3rd-Generation Direct Liquid Cooling Power Module for Automotive Applications

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ABSTRACT

Fuji Electric has developed a 3rd-generation direct liquid cooling power module for hybrid and electric vehicles. The power module has a rated capacity of 750 V/800 A, which is designed for motor capacity of 100 kW. The market for automotive application based power modules has been requiring increased efficiency and module miniaturization. To meet these demands, we have improved exothermicity by adopting a water jacket for integrating the cooling fins and cover while also increasing the reliability of the solder, thus enabling the module to achieve continuous operation at 175 °C. Furthermore, we have miniaturized the power module by adopting an RC-IGBT that integrates IGBT and FWD.

1. Introduction

There is a need to reduce CO_2 emissions in order to prevent global warming, and hybrid electric vehicles (HEVs) and electric vehicles (EVs) driven by electric motors are raising expectations with their significant effectiveness for CO_2 reduction. Inverters used for HEVs and EVs are mounted in a limited space of vehicles and are required to offer high power and low loss. Accordingly, in-vehicle power modules, which are a major part of inverters, need to be made smaller and have improved efficiency.

Fuji Electric has developed the 3rd-generation direct liquid cooling power module for automotive applications as an in-vehicle power module for the next generation (see Fig. 1). This power module has achieved higher heat dissipation performance than the previous product by using an optimized flow channel design. In addition, it employs a cover-integrated aluminum water jacket and a flange structure for the refrigerant inlet and outlet[(1)]. All the user has to do is to make sure that the refrigerant is run at the specified flow rate.

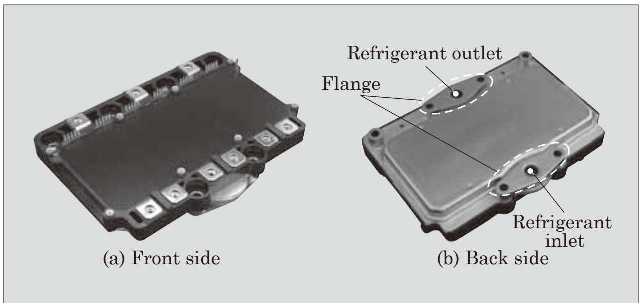

Fig.1 3rd-generation direct liquid cooling power module for automotive applications

Furthermore, the 7th-generation chip technology has been used for the insulated-gate bipolar transistor (IGBT) to reduce losses. Moreover, a reverse-conducting IGBT (RC-IGBT), which requires no free wheeling diode (FWD), has been used to make the module smaller.

2. Features

The following describes the features of the 3rd-generation direct liquid cooling power module for automotive applications. Table 1 lists the major specifications.

(a) Cooling technology to realize high heat dissipation performance

A water jacket integrating the liquid cooling fins and cover has been used to improve heat dissipation performance.

(b) Guaranteed continuous operation at 175°C

This feature has improved the reliability of the solder.

(c) Module size reduction

An RC-IGBT that integrates an IGBT and FWD has been applied.

Of these features, this paper describes the cooling technology and the RC-IGBT application technology.

Table 1 Major specifications of 3rd-generation direct liquid cooling power module for automotive applications

Item	Rating
Collector-emitter voltage	750 V
Rated current	800 A
Maximum operating temperature	175 °C
Dimensions	162×116×24 (mm)
Mass	520 g

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3. Cooling Technology to Realize High Heat Dissipation Performance

Inverters used for power control of vehicles are mounted in a limited space. This means they must be compact, have a high degree of freedom of the mounting method and undergo weight reduction and efficiency improvement for a better fuel efficiency. Power modules mounted in inverters also require size and weight reduction and efficiency improvement. We have successfully achieved a size and weight reduction of over 20% with each generation. With in-vehicle power modules, in particular, the heat dissipation performance has been improved by using a direct liquid cooling structure. The weight has also been reduced by using an aluminum cooler.

For improved heat dissipation performance, Fuji Electric has enhanced the heat dissipation performance of the aluminum cooling fins in the direct liquid cooling structure of the power module, achieving a 30% reduction in the thermal resistance.

3.1 Issue with cooling technology

Figure 2 shows a cross-sectional view of the conventional structure in the 2nd-generation aluminum direct liquid cooling intelligent power module (IPM). This structure has the module and heat sink directly joined by solder. The water jacket is independently designed by the user, and consequently the heat sink and water jacket need to be separate parts. A design that considers watertightness and tolerance is required in addition to flow channel design. For that reason, the material and thickness of the base must be carefully selected so that the device can resist buckling and deformation. This has been a factor causing an increase in the thermal resistance. The issue is to ensure both improved heat dissipation performance and high reliability of the aluminum direct liquid cooling structure. To solve this issue, we have developed an aluminum cooler integrating a heat sink and water jacket.

3.2 Third-generation cooling design technology

The heat dissipation performance of a power module can be represented by 2 factors: thermal resistance and heat transfer coefficient. Thermal resistance and heat transfer coefficient have a relationship as represented by Equation (1).

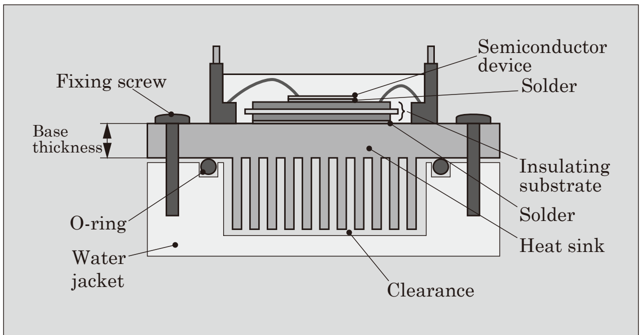

Fig.2 Cross-sectional view of conventional structure

$$h = \frac{1}{R_{\mathrm{th}} \cdot A} \quad \cdots\cdots (1)$$

h : Heat transfer coefficient [W/(m^2·K)]
R_{th} : Thermal resistance (K/W)
A : Fin surface area (m^2)

The heat transfer coefficient h represents the heat exchanging performance of the refrigerant and fins. To reduce the thermal resistance, it is effective to increase the heat exchanging performance of the fins. In addition, a higher flow speed on the fin surface provides a larger heat transfer coefficient representing the heat exchanging performance (Equation (2)).

$$h = \frac{0.664\, k \times \frac{\eta C_{\mathrm{p}}}{k}^{1/3}}{L} \times \frac{\rho L}{\eta} \times \frac{\rho v L}{\eta}^{1/2} \quad \cdots\cdots (2)$$

h : Heat transfer coefficient [W/(m^2·K)]
k : Thermal conductivity [W/(m·K)]
η : Refrigerant viscosity (Pa·s)
C_{p} : Specific heat [J/(kg·K)]
L : Characteristic fin length (m)
ρ : Refrigerant density (kg/m^3)
v : Refrigerant flow speed (m/s)

With the conventional cooling structure that uses a sealant, the water jacket is designed and prepared by the user, and hence a clearance is needed between the fin ends and the water jacket. We made a trial calculation of the effect of this clearance on the heat dissipation performance by using a simplified model.

The fins were specified to be 1 mm thick, provided at intervals of 1 mm and have a height of 10 mm and we assumed the refrigerant would run evenly at 1 L/min into the refrigerant inlet. As a result of the trial calculation, it has been found that a larger clearance causes the thermal resistance to increase, which is undesirable. The refrigerant flows through places where the pressure resistance is low, causing it to flow out to the clearance with a large opening. Further, the flow speed between fins, which contributes to the heat dissipation performance, decreases. In addition, it can be expected that connecting modules in parallel will make the decrease of the refrigerant flow speed more significant. Eliminating the clearance by integrating the heat sink and water jacket is effective for increasing the speed of the refrigerant flow between fins to reduce the thermal resistance[(2)].

Figure 3 shows a cross-sectional view of the new structure adopted for the 3rd-generation direct liquid cooling power module for automotive applications. With the new structure, the fin shape has been elaborated and the clearance has been eliminated by joining the water jacket and fin ends. In this way, the cooling structure can make use of the refrigerant more efficiently. Furthermore, the thickness of the part corre-

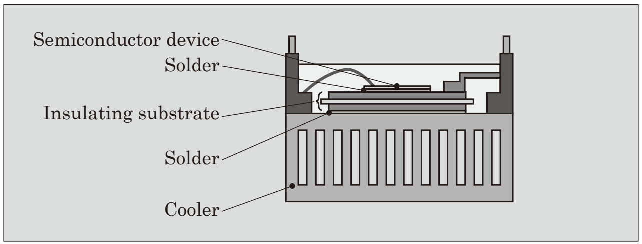

Fig.3 Cross-sectional view of new structure

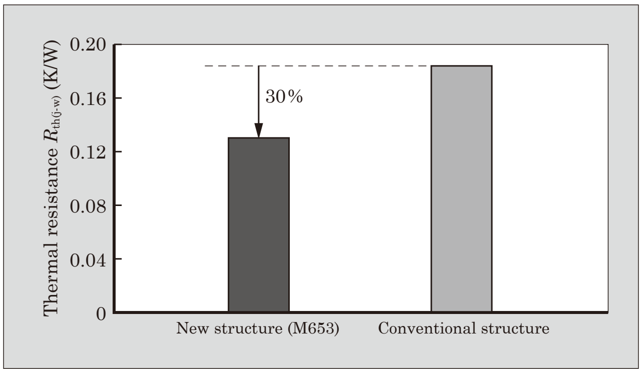

Fig.4 Thermal resistance

sponding to the base has been reduced.

Figure 4 shows the result of comparing thermal resistances. The new structure, which takes the refrigerant and heat transfer into consideration, has achieved a 30% reduction in thermal resistance from the conventional structure.

4. RC-IGBT Application Technology

In the development of 750-V/800-A class power modules for automotive applications, Fuji Electric has developed a 750-V withstand voltage RC-IGBT integrating an IGBT and FWD into one chip. The aim is to meet the requirements for a module size reduction in addition to loss reduction so as to improve the fuel efficiency. RC-IGBTs have been put to practical use as small-capacity chips for consumer electronics. However, as large-capacity chips required for automotive applications, the technological hurdle to overcome before loss can be reduced has been too high(3). This section describes the design technology in RC-IGBT application and the effect of application.

4.1 RC-IGBT design technology

Figure 5 shows the schematic structure of the RC-IGBT. The structure uses a field stop (FS) IGBT as the basis and has the IGBT and FWD regions alternately laid out in stripes. Accordingly, integrating 2 chips into one makes it possible to reduce the invalid region (region called a guard ring for ensuring withstand voltage around the chip) to achieve a size reduction(4). The heat generated during IGBT operation is dissipated also from the FWD section and vice versa. This has

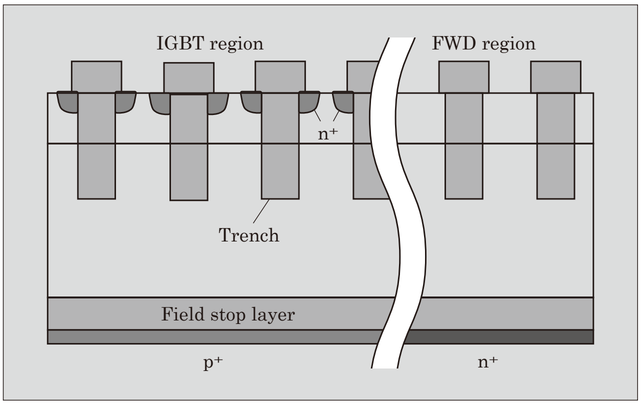

Fig.5 Schematic structure of RC-IGBT

the effect of reducing thermal resistance.

The current capacity of 750-V/800-A class power modules may vary depending on the motor capacity but they generally operate at the power supply voltage V_{cc} of 400 to 450 V and carrier frequency f_{sw} of 5 to 10 kHz. Figure 6 shows the loss generated during inverter operation when the 750-V withstand voltage RC-IGBT is employed to a power module.

If the switching frequency increases to 10 kHz, the switching losses (P_{on}, P_{off}, P_{rr}) also increase but the steady-state losses of the IGBT and FWD (P_{sat}, P_f) account for a large portion: 40%. In order to reduce the steady-state losses, the collector-emitter saturation voltage, which is a parameter determining the steady-state losses, has been minimized. This has been achieved by elaborating the design of the device surface including the trench pitch of the IGBT region(5). In addition, a thinner chip allows for a greater reduction of the saturation voltage and forward voltage. Accordingly, we have thinned the wafer to the minimum thickness required for 750-V withstand voltage to reduce losses. The collector p-type layer of the IGBT and cathode n-type layer of the FWD have been formed on the back side of the same chip. The switching loss of the IGBT and FWD have a trade-off relationship with the steady-state loss. Therefore, carrier lifetime control has been provided so as to optimize the trade-

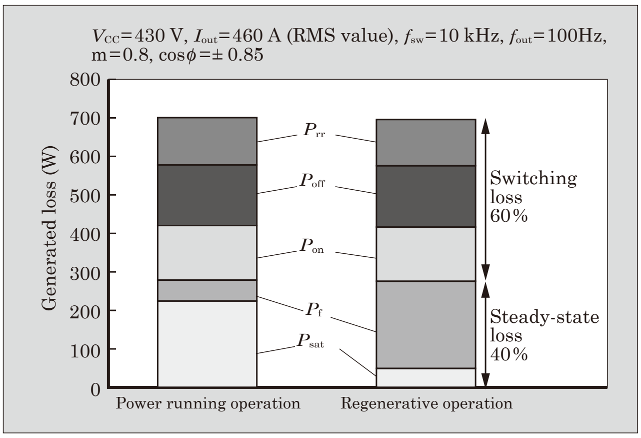

Fig.6 Loss generated during inverter operation

off.

4.2 Improvement of loss of RC-IGBT

This section describes the electrical characteristics of the RC-IGBT based on the same active area as that with the common combination of IGBT and FWD.

(1) IGBT characteristics

Figure 7 shows the saturation voltage output characteristics of the RC-IGBT and a common IGBT. The RC-IGBT realizes a lower saturation voltage than that of a common IGBT by wafer thinning and surface design optimization. In addition, it has been reported that, with RC-IGBTs, conductivity modulation is unlikely to occur in the low saturation voltage region and snapback*1 is observed in the current-saturation voltage curve(6). Accordingly, we have optimized the structures of the IGBT and FWD regions so that it is easier to carry out conductivity modulation and thus suppress snapback.

Figure 8 shows the turn-off characteristics of the RC-IGBT and a common IGBT. The RC-IGBT is shown to offer larger dv/dt at turn-off and a higher carrier emission rate as compared with a common

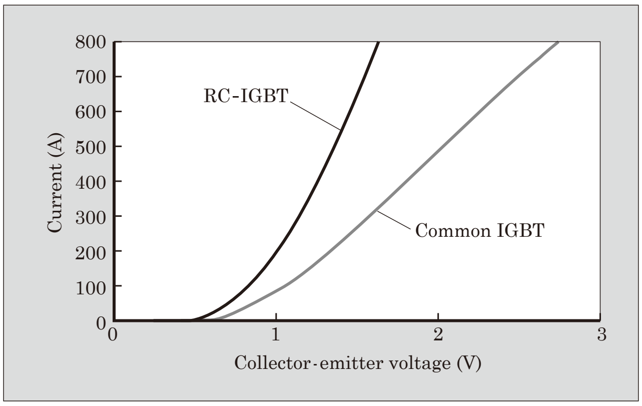

Fig.7 Saturation voltage output characteristics of IGBT

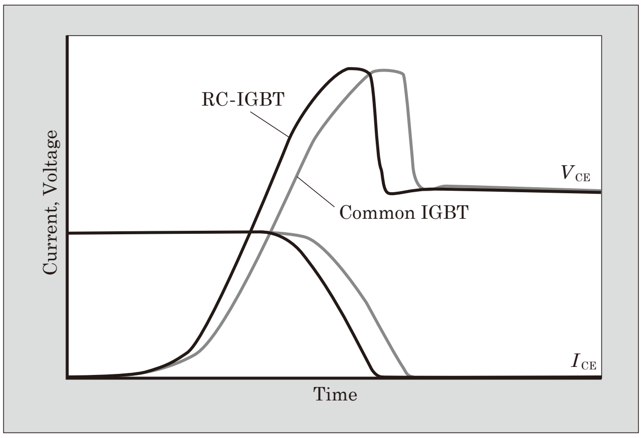

Fig.8 Turn-off characteristics of IGBT

*1: Snapback: Refers to a phenomenon in which the current and saturation voltage increase following a decrease in the process.

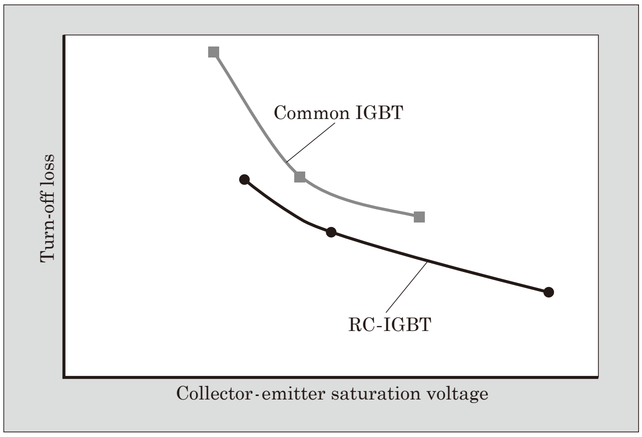

Fig.9 Trade-off characteristics of IGBT

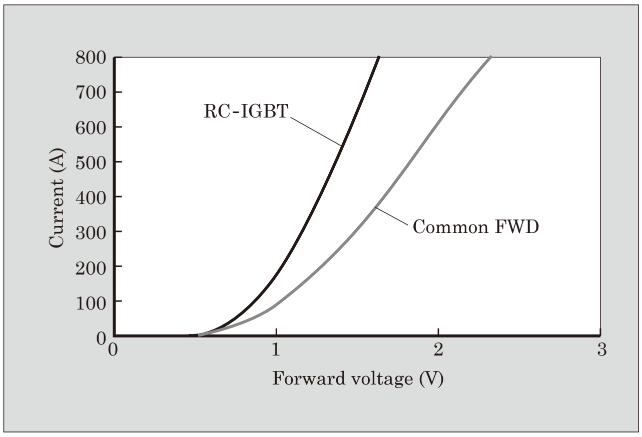

Fig.10 Forward output characteristics

IGBT. This is because the RC-IGBT has the collector short-circuited, in which the p-type layer (IGBT region) and n-type layer (FWD region) are short-circuited on the back side. This causes electrons to be emitted at turn-off not only from the collector p-type layer but also from the cathode n-type layer in the adjacent FWD region. As a result, the RC-IGBT offers a lower turn-off loss than a common IGBT. With the RC-IGBT, the turn-off loss can be reduced as compared with that of a common IGBT even if adjustment is made in the direction to improve the steady-state losses (to reduce the saturation voltage). This has significantly improved the trade-off characteristics (see Fig. 9).

(2) FWD characteristics

Figure 10 shows the forward output characteristics of the RC-IGBT and a common FWD. As with the steady-state losses of the IGBT, with the RC-IGBT, wafer thinning and optimization of the surface structure have led to a reduction in the forward voltage drop from that of a common FWD.

4.3 Heat dissipation performance

The RC-IGBT has the IGBT and FWD integrated to reduce the chip and module areas. In addition, with the RC-IGBT, the heat generated from the FWD re-

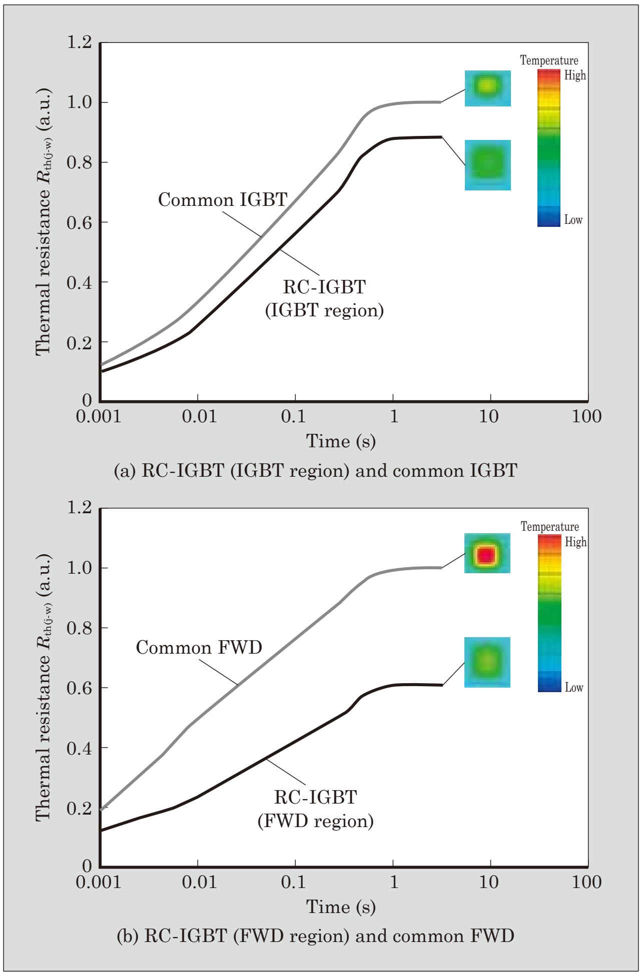

Fig.11 Thermal resistance comparison based on the same active area

gion is released also through the IGBT region. This significantly reduces the thermal resistance from that of a common FWD. We have assumed a module with a direct liquid cooling structure and compared thermal resistance between the RC-IGBT and a common IGBT/FWD based on the same active area (see Fig. 11). With the RC-IGBT, the thermal resistance of the IGBT region is shown to be 12% lower than that of a common IGBT and the thermal resistance of the FWD region 40% lower than that of a common FWD[1].

4.4 Performance achieved

Figure 12 shows the result of calculating the loss generated and temperature during inverter operation for a common IGBT/FWD, an RC-IGBT with the same active area and an RC-IGBT with the area reduced by 30%.

The saturation voltage, forward voltage and turn-off loss have been reduced from those of a common IGBT/FWD. This makes it possible for the RC-IGBT to achieve a reduction in the power loss of over 20% during inverter operation. In addition to loss reduction, the maximum chip temperature can be reduced by about 28 °C thanks to the excellent heat dissipation

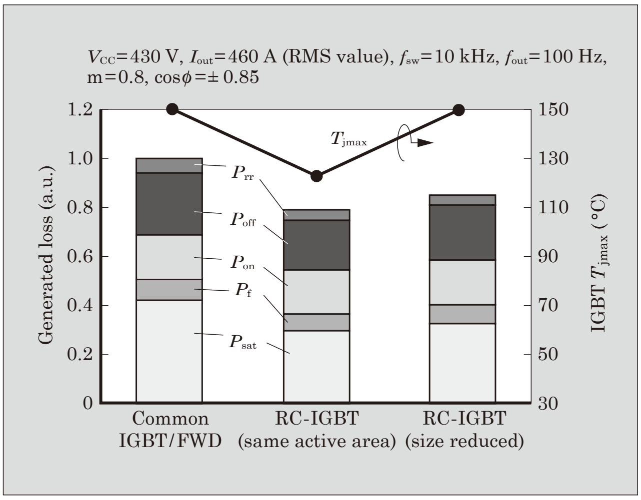

Fig.12 Result of calculating loss generated and temperature during inverter operation

performance. The chip size of a module depends on the maximum temperature during operation. Therefore, this result indicates that, with the RC-IGBT, operation of an inverter with the same rating can be achieved with a smaller chip size than a common IGBT/FWD. The RC-IGBT with the area reduced by 30% offers about the same temperature as that of a common IGBT/FWD and the module area can be reduced by 15%.

5. Postscript

This paper has described the 3rd-generation direct liquid cooling power module for automotive applications. The high heat dissipation performance and continuous operation at 175 °C have been achieved. Moreover, by applying an RC-IGBT, the volume per current capacity has been successfully reduced by 40% from that of the previous product.

In the future, we intend to implement further technological innovations to develop compact, low-loss products.

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