Technological Innovation for Super-low-loss U-series IGBT Modules

Noriyuki Iwamuro
Tadashi Miyasaka
Yasukazu Seki

1. Introduction

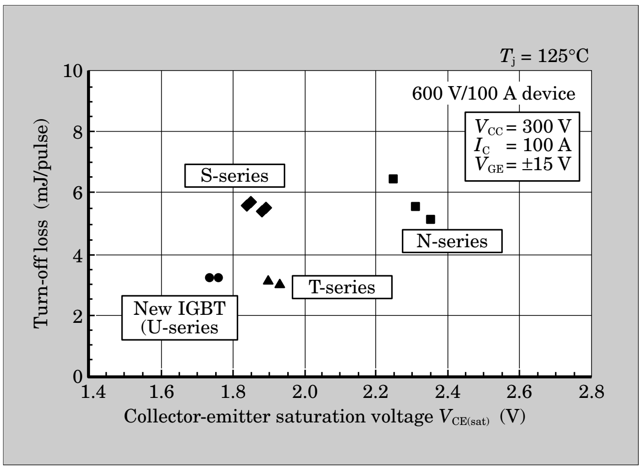
The IGBT (insulated gate bipolar transistor) originated in the first half of 1980s as a power device having both the high impedance characteristic of a MOSFET (metal oxide semiconductor field effect transistor) and the low on-state voltage characteristic of a bipolar transistor. Since the advent of the first generation IGBT in the latter half of 1980s, IGBTs have played an important role in power electronics technology in the fields of industry, information, traffic control, etc. The IGBT has attracted attention year after year because of its advantageous voltage/current ratings and excellent switching capability which is superior to that of the bipolar transistor. Accordingly, there is strong demand for the development of lower power loss IGBTs. Through the adoption of finer surface cell construction and the resultant high-performance technical innovations, first, second and third generation IGBTs have been developed, subsequently enabling smaller size and higher performance equipment. In recent years, the performance of IGBT modules has been improved dramatically. This paper describes the design concept and characteristics of the super-low-loss U-series IGBT module developed by Fuji Electric and introduces the IGBT module technological innovations achieved by Fuji Electric.

2. Development of Super-low-loss IGBT Chips

Fuji Electric started producing IGBTs in 1988, and has been supplying them to the market ever since. Based on the design concept to increase injection efficiency of the wide base pnp transistor and decrease the transportation factor by lifetime control, we improved the characteristics of PT (punch through) type IGBTs by adopting fine surface cell construction to increase the supply of electron current from the MOSFET portion. First, second and third generation (N-series) IGBTs were developed in 1988, 1990 and 1994, respectively, based on this technology. Thereafter, to improve the performance further, we developed the NPT (non-punch through) type IGBT (NPT-IGBT) based on the design concept to decrease injection efficiency of the above pnp transistor and to increase the transportation factor without using lifetime control. In developing the NPT-IGBT, we were able to improve its characteristics by adopting a new thin wafer process technology in which the devices are fabricated from a wafer shaved down to a thickness of almost 100 μm. Based on this technology, the S-series (1,200 V type) and T-series (600 V type) IGBTs were developed in 1999 and 2001, respectively.

The newly developed super-low-loss IGBT chip (U-IGBT chip) is a power semiconductor, featuring improved characteristics enabled by the adoption of thin wafer process technology developed for NPT-IGBT chip and trench gate technology and which will realize fine surface cell construction. Figure 1 compares the saturation voltage turn-off loss trade-off for 600 V type IGBT chips of several generations. From this figure, it is clear that a great improvement has been achieved by trench gate structure and thin wafer NPT construction. To improve thin wafer NPT technology, we developed thin wafer FS (field stop) technology[1] and applied it to 1,200 V and 1,700 V IGBT chips. As shown on Fig. 2, saturation voltage turn-off loss characteristic was improved dramatically. Because the U-IGBT chip adopts the design concept of reduced injection efficiency of the pnp transistor and increased transportation factor without lifetime control, the

Fig.1 600 V IGBT trade-off comparison



saturation voltage has a positive temperature coefficient as shown in Fig. 3. Therefore, this device is suitable for high rated current applications.

In designing IGBTs, it is already known that saturation voltage can be reduced by adopting a fine surface cell construction, such as a trench gate structure. But, on the contrary, during abnormal conditions such as a load short circuit, a high current may flow into the device. Therefore, the device could be damaged. A solution to this problem was an important theme of the development. In the newly developed U-IGBT chip, the current during a load short circuit is suppressed by an optimized trench gate structure that does not sacrifice the on-voltage, and as a result, the endurance is improved. Figure 4 shows the load short circuit waveform of a 1,200 V / 450 A U-IGBT module. The current during a load short circuit is limited to within about 5 times the rated current. Even at 125°C, the device can withstand this current for more than 10 μs.

Fig.2 1,200 V & 1,700 V IGBT trade-off comparison

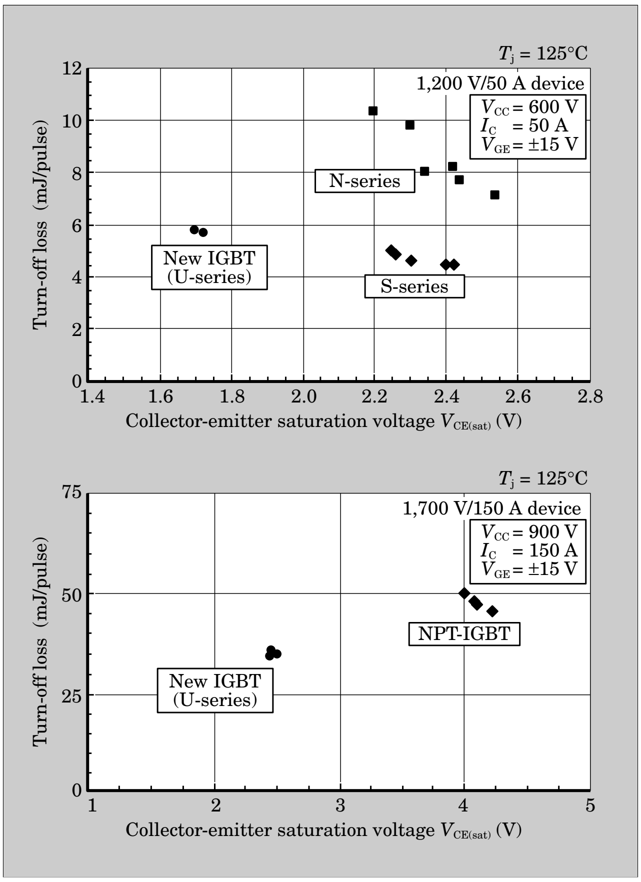
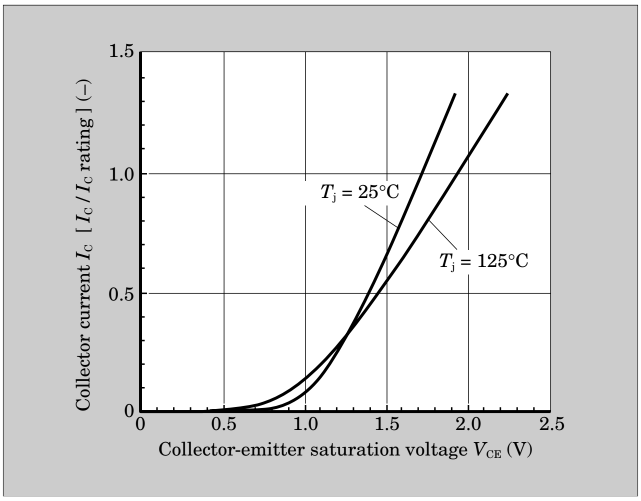


Fig.3 U-IGBT output characteristics (1,200 V device)



3. Features of New FWD Chips

The new FWD (free wheeling diode) has a soft reverse recovery characteristic that is achieved by controlling the injection of minority carriers from the anode layer. As in the case of the IGBT, the new FWD is designed with optimized lifetime control such that on-state voltage has a positive temperature coefficient. Therefore, this device is suitable for high rated current applications. Through the adoption of the new FWD, peak current during turn-on of the IGBT was reduced

Fig.4 U-IGBT (1,200 V / 450 A) waveforms during load short circuit

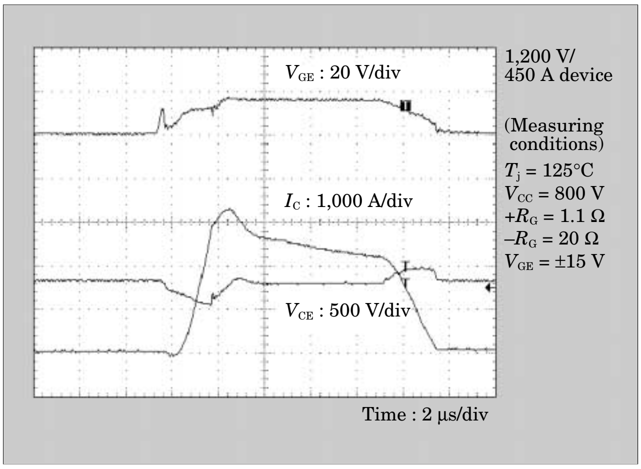
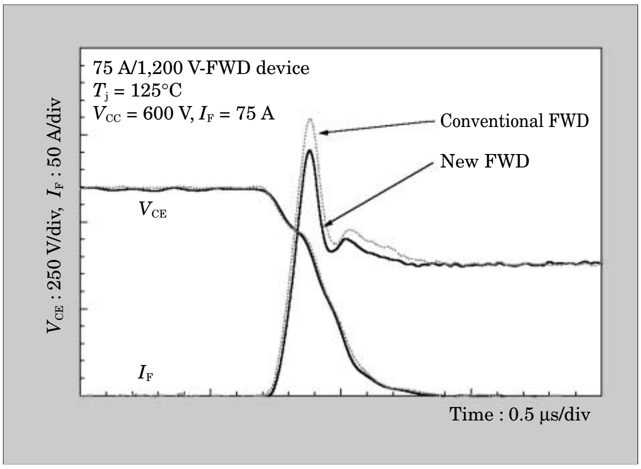


Fig.5 Comparison of IGBT turn-on waveforms for U-FWD and conventional FWD



as shown on Fig. 5. As a result, turn-on power loss was reduced.

4. Thermal Characteristics of U-IGBTs when applied to Inverters

IGBT modules are widely used in general-purpose inverters. Further improvement in performance and reliability is requested to enhance the cost-performance attribute. Figure 6 shows the correlation between chip size and power loss when an IGBT is used in an inverter. For example, the power loss of a 30 kW inverter using a new 1,200 V / 150 A device at the rated load condition can be reduced by about 30 % compared with the power loss when using conventional devices with the same chip size. Dependency of the chip size on the power loss is relatively low. This suggests that the chip size could be shrunk by about 20 % assuming the same power loss. By adopting the above mentioned chip technology, the IGBT output characteristic was improved as shown on Fig. 7. This improvement was realized because of the fact that the saturation voltage will not be increased by the increase in current density.

As shown on Fig. 8, the thermal resistance ($R_{th(j\text{-}c)}$) is inversely proportional to the chip size. If we calculate the chip temperature rise ($\Delta T_{j\text{-}c}$) simply by the formula $\Delta T_{j\text{-}c}$ = power loss $\times R_{th}$, the temperature rise can be increased rapidly by shrinking the chip size. This may cause problems with the reliability of power cycle capability.

4.1 Temperature rise of an IGBT chip (including the cooling system)

The temperature rise of an IGBT chip is dependent on the cooling system, including the radiators. In the

Fig.6 Comparison of power loss and chip size of IGBT

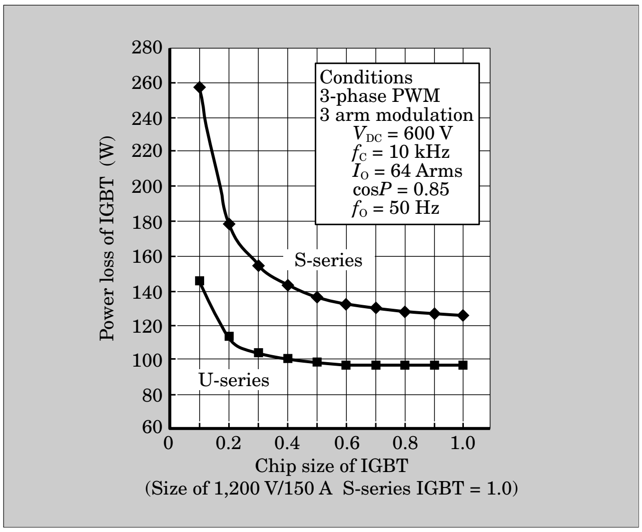


Fig.7 Comparison of output characteristics of IGBT

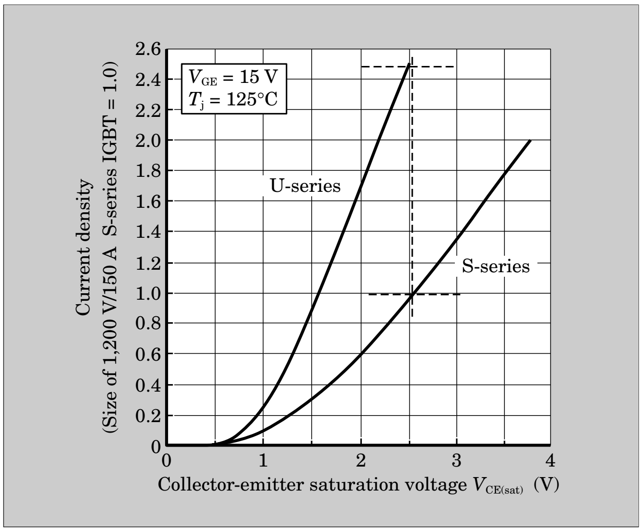


Fig.8 Comparison of $\Delta T_{j\text{-}c}$ and chip size of IGBT

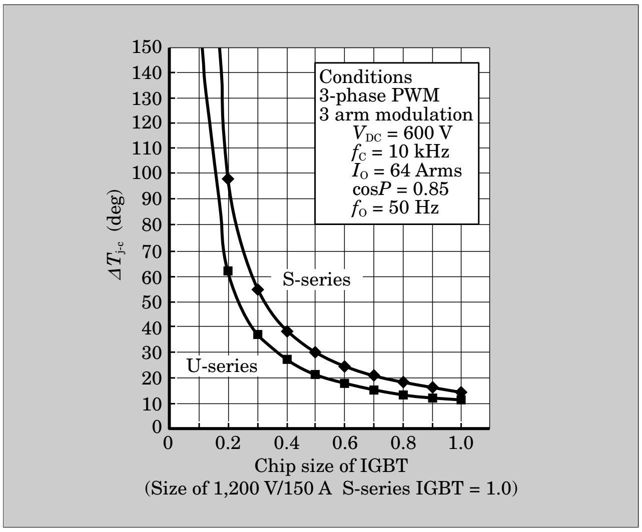


Fig.9 FEM analysis results of chip temperature rise of IGBT

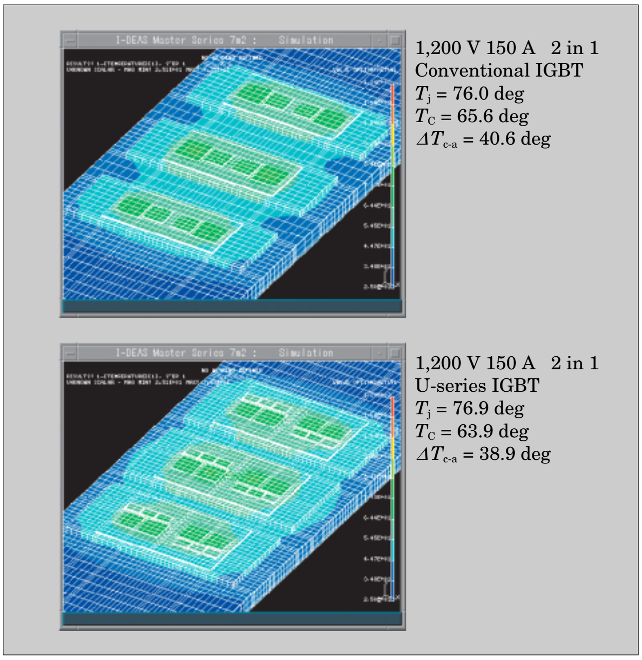


Fig.10 Improvement of power cycle capability

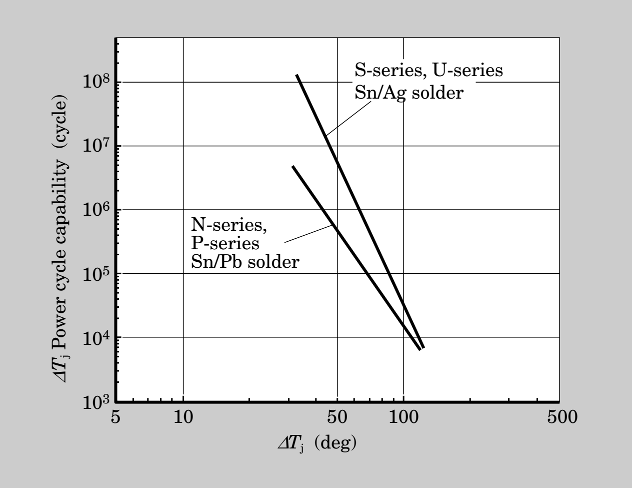
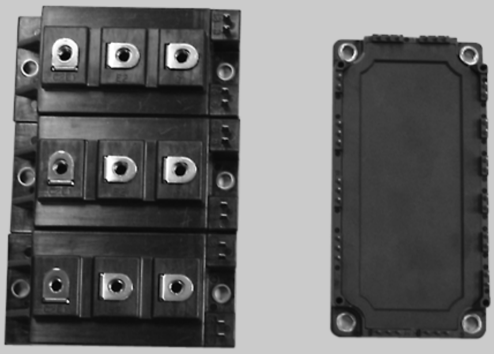


Fig.11 Comparison of appearance of U-IGBT and conventional module



(a) Conventional module (2 in 1 × 3)

(b) U-series (6 in 1)

past, the temperature rise of an IGBT chip was calculated assuming a constant cooling fin temperature and the chip temperature rise was calculated as the summation of the constant cooling fin temperature and $\Delta T_{j\text{-}c}$.

Figure 9 shows the results of calculating the temperature rise of an IGBT chip, including the cooling system, by the finite elements method (FEM). Results of three-dimension model analysis suggest the following possibilities for controlling chip temperature rise.

(1) Sideways thermal spreading of the cooling system mounting base
(2) Reduction of mutual interference by the optimizing chip intervals
(3) Optimization of module arrangement

With this analysis method, the temperature rise, which is important for verifying the reliability, can be calculated easily and precisely.

4.2 Improvement of power cycle capability

Based on the analysis of test devices subject to power cycles in an IGBT module, we verified that the power cycle capability is dependent on the combined total life of solder and bonding wires at the bottom of the chip. We reported a new technique for changing to a high elasticity tin solder on the chip bottom to extend the life [2].

We applied this technology to the U-series. As shown on Fig. 10, the power cycle capability of the U-series is more than 10 times that of the conventional series at Δ40 deg. In other words, to keep the same power cycle capability, the allowable temperature rise can be increased to up to 60 deg as contrasted with the usual allowable temperature rise of 40 deg.

Figure 11 compares the modules of the conventional 1,200 V / 150 A device and those of the U-series device. The new technology achieves a space savings of 40 % (area of the base).

5. Conclusion

An overview of the chip and packaging technology of the new super-low-loss U-series IGBT module was presented above. The U-series IGBT chip, with its almost ideally shaped IGBT due to the combination of trench gate structure and thin wafer technology, contributes to the loss reduction and miniaturization of equipment. To make maximum use of an IGBT module, it is necessary to fully understand the worst operating condition and to select the most appropriate device for that condition, considering the thermal characteristics of the cooling device. Fuji Electric has developed device technology for this purpose and will strive to further enhance this new technology and apply it to equipment.

References

(1) Laska, T. et al. The Field Stop IGBT (FS-IGBT) - A New Power Device Concept with a Great Improvement Potential. Proceedings of the 12th ISPSD. 2000, p.355-358.
(2) Morozumi, A. et al. Reliability of Power Cycling for IGBT Power Semiconductor Module. Conf. Rec. IEEE Ind. Appl. Conf. 36th. 2001, p.1912-1918.