“M677” 100-kW Class Ultra-Compact IGBT Module for xEVs

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ABSTRACT

The electrification of automobiles has been dramatically accelerated worldwide in the last decade and power modules are required to be compact, low-cost, and higher power output at the same time. In order to meet the market requirement, Fuji Electric has developed the “M677,” an industry-leading ultra-compact RC-IGBT module for xEVs targeting motors with output capacity of 100 kW. By combining low-loss RC-IGBTs, a new package with lead frame wiring, and a high thermal performance cooler, it has lower generated loss by 20% during inverter operation and smaller module size by 50% than a conventional product. This enhancement has resulted in a palm-sized 100 kW-class RC-IGBT module that achieves twice the power density compared with the conventional one.

1. Introduction

Since the Paris Agreement was adopted as an international framework for global warming measures in 2015, the reduction of CO_2 emissions has become increasingly important worldwide. In order to reduce CO_2 emissions, the automotive industry is increasingly promoting electrified vehicles (xEVs), which use electric motors as power sources, including hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), and electric vehicles (EVs). The inverter unit used to control these motors is mounted in the limited space of the engine compartment, and it is thus required to be compact and deliver high output power. Accordingly, the power module, which is the core of the inverter unit, is also required to have reduced size and increased output power, and thus, high power density is essential. Fuji Electric is working to develop technologies for semiconductors, packaging, and cooling for the high power density challenge. Our semiconductor technology include a reverse-conducting IGBT (RC-IGBT). It integrates two chips, an insulated gate bipolar transistor (IGBT) and a free wheel diode (FWD), into a single chip to reduce the footprint of the chips, thereby reducing the size of power modules. Developments in packaging technology include lead frame technology that reduces the amount of area required for wiring in comparison to aluminum wiring. Advancements in cooling technology include the development of an integrated fin. The gap between fins and a water jacket is eliminated to increases the flow rate of coolant and improve cooling performance. By applying these various technologies, we were able to increase the power density of power modules, and in 2017, we released the “M660” RC-IGBT module[(1),(2)] for 200-kW class motors.

Fuji Electric has recently developed the industry-leading ultra-compact “M677” RC-IGBT module for xEVs, designed to target 100-kW class motors. This paper describes its features and performance.

2. New Technologies for “M677”

Figure 1 shows the newly developed M677. Table 1 compares its performance with the “M653” (the conventional product). To achieve high power density, the M667 achieves higher chip performance, smaller wiring area, and higher cooling performance. While maintaining the output performance, the size (cubic volume) is reduced by more than 50%, and the power density is increased to approximately twice that of the conventional product. The following describes the characteristics of this module compared to the M653, which has a similar output capacity.

(a) Improved performance of the 7th-generation RC-IGBT

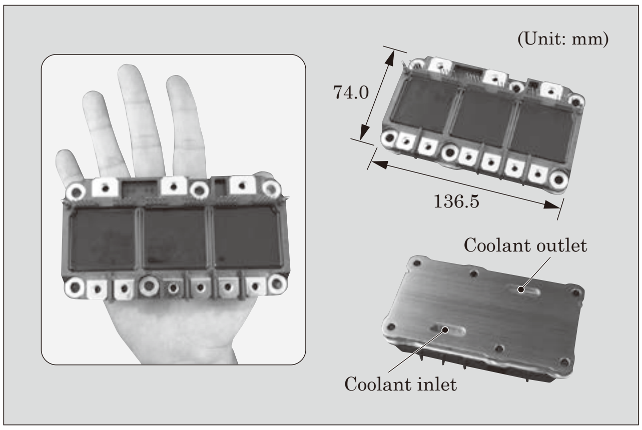

Fig.1 “M677” (newly developed product)

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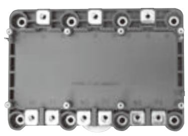
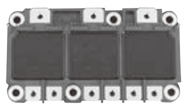
Table 1 Comparison of performance

Item	M653 (conventional product)	M677 (newly developed product)
Appearance		
Motor output capacity range	100 kW	100 kW
Collector-emitter saturation voltage	750 V	750 V
Chip	7th-generation RC-IGBT	7th-generation RC-IGBT (Improved performance)
Internal wiring	Aluminum wire	Lead frame
Cooler	Water jacket integrated wave fins	Water jacket integrated pin fins
External dimensions	W162.0 × D116.0 × H24.0 (mm)	W136.5 × D74.0 × H21.0 (mm)
Size	0.45 L	0.21 L
Power density (arb.unit)	1.00	1.98

Compared with the 7th-generation RC-IGBT used in the conventional modules, the new module achieves the same motor capacity while reducing the chip size by using IGBTs with improved output characteristics and reducing switching loss. Details are described in Chapter 3.

(b) Lead frame wiring

Instead of the conventional aluminum wires, we use lead frame wiring, thereby reducing the wiring area in the module by approximately 20%.

(c) New cooler with pin fins

To improve the cooling performance, the cooling fin structure is changed from the conventional wave fin structure to a pin fin structure, thereby reducing heat resistance by 10%. Details are described in Chapter 4.

(d) Adoption of a new cooler interface

In the conventional structure, the water channel interface between the cooler and an inverter housing, which is required for the water jacket-integrated fins, was configured using flanges and studs. A new cooling interface only use a bottom plate to reduce six interface components resulting in a smaller power module.

3. Improved Performance of the “M677” RC-IGBT

Fuji Electric has developed and mass-produced RC-IGBTs for automotive inverters for the main drive, a first in the industry.[(3)-(6)] Since two chips, an IGBT and a FWD, are integrated into one chip, the RC-IGBT module has the advantage of having the smaller area for the chip and package than conventional modules using discrete IGBT and FWD chips. However, even

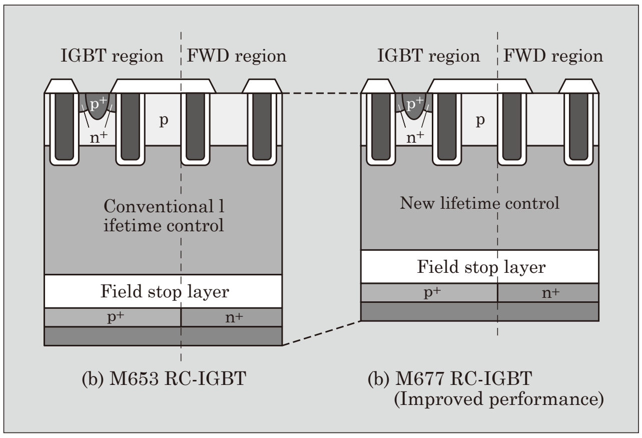


Fig.2 Cross section of the RC-IGBT

when a power module uses a RC-IGBT chip, the chip area will still remain a large part of the module area. Chip size reduction is thus important to reduce the module size further. To reduce the size of the chip, it is necessary to suppress the increase in conduction losses, which are inversely proportional to the chip area, and to reduce switching losses during inverter operation to reduce heat density. Building on the 7th-generation chip technology, the M677 features improved performance. The improved output characteristics per unit area suppresses the increase in conduction loss associated with the size reduction of the chip and reduces switching losses during inverter operation. Figure 2 shows a cross section of the RC-IGBT. Sections 3.1 and 3.2 describe the improved output characteristics and the method of reducing the switching loss.

3.1 Improved output characteristics

Although RC-IGBTs have the advantage of being able to adopt the one chip, the optimization of IGBT and FWD characteristics in RC-IGBTs is more difficult than in case of using IGBTs and FWDs. For example, to reduce switching loss, lifetime control is performed by adjusting the reverse recovery current of the FWD, but in such cases, there is a trade-off relationship in

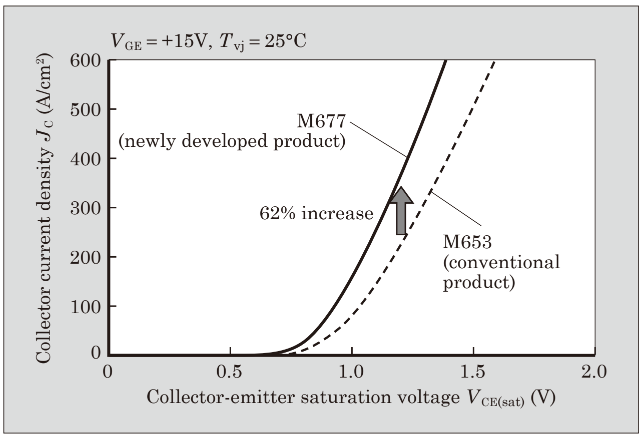


Fig.3 Collector-emitter saturation voltage $V_{CE(sat)}$

which the conduction loss increases for the IGBT and the FWD. In developing the RC-IGBT for the M677, we have developed a new lifetime control technology to improve the trade-off between switching loss and conduction loss. In addition, reducing the Si wafer thickness and optimizing the surface structure reduce the conduction loss. Figure 3 shows the collector-emitter saturation voltage $V_{CE(sat)}$. In comparison with the RC-IGBT for the M653, the collector current density increases by 62% under the same saturation voltage. Improving the current output performance per unit area has reduced the chip size without increasing the conduction loss.

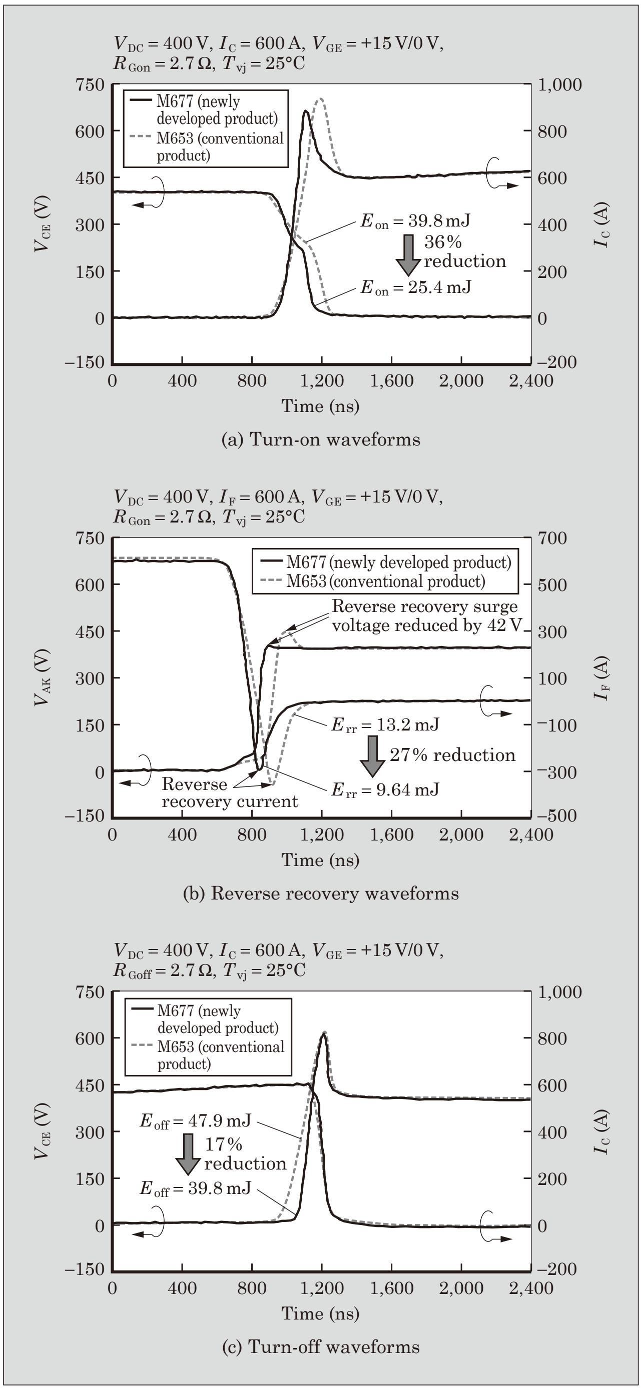


Fig.4 Switching characteristics of the newly developed "M677"

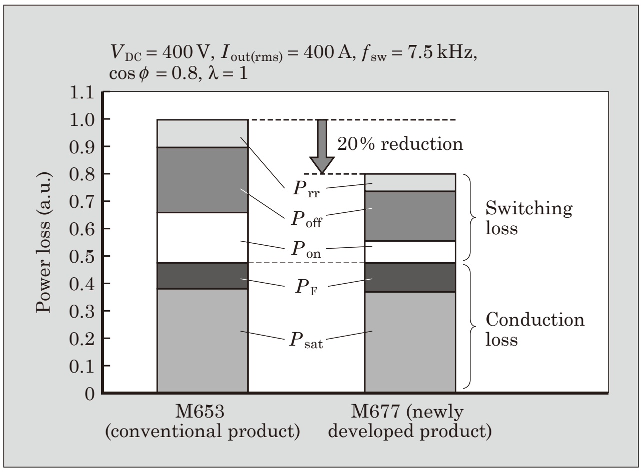


Fig.5 Comparison of generated loss when the inverter is operated

3.2 Reduction of switching loss

The switching speed at turn-on should be in the range where the reverse recovery surge voltage is suppressed below the breakdown voltage. To reduce loss by increasing switching speed, it is pivotal to reduce the reverse recovery current, which is the main factor of controlling the reverse recovery surge voltage. For this reason, a new lifetime control technology is introduced to the M677 to control the reverse recovery current of the diodes, and as a result, the turn-on loss (E_{on}) and the reverse recovery loss (E_{rr}) that occur at turn-on are reduced by 36% and 27%, respectively, in comparison with the conventional M653, as shown in Fig. 4. In addition, the reverse recovery surge voltage is reduced by 42 V. The surface structure optimization and size reduction of the chip have reduced the parasitic capacity of the device, reducing the turn-off loss (E_{off}) by 17%.

Figure 5 compares the generated losses of the M677 and the M653 during the operation of an inverter. While the conduction loss of the M677 is almost equal to the M653, the switching loss is significantly reduced (in particular, the reverse recovery loss P_{rr} and the turn-on loss P_{on}), which reduces the total generated loss by 20%.

4. Cooling Structure and Output Performance

4.1 Improved Cooling Performance

As the size reduction of chips and modules is accompanied by an increase in heat density, cooling performance must be improved in addition to loss reduction. For this reason, we have optimized the cooling structure of the M677. As shown in Fig. 6, using pin fins for the new cooling structure has reduced the thermal resistance by more than 10% at the same pressure loss. Details of the cooling structure are described in "Cooling Technology for Ultra-Compact RC-IGBT

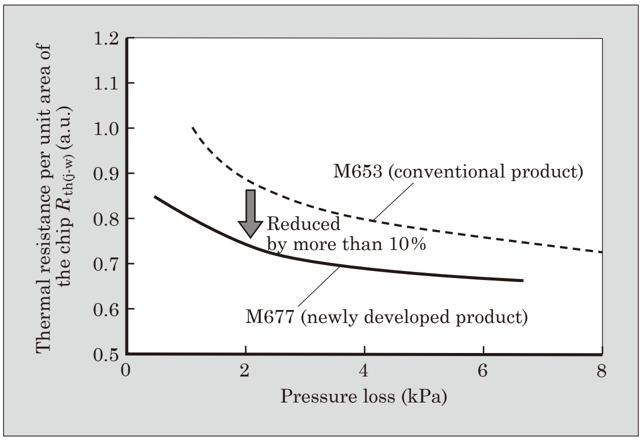


Fig.6 Thermal resistance and pressure loss per unit area of the chip

Module for xEVs" on page 236.

4.2 Output Performance

To drive a 100-kW class motor, the inverter with a system voltage of 400 V requires a current output of 350 $A_{(rms)}$ or higher with not exceeding a maximum chip junction temperature of T_{vj} 175°C. At the same time, switching frequency is generally required to operate at 5 to 10 kHz. Figure 7 shows the simulation results of the M677 for T_{vj}, when using the output current parameter I_{out}. Due to the effect of the newly developed RC-IGBT, packaging, and cooler, the M677 achieves the output current of 350 $A_{(rms)}$ at a high carrier frequency of 10 kHz, even when thermal design margins are considered. With lower carrier frequencies, an even larger output current can be achieved. In this way, the M677 can deliver high output performance with a power of more than 100 kW.

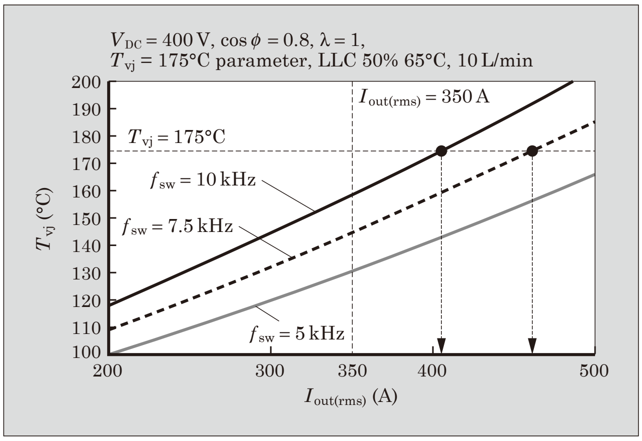


Fig.7 Simulation of T_{vj} for the "M677" (newly developed product)

5. Postscript

This paper described the "M677" 100-kW class ultra-compact RC-IGBT Module for xEVs. Based on 7th-generation technology, we have improved RC-IGBT performance and cooling performance to reduce the size of power modules. Using these technologies, the "M677" has reduced the size by more than 50% and approximately doubled the power density compared with the conventional product. We achieved a 100-kW class IGBT module that fits in the palm of one's hand. Fuji Electric will continue to contribute to the realization of a decarbonized society by meeting requirements for size reduction and increased power density of inverter systems for electrified vehicles.

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