1. Introduction

Silicon (Si) power modules have been widely used for industrial inverters, such as in the railway and electric power fields. Recently, for more efficient use of energy, there is a growing need for reduced power loss, smaller size and higher performance, and so attention is focusing on silicon carbide (SiC) as a new semiconductor material, which can reduce power loss and operate at high temperature.

Mitsubishi Electric has commercialized a 1.7 kV hybrid SiC power module integrating SiC schottky barrier diodes (SBDs) and 6th-generation Si insulated gate bipolar transistors (IGBTs), achieving a large current capacity of dual 1.2 kA and maximum operation temperature of 150°C.

2. Structure of 1.7 kV Hybrid SiC Module

2.1 SiC-SBD and Si-IGBT chips

The breakdown electric field strength of SiC is about 10 times higher than that of Si, which makes it possible to have a thinner chip, and hence achieve a lower on-state voltage. As a result, SiC allows the use of SBDs, which was previously impractical due to the high on-state voltage in conventional high-voltage applications. As a unipolar device, SBDs have no reverse recovery action, which is common in conventional Si diodes, and thus the SiC-SBD dramatically reduces the diode turn-off loss. In addition, because of the absence of reverse recovery charge, the turn-on loss of IGBTs can also be reduced.

Figure 1 shows an outline view of the 1.7 kV SiC-SBD chip. The chip size is 6.58 × 6.58 mm. For the termination structure that ensures the withstand voltage, the field-limiting ring termination structure has been adopted to achieve a reverse withstand voltage of 1.9 kV or higher at room temperature.

In addition, based on the conventional N-series Si-IGBT module, a new 6th-generation Si-IGBT was developed (Fig. 2). The turn-off loss has been successfully reduced by optimizing the structure in the rear surface region and the front surface pattern.

2.2 Module structure

Figure 3 shows the appearance of the newly developed 1.7 kV hybrid SiC power module. As shown in the circuit diagram illustrated in Fig. 4, this module is configured with dual 1.2 kA circuits. The package is designed to be compatible with the conventional N-series Si module having the same rating.

Figure 5 shows the internal design of the module consisting of four substrates as shown in Fig. 6. Each pair of these substrates makes up one 1.2 kA circuit consisting of 16 SiC-SBD and 8 Si-IGBT chips.
While the maximum operation temperature is 125°C for the Mitsubishi Electric N-series Si modules, it has been improved to 150°C for the new hybrid SiC module by employing the new chips and heat-resistant encapsulation material. In addition, a large current capacity of dual 1.2 kA has also been achieved by optimizing the chip layout, wiring arrangement and electrode structure.

3. Characteristics of 1.7 kV Hybrid SiC Power Module

3.1 Static characteristics

Figures 7 and 8 respectively show the on-state characteristics of the IGBTs and SBDs integrated in the 1.7 kV hybrid SiC module. In either case of the IGBT and SiC-SBD, the on-state voltage, $V_{CE(sat)}$ and $V_{EC}$ at the junction temperature $T_j = 150°C$ is higher than that at $T_j = 25°C$. These characteristics are advantageous for establishing the current balance in a large current capacity module consisting of many parallel-connected chips.

3.2 Switching characteristics

Figure 9 shows the turn-off waveform of the SiC-SBD under rated operation at 150°C. The conventional Si diode is a bipolar device and there is a reverse recovery current, whereas the SiC-SBD is a unipolar device and there is no reverse recovery charge. Consequently, the SBD turn-off loss, which corresponds to the recovery loss of the conventional Si diode, has been reduced by more than 95%, from a previous value of 0.22 J/P at 125°C to 0.01 J/P at 150°C.

Figure 10 shows the turn-on waveform of the IGBT under rated operation at 150°C. The SBD is a unipolar device, and thus due to the absence of reverse recovery charge, which is common in conventional Si diodes, the turn-on loss of the IGBT has also been drastically reduced by about 55%, from a previous value of 0.40 J/P for the conventional Si diode at 125°C to 0.18 J/P for the hybrid module at 150°C.

Figure 11 shows the turn-off waveform of an IGBT. For the conventional IGBT under rated operation at 125°C, the on-state voltage, $V_{CE(sat)}$, is 2.60 V and the turn-off loss is 0.37 J/P. In contrast, for the hybrid mod-
ule that has adopted the 6th-generation IGBT, the on-state voltage is 2.30 V and the turn-off loss is 0.34 J/P under rated operation at 150°C. Despite the 0.3 V lower on-state voltage, the turn-off loss remains at an equivalent or even lower level than that of the conventional IGBT. There is a trade-off relationship between the on-state voltage and the turn-off loss, and if the turn-off loss were equal, the newly developed IGBT chip would provide a V\(_{CE(sat)}\) value about 20% lower than that of the conventional IGBT.

Table 1 compares the key characteristics between the new hybrid SiC module and conventional Si module having the same current rating. A significant loss reduction has been achieved.

3.3 Switching capability

While the maximum operation temperature was specified to be 150°C, even at this high temperature, sufficient turn-off and short-circuit capabilities are ensured. Figure 12 shows the turn-off test results at the op-

<table>
<thead>
<tr>
<th>Item</th>
<th>Si N-series Module (Tj = 125°C)</th>
<th>Hybrid SiC Module (Tj = 150°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IGBT on-state voltage</td>
<td>2.60 V</td>
<td>2.30 V</td>
</tr>
<tr>
<td>IGBT turn-on loss</td>
<td>0.40 J/P</td>
<td>0.18 J/P</td>
</tr>
<tr>
<td>IGBT turn-off loss</td>
<td>0.37 J/P</td>
<td>0.34 J/P</td>
</tr>
<tr>
<td>Diode on-state voltage</td>
<td>2.30 V</td>
<td>2.30 V</td>
</tr>
<tr>
<td>Diode turn-off loss</td>
<td>0.22 J/P</td>
<td>0.01 J/P</td>
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</table>
erating temperature of 150°C, where the new module successfully turns off a current of 4,100 A, more than three times the rated current.

Figure 13 shows the short-circuit test results at the same operating temperature of 150°C. A short-circuit capability of 10 μsec is demonstrated at a gate voltage of 18 V, which is a more severe condition due to a larger short-circuit current than the standard gate voltage of 15 V.

3.4 Inverter loss

The inverter losses were estimated for railway motor applications. In the case of travel patterns on a city-area commuting line, the hybrid SiC power modules are expected to reduce the total energy consumption of the railway inverter system by 30% (Fig. 14).

4. Conclusion

Mitsubishi Electric has commercialized a 1.7 kV large-capacity hybrid SiC power module integrating SiC-SBDs. While the package outline remains compatible with the conventional N-series Si module, the internal structure of the module has been redesigned, and the newly developed 6th-generation Si-IGBT and SiC-SBD chips have been integrated to achieve a high withstand voltage of 1.7 kV, a large capacity of dual 1.2 kA, and a maximum operation temperature of 150°C.

Compared to the conventional Si module, the diode turn-off and IGBT turn-on losses have been reduced by more than 95% and 55%, respectively. The IGBT on-state voltage has also been reduced by about 20%, provided that the turn-off loss is the same. If the new modules are applied to railway traction motor applications, the inverter loss is estimated to be about 30% lower than that of the conventional Si inverters for travel patterns on a city-area commuting line.

The Mitsubishi Electric Railway Group has already applied the hybrid SiC module introduced in this paper, and commercialized the world’s first SiC inverter equipment for railway applications. We will continue to develop hybrid SiC modules for wider applications to help conserve energy usage in social infrastructures.

References