When comparing the IGBT-performance of newly developed hybrid SiC-module with

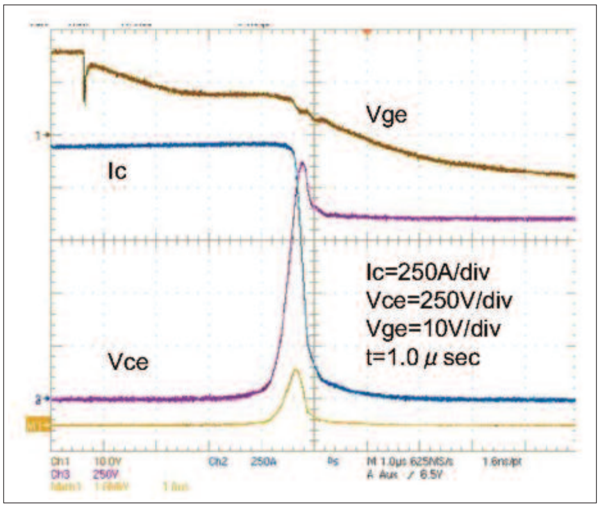


Figure 11: **IGBT turn-off**

N-series Si modules is 125°C. Compared to the same rating conventional Si N-series module the diode turn-off loss of the newly developed hybrid SiC power module is reduced by 95%, and the IGBT turn-on loss is reduced by 55% respectively in spite of higher operation temperature. When comparing to Si module the IGBT on-state voltage of the hybrid SiC power module is smaller than that of conventional Si module by 0.3 V, but turn-off loss is nearly equal or less in spite of at higher operation temperature. Though the nominal current of the hybrid SiC module is large and the maximum operation temperature is 150°C, it has a wide switching operating area such as the large current turn-off and the short circuit capability. The advantage of SiC in a power module has been confirmed.

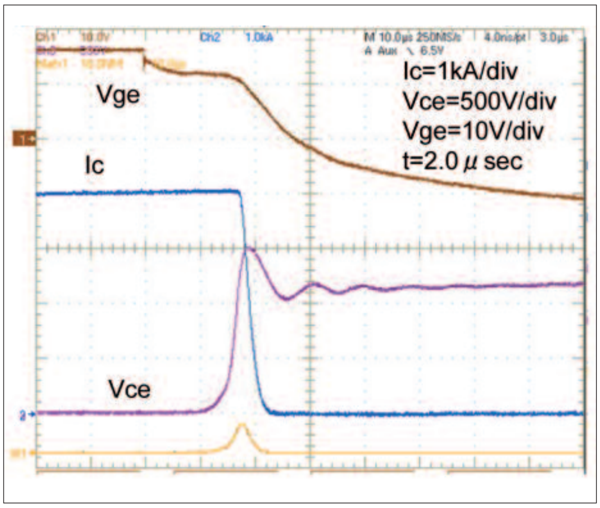


Figure 12: **IGBT turn-off capability**

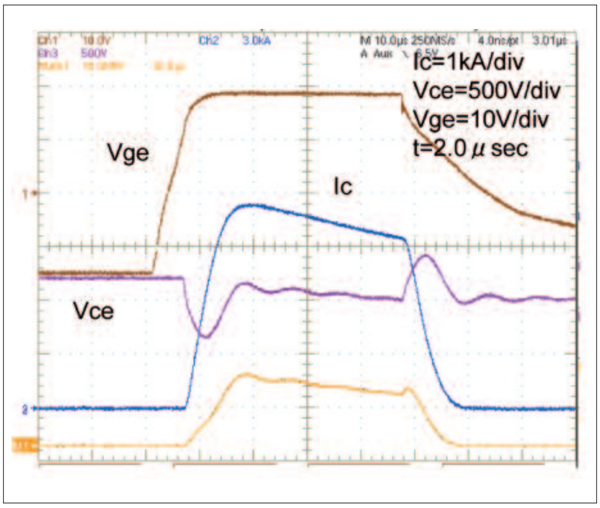


Figure 13: **IGBT short circuit capability**

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 T_j=150°C of hybrid SiC module compared to T_j=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 T_j=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 T_j=150°C and V_{cc}=1.2 kV. Although the standard gate voltage is 15 V, the hybrid SiC module has the short circuit capability at V_{GE}=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

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

Item	Si N-series Module Tj=125°C (Si-IGBT,Si-diode)	Hybrid SiC Module Tj=150°C (Si-IGBT,SiC-SBD)
IGBT on-state voltage	2.60V	2.30V
IGBT turn-on loss	0.40J/P	0.18J/P
IGBT turn-off loss	0.37J/P	0.34J/P
Diode on-state voltage	2.30V	2.30V
Diode turn-off loss	0.22J/P	0.01J/P

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 foot print 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. AS

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