RC-IGBT Module with New Compact Package for Industrial Use

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ABSTRACT

Fuji Electric has developed an reverse conducting IGBT (RC-IGBT) for industrial use and it integrates an IGBT and freewheeling diode (FWD). We have combined it with a new package that achieves both low thermal resistance and high reliability to successfully realize a significant miniaturization of the IGBT module and power density improvement. The RC-IGBT has reduced power loss to a level equivalent to that of the conventional IGBT+FWD and achieved a reduction in thermal resistance of 30%. The new module, combining the RC-IGBT and new package, which has a footprint 42% that of the conventional module, realizes an almost equivalent inverter loss and a significant reduction in the IGBT junction temperature. A comparison based on the same IGBT junction temperature shows that it operates with a 58% larger output current.

1. Introduction

Recently, from the perspective of preventing exhaustion of fossil fuel and global warming, improvement of energy efficiency and reduction of CO_2 have been called for. As one important item for that purpose, demand for inverters is increasing. As power semiconductors for inverter use, insulated-gate bipolar transistor (IGBT) modules are widely applied in the industrial, consumer, automobile and renewable energy fields.

Ever since their commercialization in 1988, Fuji Electric's IGBT modules have achieved significant miniaturization by many technological innovations and contributed to miniaturization and cost reduction of inverters. However, while the size of IGBT module becomes smaller, the power density and operating temperature of IGBT module are increasing. These trends have negative effects on the reliability and lifetime of IGBT module. To realize a compact module with high reliability, technological innovations of IGBT chips and packages are necessary.

In order to enable compact IGBT module with high reliability, Fuji Electric has developed a reverse-conducting IGBT (RC-IGBT[(1)–(4)]) for industrial use, which integrates IGBT and free wheeling diode (FWD), and combined it with a new package[(5)–(8)] that has achieved both low thermal resistance and high reliability.

2. Characteristics of RC-IGBT and New Package

2.1 Characteristics of RC- IGBT

(1) Parts count reduction and miniaturization of IGBT module

Figure 1(a) shows a half-bridge inverter circuit, which is the main circuit of a pulse-width modulation (PWM)-controlled inverter. The conventional IGBT is a switching device that can conduct a current only in the direction from the collector to the emitter; therefore an FWD is required for conducting the reverse current. The RC-IGBT developed is an IGBT device

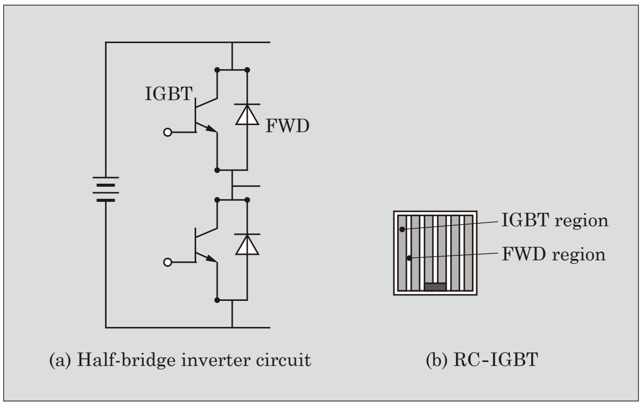

Fig.1 Half-bridge inverter circuit and RC-IGBT

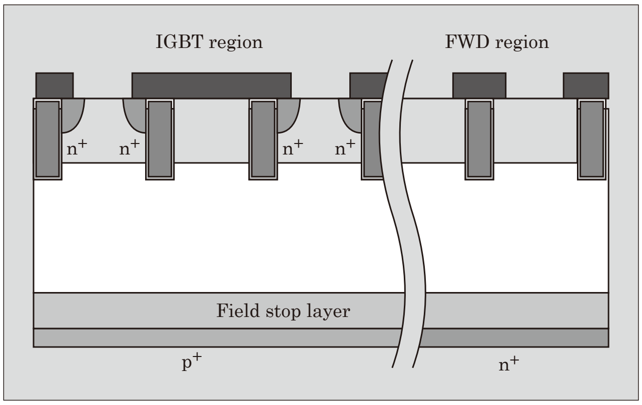

Fig.2 Cross-sectional view of RC-IGBT

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capable of running the current in the reverse direction by integrating FWD as shown in Fig. 1(b) and allows reduction in the parts count of the applied circuit and miniaturization of the equipment.

As shown in Fig. 2, an RC-IGBT is a trench gate thin wafer IGBT based on the 6th-generation IGBT "V Series," which is Fuji Electric's latest product line. The manufacturing process is almost the same as that of the conventional IGBTs, and includes the process for forming the p-layer/n-layer on the back side and lifetime control process.

(2) Output characteristics and switching waveforms

Figure 3 shows output characteristics of the RC-IGBT. The RC-IGBT is capable of outputting current in the forward direction (IGBT) and reverse direction (FWD) with one chip. Three RC-IGBTs with different lifetime control amounts have been prepared as A, B and C to compare the output characteristics. A, with the smallest control amount, shows the smallest electric resistance for both the IGBT and FWD operation.

RC-IGBT turn-off waveforms are shown in Fig. 4, turn-on waveforms in Fig. 5 and reverse recovery waveforms in Fig. 6. While IGBT and FWD have conventionally been used as the switching element and reverse conducting element respectively, with an RC-IGBT, the RC-IGBT alone is responsible for switching for both the switching and reverse conducting elements. The switching waveforms of the RC-IGBT (B) are almost the same as those of the conventional IGBT + FWD and combination of RC-IGBTs allows switching operation similar to that of the conventional device. In addition, C with the largest lifetime control amount shows the smallest IGBT tail current at turn-off and FWD reverse recovery current at reverse recovery. The IGBT loss trade-off of RC-IGBT is shown in Fig. 7 and FWD loss trade-off in Fig. 8. RC-IGBT has similar loss trade-off characteristics to those of the conventional IGBT and FWD and the lifetime control amount can be used to adjust the trade-off from A with low con-

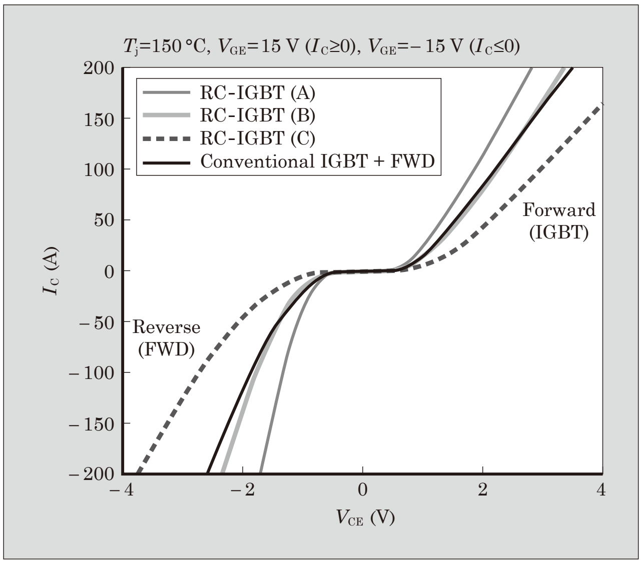

Fig.3 Output characteristics of RC-IGBT

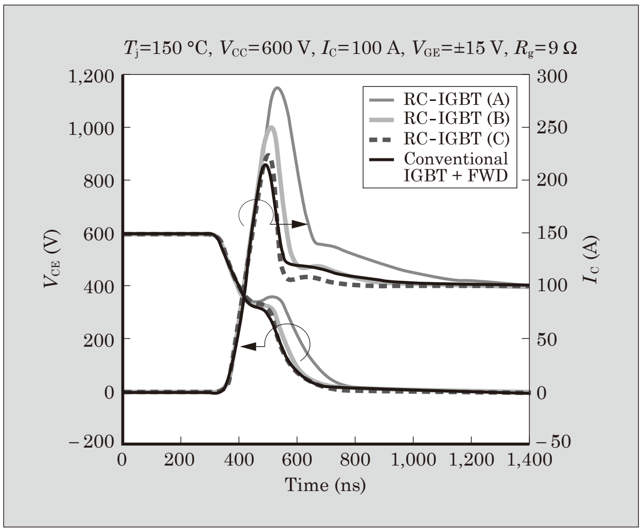

Fig.5 Turn-on waveforms of RC-IGBT

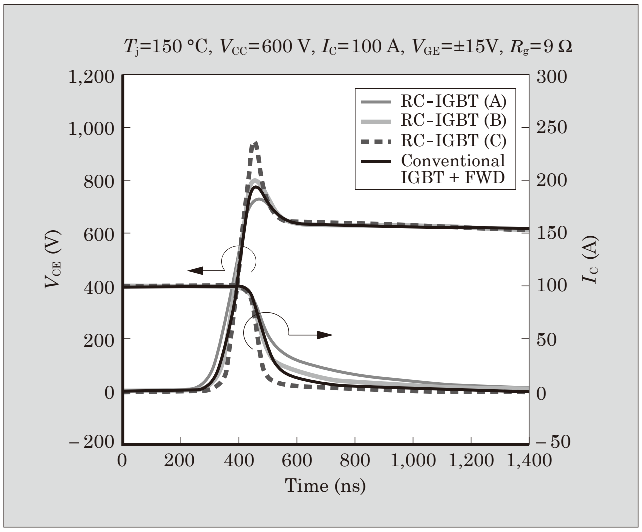

Fig.4 Turn-off waveforms of RC-IGBT

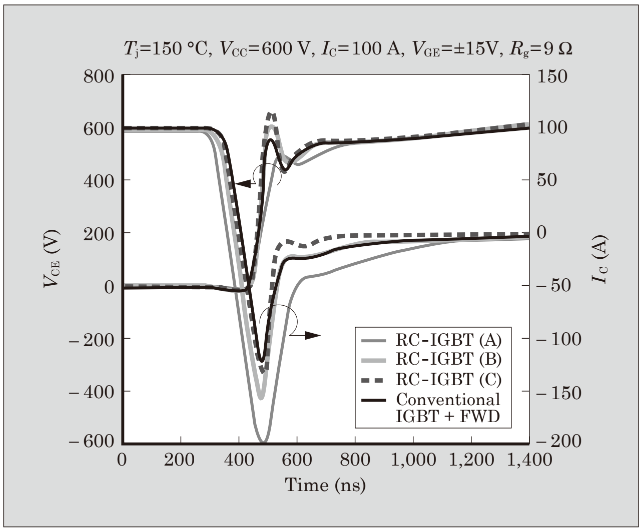

Fig.6 Reverse recovery waveforms of RC-IGBT

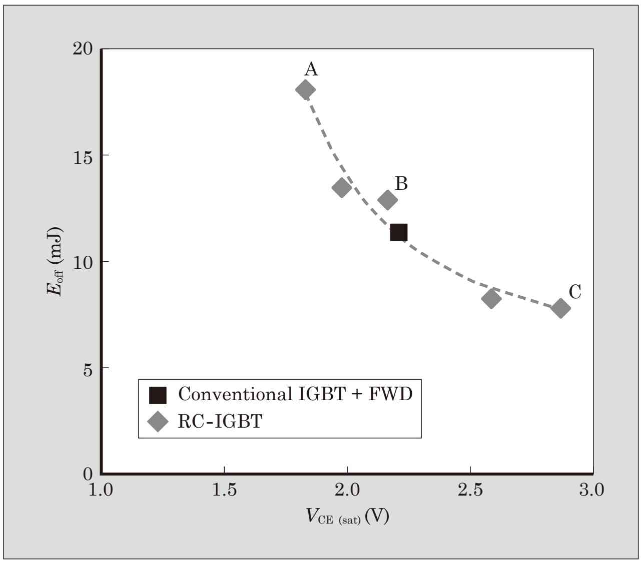

Fig.7 IGBT loss trade-off of RC-IGBT

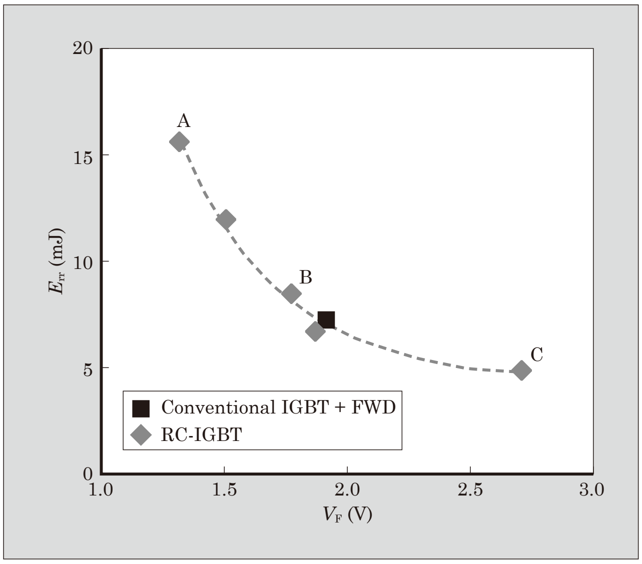

Fig.8 FWD loss trade-off of RC-IGBT

Table 1 Chip area and thermal resistance of RC-IGBT

Chip	Conventional IGBT + FWD	RC-IGBT
Rating	1,200 V 100 A	1,200 V
Active area (a.u.)	IGBT: 0.64, FWD: 0.36 (Total: 1.00)	1.00
Chip area (a.u.)	IGBT: 0.62, FWD: 0.38 (Total: 1.00)	0.91
Thermal resistance $R_{th(j-c)}$ (K/W)	IGBT: 0.24, FWD: 0.36	IGBT: 0.17, FWD: 0.18

ducting loss to C with low switching loss.

(3) Reduction of thermal resistance $R_{th(j-c)}$

Table 1 shows the chip area and thermal resistance $R_{th(j-c)}$ of the RC-IGBT. Even though the active area is the same, the chip size of the RC-IGBT is 9.4% smaller compared to the 6th-generation IGBT chip size and the 6th-generation FWD chip size. This is a result of the fact that the conventional IGBT and FWD need two edge regions for IGBT and FWD, where the RC-IGBT needs only one edge region. In addition, as shown in Fig. 1, the RC-IGBT has the IGBT and FWD regions arranged in stripes, which have short intervals of approximately a few hundred μm, and heat is radiated from the entire chip including the FWD regions during IGBT operation. That is, the heat radiation area is larger than the conventional separate IGBT and FWD chips and $R_{th(j-c)}$ has been reduced by 30% during IGBT operation and 59% during FWD operation.

2.2 Characteristics of new package

(1) Footprint reduction

Figure 9 shows a cross-sectional view of the new package. Conventionally, wiring between the chip and respective terminals was achieved by wire bonding and copper pattern on the direct copper bonding (DCB) substrate (insulation substrate). With the new package, copper pins instead of wire bonding and the power substrate arranged above the chip instead of the copper pattern wiring on the DCB substrate provide wiring between the chip and respective terminals. This makes it possible to reduce the wire bonding area and copper pattern area, which has led to the realization of a footprint reduction of as much as 58%, as shown in Fig. 10.

(2) Reduction of thermal resistance $R_{th(j-c)}$

As the insulation of the DCB substrate, the new package uses Si_3N_4, which has higher thermal conductivity than the conventional Al_2O_3, and our new structure uses a thick copper block on both sides of the DCB substrate to diffuse heat in the lateral direction, thereby increasing the effective heat radiation area. This has successively reduced $R_{th(j-c)}$ by 55% in a comparison on the same chip area.

(3) Improvement of power cycling lifetime

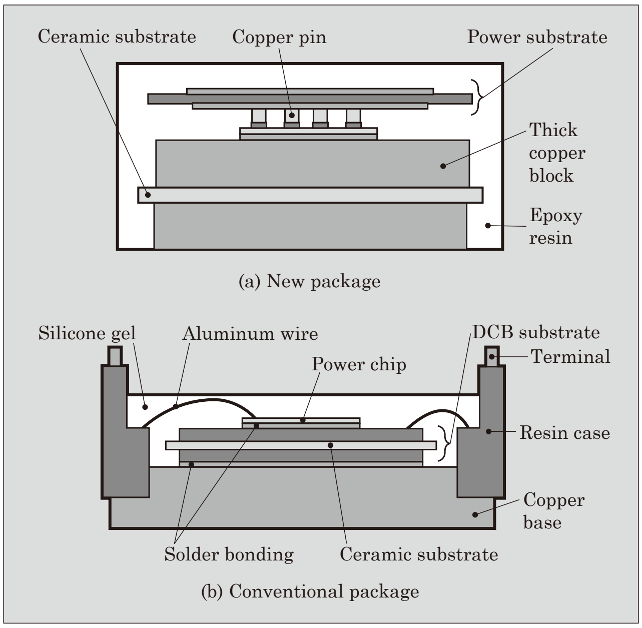

Fig.9 Cross-sectional view of new package

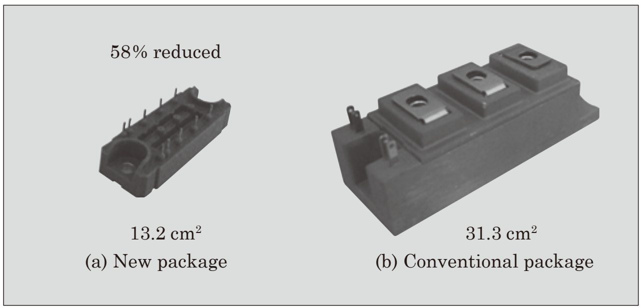

Fig.10 Footprint of new package (1,200 V/100 A)

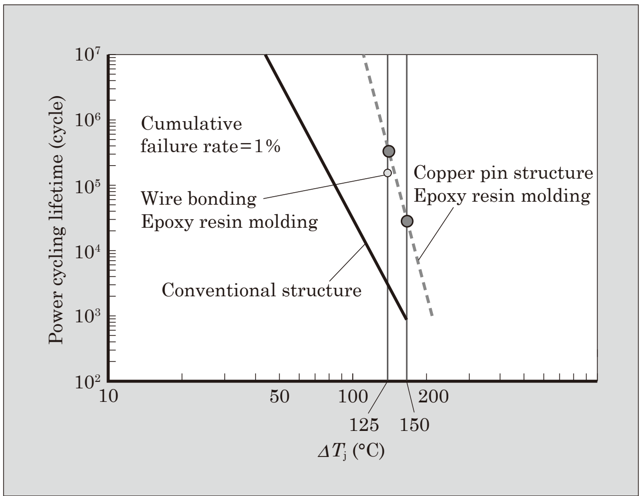

Fig.11 Power cycling lifetime of new package

Power cycling lifetime is restricted by breakage of the bonding contacts and the solder layer between the chip and DCB substrate due to thermal stress, which is caused by heat cycling. With the new package, the drawback of bonding contacts has been eliminated by replacing wire bonding, which was used for conventional packages, with a copper pin structure. In addition, epoxy resin molding has been used in place of the conventional gel molding to firmly secure the copper pins, chip and DCB substrate as a whole. This mitigates the heat stress (strain) on the solder layer and, as shown in Fig. 11, the power cycling lifetime has been improved by more than 20 times in a comparison at $\Delta T_j = 150\,°C$.

3. Inverter Loss and IGBT Junction Temperature

To compare the performance between the conventional IGBT + FWD and RC-IGBT and between the conventional and new packages, we have made a comparison of the inverter loss and IGBT junction temperature T_j (see Fig. 12).

With a combination of the RC-IGBT and conventional package, the inverter loss of the RC-IGBT is lower by 3% from the conventional module and T_j is reduced by 5 °C. The RC-IGBT features heat radiation from the entire chip including the FWD regions, which offers a larger heat radiation area, and $R_{th(j\text{-}c)}$ is 30% lower than the conventional IGBT, allowing T_j to be reduced. In the same active area, the RC-IGBT offers lower T_j than that of the conventional module and the chip area can be made smaller by that much.

The RC-IGBT with the chip area reduced by 26% achieves an inverter loss and T_j equivalent to those of the conventional module. That is, as compared with

Package	Conventional package			New package
Chip	Conventional IGBT + FWD	RC-IGBT	RC-IGBT (downsized)	
Module footprint (cm^2)	31.3			13.2
Chip area (a.u.)	IGBT: 0.62, FWD: 0.38 (Total: 1.00)	0.90	0.74	
Thermal resistance $R_{th(j\text{-}c)}$ (K/W)	IGBT: 0.24, FWD: 0.36	IGBT: 0.17, FWD: 0.18	IGBT: 0.21, FWD: 0.22	IGBT: 0.10, FWD: 0.10

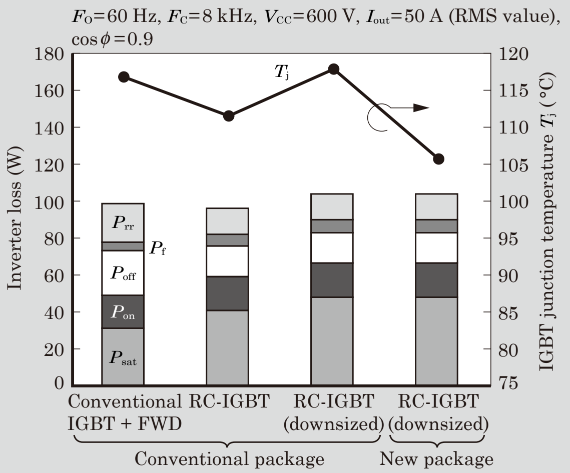

Fig.12 RC-IGBT inverter loss and IGBT junction temperature calculation results

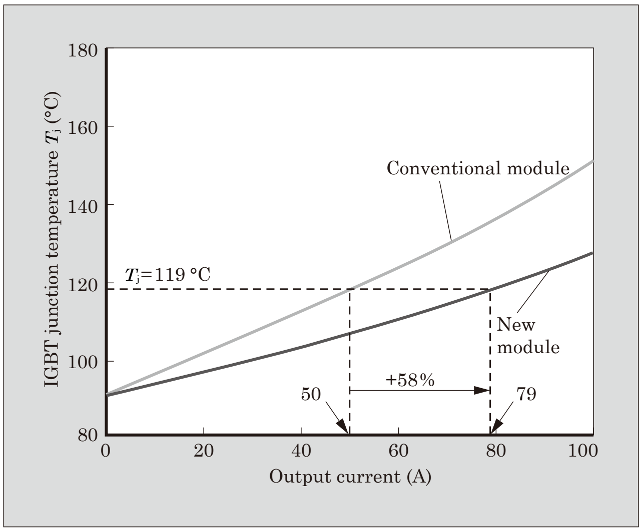

Fig.13 T_j of new module

the conventional IGBT + FWD, the RC-IGBT allows a 26% chip area reduction in the same package and IGBT module miniaturization contributes to the miniaturization of the entire inverter device.

Lastly, we have discussed a new module combining the new RC-IGBT and the new package. The combination of the new RC-IGBT and the new package has successfully reduced $R_{th(j-c)}$ of the IGBT by 62%. In this way, the IGBT junction temperature of the new module has been lowered by 11 °C while the inverter loss remains equivalent to that of the conventional module. The relationship between the output current and IGBT junction temperature of the new and conventional modules is shown in Fig. 13. In the case of T_j=119 °C, as compared with I_{out}=50 A (RMS value) of the conventional module, the new module can conducts I_{out}=79 A (RMS value), a 58% increase in the output current.

4. Postscript

In this paper, we have described a newly developed RC-IGBT integrating diode functions and a newly developed compact package with low thermal resistance and high reliability. These innovations make significant contributions to miniaturization and cost reduction of inverters. In the future, we will continue to work on technological innovations of IGBT chips and packages in order to help realization of an energy-saving society.

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