Speed Enhancement for the 3rd-Generation Direct Liquid Cooling Power Modules for Automotive Applications with RC-IGBT

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ABSTRACT

Fuji Electric has employed a thin reverse-conducting IGBT (RC-IGBT) in the development of a 3rd-generation direct liquid cooling module for automotive applications that is characterized by its high-speed packaging structure. By utilizing an RC-IGBT that integrates an IGBT and FWD on a single chip, the module achieves faster switching at turn-on and turn-off. In addition, parasitic inductance has been decreased by 50% compared with conventional packages through use of the RC-IGBT and internal layout optimization. Furthermore, superimposed surge voltage has been reduced by adopting a packaging structure that equips all 3 phases with a PN terminal pair. These technologies have enabled the 3rd-generation module to reduce switching loss by 30% compared with 2nd-generation modules.

1. Introduction

As the control of CO_2 emissions becomes tighter in order to prevent global warming, hybrid electric vehicles (HEVs), which use both engines and motors, and electric vehicles (EVs), which are propelled only by motors, have been commercialized. Their development is still vigorously in progress and their further proliferation is anticipated. Inverters are used for the power control of HEVs and EVs, and they need to be made smaller so that they can be installed in the limited on-board space while also being given a greater power density so that they can accommodate the high output of batteries and motors.

Figure 1 shows the power density trends of Fuji Electric's insulated gate bipolar transistor (IGBT) modules. The power density of the 7th-generation modules, or the latest generation of IGBT modules for industrial use, is around 300 kVA/L. In comparison, the power density of the 3rd-generation modules, which is the latest generation of automotive IGBT modules, is 800 kVA/L, or approximately 2.5 times higher.

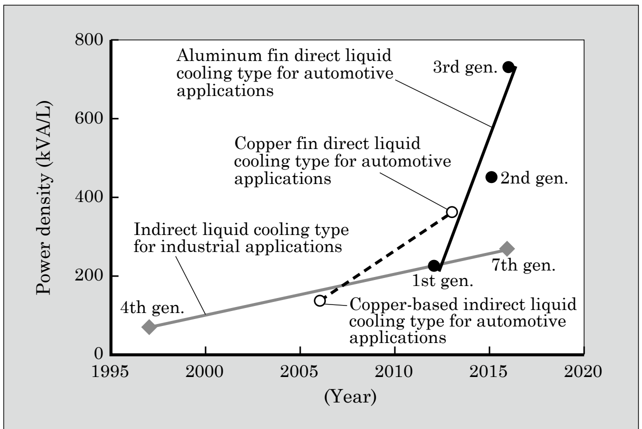

Fig.1 Power density trends of IGBT modules

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In order to meet the need for a greater power density, Fuji Electric has developed the 7th-generation reverse-conducting IGBT (RC-IGBT), which integrates an IGBT thinned by applying the latest wafer thinning technology and free wheeling diode (FWD) into one chip[(1)(2)]. When operating an inverter, switching loss as well as steady-state loss must be reduced so as to decrease the generated loss.

This paper describes the thinned RC-IGBT technology and a packaging structure in which the switching loss has been reduced by enhancing the speed. They are intended to be used to reduce the loss of the 3rd-generation direct liquid cooling power module for automotive applications (3rd-generation automotive module).

2. Low-Inductance Package Design

2.1 Features of RC-IGBT in inductance reduction

Figure 2 shows a schematic structure of an RC-IGBT. The RC-IGBT for HEVs is based on a field stop (FS) RC-IGBT, which is mass-produced, and has

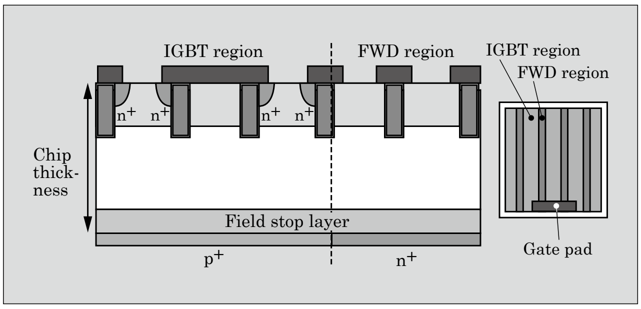


Fig.2 Schematic structure of RC-IGBT

the IGBT and FWD regions formed in stripes. The latest wafer thinning technology has been used to reduce power loss, and the surface structure including the trench intervals, channel density and contact has been optimized to improve the performance of the RC-IGBT. Figure 3 shows the output characteristics of the 7th-generation RC-IGBT and the conventional 6th-generation IGBT and FWD based on the same current density. By using the wafer thinning technology and optimizing the surface structure, $V_{CE(sat)}$ and V_F have been dramatically reduced as compared with the conventional combination of the 6th-generation IGBT and FWD.

With the RC-IGBT, the IGBT and FWD are integrated into one chip, and this makes it possible to reduce the size of the package. The 7th-generation RC-IGBT can achieve the same output power as that of the conventional chip but with a size that is equivalent to 70% of the conventional product. Figure 4 shows the board layout of the RC-IGBT and a common conventional half-bridge circuit. With the RC-IGBT, the board area can be decreased to 75% of that of a conventional IGBT module composed of an IGBT and FWD and the length of the current pathway from the P- to the N-terminal can be reduced to 78%.

The parasitic inductance of an IGBT module depends on the width of the current pathway from the P- to the N-terminal and the distance between the P- and N-terminals. Constituting an IGBT module with an IGBT and FWD sets a limit to the length of the current pathway. For that reason, in order to reduce the parasitic inductance, parallel connections, which allow the current pathway width to be larger, and a laminated bus bar, which allows the distance between the P- and N-terminals to be shorter, are often applied. However, these measures tend to cause the package size to increase[(3)-(6)]. The RC-IGBT features a shorter current pathway and the parasitic inductance can be dramatically reduced while the package can be miniaturized as well.

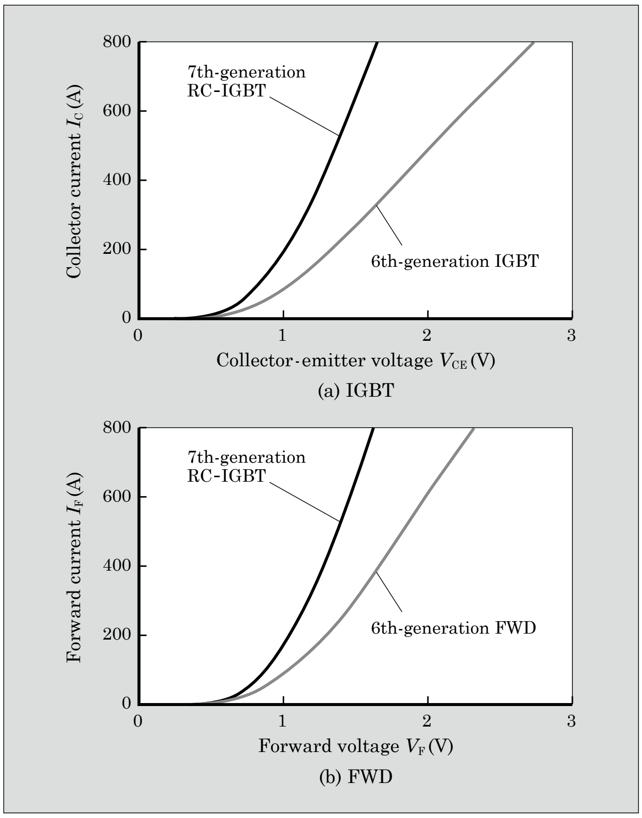


Fig.3 Output characteristics of RC-IGBT and conventional IGBT + FWD

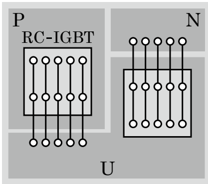
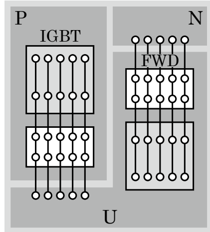
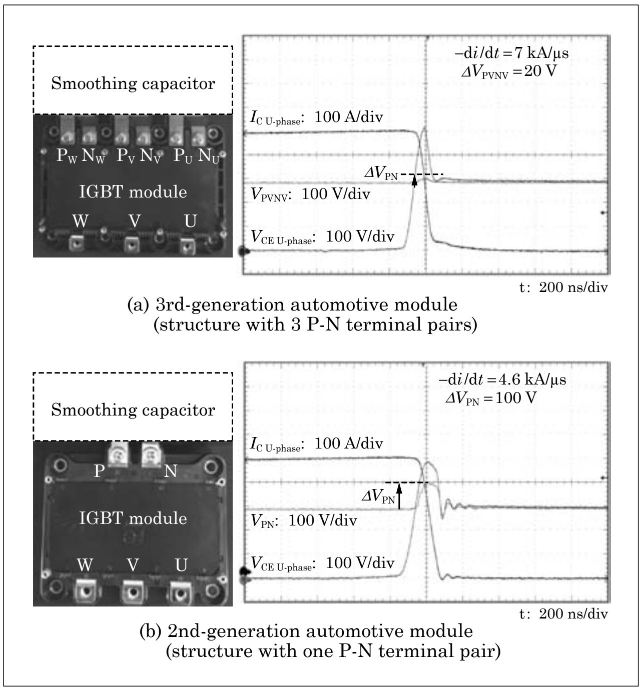
Item	7th-generation RC-IGBT	6th-generation IGBT + FWD
Board layout		
Board size ratio	0.75	1
Ratio of current pathway between P and N	0.78	1

Fig.4 Comparison between RC-IGBT and conventional board layouts

2.2 Package design for reduction of superimposed surge voltage

As is well known, reducing the inductance of a package causes the surge voltage at turn-off and reverse recovery to decrease. The parasitic inductance of the 3rd-generation automotive module (6MBI800XV-075V) has been decreased by applying the 7th-generation RC-IGBT and optimizing the internal layout to around a half of that of the 2nd-generation automotive module (6MBI600VW-065V[(7)]), which employs a 6th-generation IGBT and FWD. However, it is important to not only reduce the parasitic inductance but also the superimposed surge voltage in inverter operation. The surge voltage of a 3-phase inverter is generated across the P- and N-terminals of the module at turn-off with the smoothing capacitor connected with the module. If turn-off occurs between the U-phase and another phase (V-phase), for example, the surge voltage generated across the P- and N-terminals is superimposed.

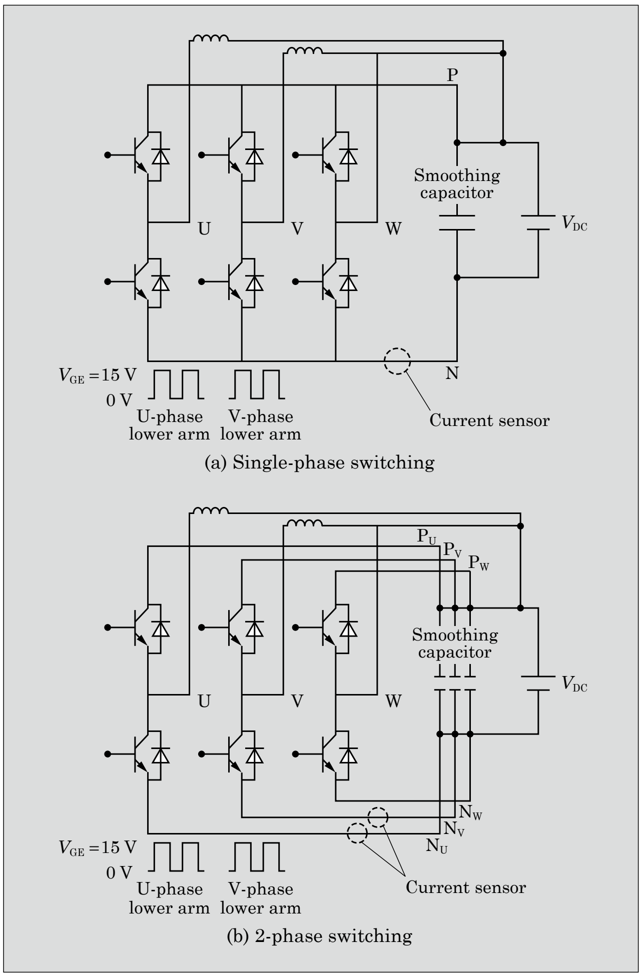
Figure 5 shows the surge voltage across the P- and N-terminals for the respective generations. In automotive inverters, a smoothing capacitor is used by connecting it in series. With the package of the 3rd-generation automotive module, while the switching speed ($-di/dt$) is 1.5 times higher, the surge voltage across the P- and N-terminals has been dramatically reduced. The surge voltage can be easily superimposed when the P- and N-terminals are common to the individual phases as in the package of the 2nd-generation



(a) 3rd-generation automotive module (structure with 3 P-N terminal pairs)

(b) 2nd-generation automotive module (structure with one P-N terminal pair)

Fig.5 Surge voltage across P- and N-terminals for respective generations



(a) Single-phase switching

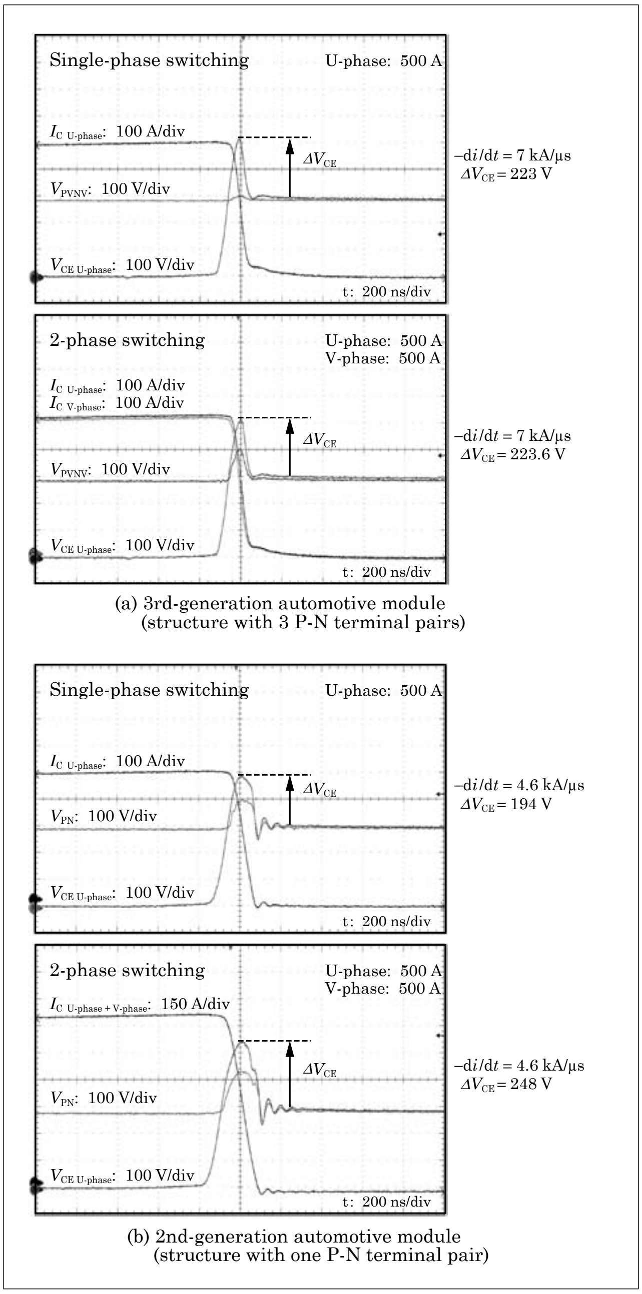
(b) 2-phase switching

Fig.6 Equivalent circuit of superimposed surge voltage measurement

automotive module. Meanwhile, with the package of the 3rd-generation automotive module, the P- and N-terminals of the individual phases are independent, which significantly reduces the surge voltage across the P- and N-terminals.

To evaluate the superimposed surge voltage, we measured the surge voltage in 2-phase switching. Figure 6 shows an equivalent circuit of superimposed surge voltage measurement in 2-phase switching.

With the 2nd-generation automotive module, the limitations of the packaging structure made it difficult to measure the current for the individual phases. Accordingly, the current was measured for the 2 phases together. Figure 7 shows turn-off waveforms for mod-



(a) 3rd-generation automotive module (structure with 3 P-N terminal pairs)

(b) 2nd-generation automotive module (structure with one P-N terminal pair)

Fig.7 Turn-off waveforms for modules of respective generations ules of the respective generations. The top waveform corresponds to single-phase switching of the U-phase alone and the bottom waveform corresponds to 2-phase switching with the U- and V-phases. With the 2nd-generation automotive module, the surge voltage in 2-phase switching showed an increase of 54 V as compared with single-phase switching. The 3rd-generation automotive module, on the other hand, showed little difference between single-phase and 2-phase switching. In addition, while the switching speed ($-\mathrm{d}i/\mathrm{d}t$) was 1.5 times higher, the surge voltage with the 3rd-generation automotive module was lower than that of the 2nd-generation automotive module. This result indicates that the 3rd-generation module allows an increase in switching speed of more than 1.5 times from the 2nd-generation automotive module with the same battery voltage and device withstand voltage conditions. Superimposed surge voltage is also generated at reverse recovery. Accordingly, with the 3rd-generation automotive module, the switching speed at turn-on can be increased as well.

3. Loss Characteristics of Module Applying RC-IGBT

Figure 8 shows the results of calculating the power loss for modules of the respective generations. It shows a comparison between the power loss of the 2nd-generation automotive module and that of the 3rd-generation automotive module combining RC-IGBT with a package having a structure with 3 pairs of P- and N-terminals. The comparison assumes inverter operation under the conditions of V_{cc}=400 V, output current (RMS value)=400 A and switching frequency f_c=10 kHz. Turn-on $\mathrm{d}i/\mathrm{d}t$ and turn-off $-\mathrm{d}i/\mathrm{d}t$ were set so that the surge voltage including the superimposed surge voltage would be the same. The size of the RC-IGBT is equivalent to 70% of the entire size of the product including the IGBT and FWD. A 30% reduction in the switching loss has been achieved by increasing the switching speed.

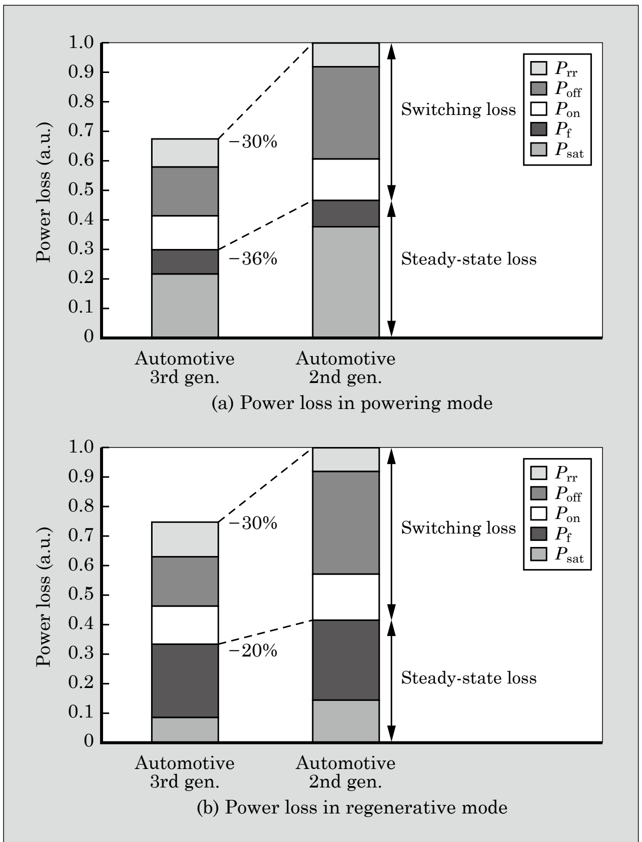


Fig.8 Results of calculation of power loss for modules of respective generations

4. Postscript

This paper has described speed enhancement for the 3rd-generation direct liquid cooling power module for automotive applications that uses RC-IGBT.

To make the reverse recovery characteristic gentler, the 7th-generation RC-IGBT has optimized the surface structure and the field stop (FS) layer. By utilizing the RC-IGBT, faster switching at turn-on and turn-off has been achieved. In addition, parasitic inductance of the 3rd-generation direct liquid cooling power module for automotive applications has been decreased by 50% compared with conventional packages. This has been achieved by using the RC-IGBT and optimizing the internal layout. Furthermore, superimposed surge voltage has been reduced by adopting a packaging structure that equips all 3 phases with a P-N terminal pair.

These technologies have allowed the 3rd-generation direct liquid cooling power module for automotive applications to achieve a 30% reduction in switching loss as compared with the 2nd-generation direct liquid cooling power module for automotive applications. These technologies can be expected to make tremendous contributions to creating HEV and EV inverter systems with higher power density.

In the future, we intend to further improve design technology and work on the development of products that can achieve miniaturization and higher power density.

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