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Pushing the limits

Mitsubishi Electric explores how highly efficient silicon carbide power semiconductors are set to play a big role in future railway traction systems

Since the second half of the 1990s, silicon-based insulated gate bipolar transistors (IGBT) power semiconductors have been used for the energy supply and traction system of railcars. Over the years, these devices have been developed further to decrease losses, increase output power, and increase lifetime. This has allowed railway traction systems to become more efficient, more compact, and more reliable.

However, silicon-based semiconductors have almost approached their physical limits. Drastic improvements of silicon-based IGBTs cannot be expected anymore. Consequently, the focus has now shifted to wide-bandgap semiconductor materials, such as silicon carbide (SiC). Changing the fundamental semiconductor material again provides new potential for system improvements. Hence, we can see a clear trend independent on application: Today, cutting-edge air conditioners, servo drives, automotive traction drives, photovoltaic inverters, and railway traction drives use Full-SiC power semiconductors.

Improving railway traction systems

As a wide-bandgap material, SiC has about 10-times higher breakdown field strength than a classical silicon semiconductor. This allows thinner, more efficient, and fast-switching power devices, even for high-voltage devices rated for 3,300V or 6,500V. In railway traction systems, electric energy can be saved, converters and their cooling systems become smaller, and regenerative braking is enhanced, which relaxes mechanical breaks and reduces maintenance costs.[1]

Japanese railway companies have gained experience with SiC converters in field operation for many years. The first Hybrid-SiC traction converters started field operations in 2013. The first traction converters with Full-SiC power modules started operating in the field in 2015. In 2022, in total more than 55 different train types in Japan used Hybrid- or Full-SiC traction inverters.[2] Hence, Hybrid- and Full-SiC traction converters have become a reliable and effective measure to increase drive-train power density, save electric energy costs and improve the railway traction system.

SiC power modules

Mitsubishi Electric is well-known for its Hybrid- and Full-SiC railway converters, as well as for its high voltage SiC power semiconductor modules. In 2017, Mitsubishi Electric introduced a 3.3kV/750A Full-SiC power module. It is specifically designed for the high power, high efficiency, and high reliability requirements of railway-traction applications.[3]

This 3.3kV/750A power module uses

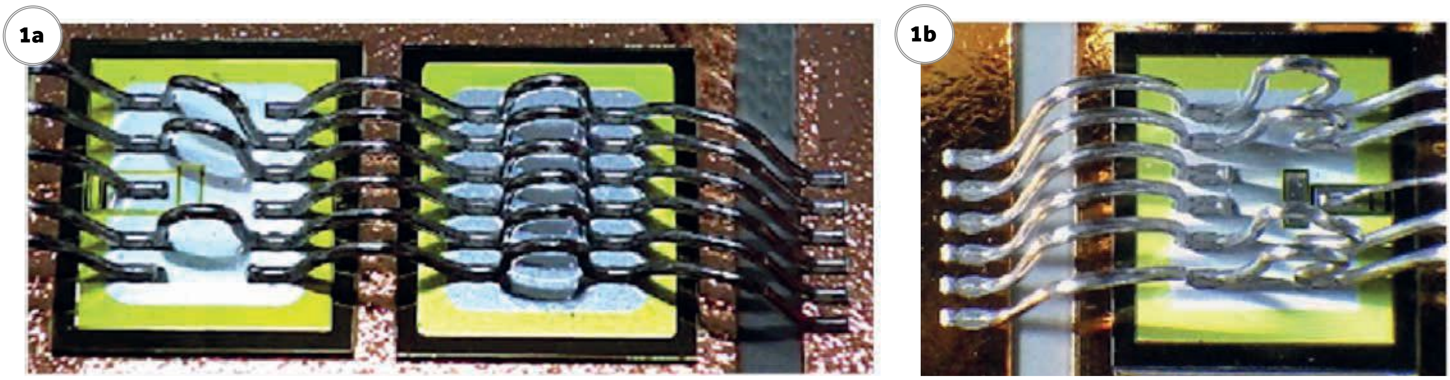

Figure 1: Saving valuable SiC chips from conventional 3.3kV SiC chips to SBD-embedded MOSFET

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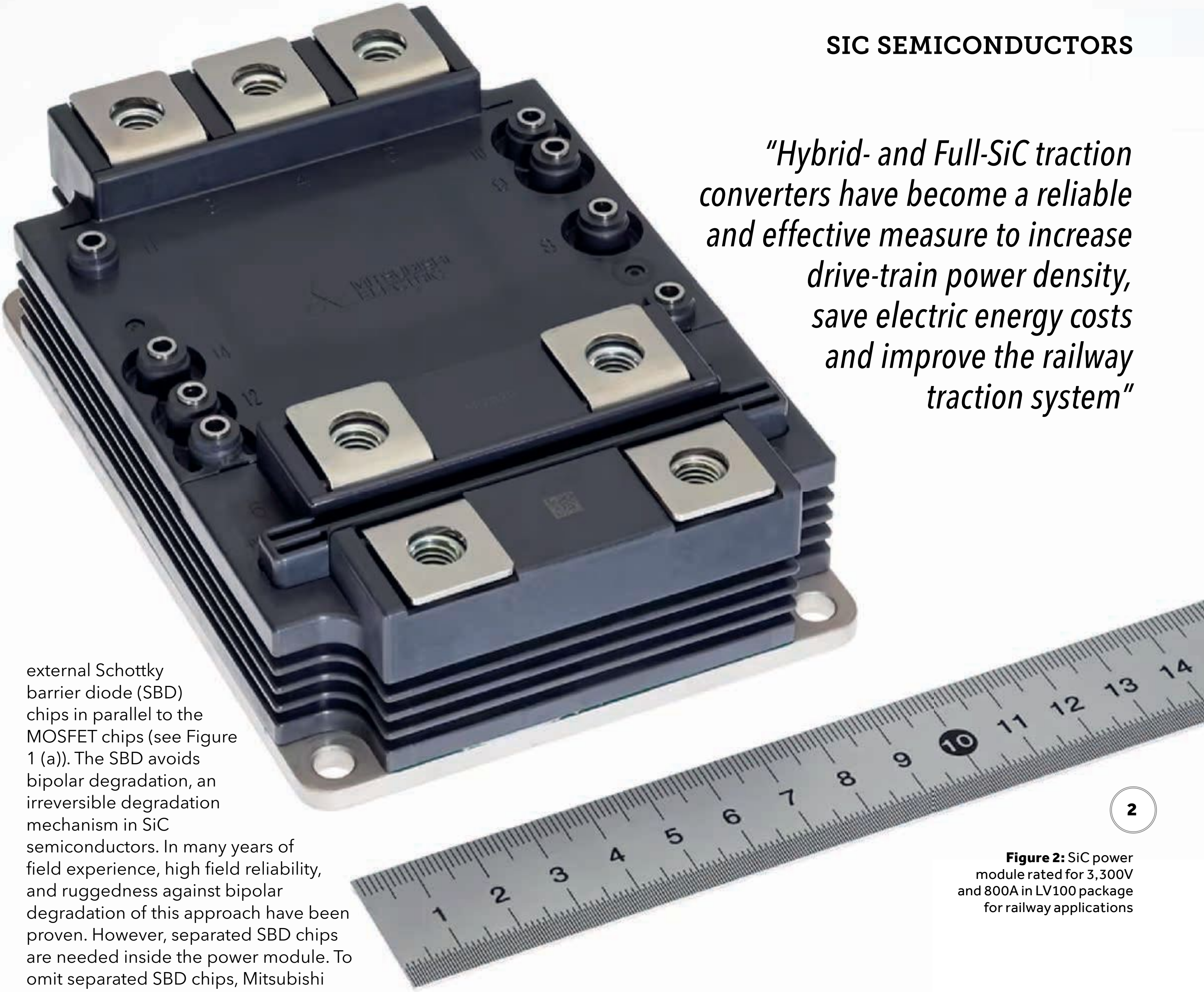

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Figure 2: SiC power module rated for 3,300V and 800A in LV100 package for railway applications

external Schottky barrier diode (SBD) chips in parallel to the MOSFET chips (see Figure 1 (a)). The SBD avoids bipolar degradation, an irreversible degradation mechanism in SiC semiconductors. In many years of field experience, high field reliability, and ruggedness against bipolar degradation of this approach have been proven. However, separated SBD chips are needed inside the power module. To omit separated SBD chips, Mitsubishi Electric has developed SiC MOSFET chips with embedded SBD.

The 3.3kV SBD-embedded MOSFET integrates SBD functionality into the MOSFET chip. Separate SBD chips are avoided. Moreover, due to the embedding, the required SBD area is reduced drastically. Hence, the current density can be improved with SBD-embedded MOSFET compared to the original MOSFET chip.[4]

Integrating the SBD-embedded MOSFET chips into the LV100 package (as shown in Figure 2), Mitsubishi Electric is now developing an 800A power module. By increased switching speed, this power module is targeted to save 66% of switching losses compared to the conventional 3.3kV SiC power module.

What the future holds

Evidently, Mitsubishi Electric strives for even higher performance for future Full-SiC power modules. And although Full-SiC power modules have much greater performance than classical silicon modules, they still must be compared with their little brothers in terms of price. Hence, Mitsubishi Electric continuously optimizes the manufacturing costs for Full-SiC power modules. For example, the company has introduced the SBD-embedded MOSFET chips to omit external SiC SBD chips.

In addition, Mitsubishi Electric has switched SiC wafer size from 4-inch to 6-inch, which allows manufacturing about 2.2- to 2.5-times more SiC chips per wafer. Moreover, Mitsubishi Electric has announced an investment of ¥260bn (US$1.7bn) in the five-year period to March 2026 to enhance its production facilities for 6-inch SiC wafers and to construct a new 8-inch SiC wafer plant.

Conclusion

Since silicon power semiconductors have almost reached their physical limits, drastic improvements cannot be expected anymore. On the other side, Full-SiC power semiconductors have become an effective measure to further improve the railway traction system, increase drive-train power density and save electric-energy costs. SiC is the future of railway converters and Mitsubishi Electric is shaping this future.

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