RC-IGBT for Mild Hybrid Electric Vehicles

NOGUCHI, Seiji* ADACHI, Shinichiro ⁑ YOSHIDA, Soichi*

ABSTRACT

Hybrid electric vehicles and electric vehicles are attracting attention as people's environmental awareness is growing. Above all, mild hybrid electric vehicles, in which one motor is responsible for both driving and power generation, is expected to account for a higher proportion of vehicles. To reduce the loss and size of Insulated-gate bipolar transistor (IGBT) modules for mild hybrid electric vehicles, Fuji Electric has developed a reverse-conducting IGBT (RC-IGBT) that has a withstand voltage of 650 V, which integrates an IGBT and freewheeling diode (FWD) into one chip. The RC-IGBT has realized a lower loss and reduced package size that surpass the conventional IGBTs and FWDs.

1. Introduction

As awareness of the need for environmental protection including prevention of global warming is growing around the world, hybrid electric vehicles (HEVs), which use both an engine and a motor for reducing CO_2 emissions, and electric vehicles (EVs), which are totally motor-driven, are becoming popular.

Among HEVs, mild HEVs are attracting particular attention. Mild HEVs use 1 motor for both driving and power generation. As compared with full HEVs, which use 2 separate motors for driving and power generation, mild HEVs have a simpler structure and offer less price differences from gasoline-fueled vehicles and are expected to account for a higher proportion of vehicles worldwide in the future.

Fuji Electric is working on the development of an insulated-gate bipolar transistor (IGBT) module to be mounted in inverters for mild HEVs. In order to meet the need for miniaturization as well as loss reduction of the in-vehicle module for improving fuel efficiency, we have developed a reverse-conducting IGBT (RC-IGBT) with a withstand voltage of 650 V that integrates an IGBT and freewheeling diode (FWD) into one chip. RC-IGBTs have already been commercialized as small-capacity chips for consumer electronics. However, as large-capacity chips required for in-vehicle use, technological hurdles for reducing loss have been too difficult to overcome up to now[1]. This paper describes the RC-IGBT for mild HEVs and the effect of its application to the module.

* Electronic Devices Business Group, Fuji Electric Co., Ltd.
⁑ Power Electronics Business Group, Fuji Electric Co., Ltd.

2. RC-IGBT Design

The 650 V withstand voltage RC-IGBT for mild HEVs has been developed based on the field stop (FS) IGBT[2] mass-produced by Fuji Electric, which has alternating IGBT and FWD regions arranged in stripes. Figure 1 shows a schematic structure of the RC-IGBT.

While the current carrying capacity of the IGBT module for mild HEVs depends on the motor capacity, it generally operates in the ranges of 300 to 400 V as the power supply voltage V_{CC} and 5 to 10 kHz as the carrier frequency f_{sw}. Figure 2 shows the loss generated in inverter operation as the RC-IGBT for mild HEVs is applied to the module.

It indicates that, even in an operating condition with a high switching frequency (10 kHz), where the

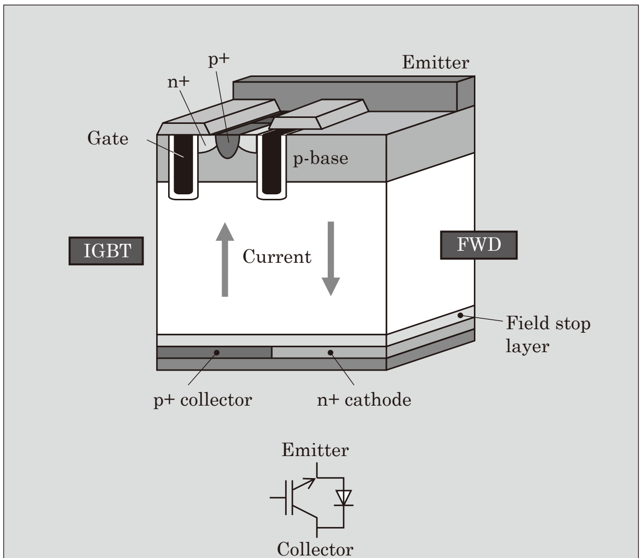

Fig.1 RC-IGBT schematic structure

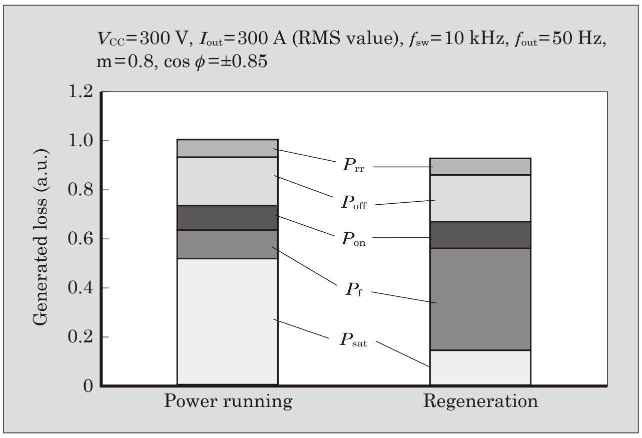

Fig.2 IGBT module generated loss during inverter operation

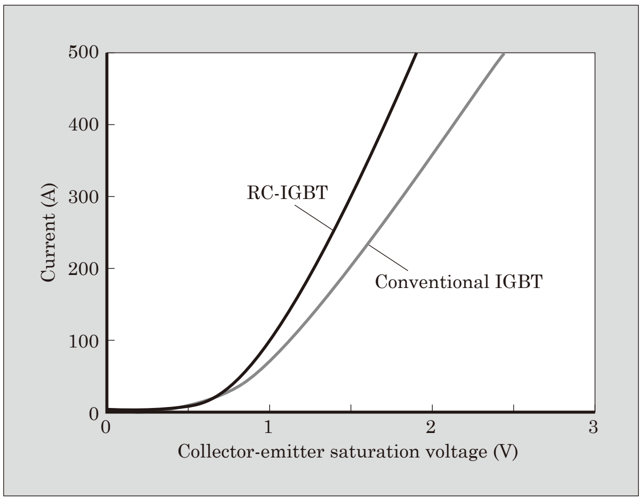

Fig.3 IGBT saturation voltage output characteristics

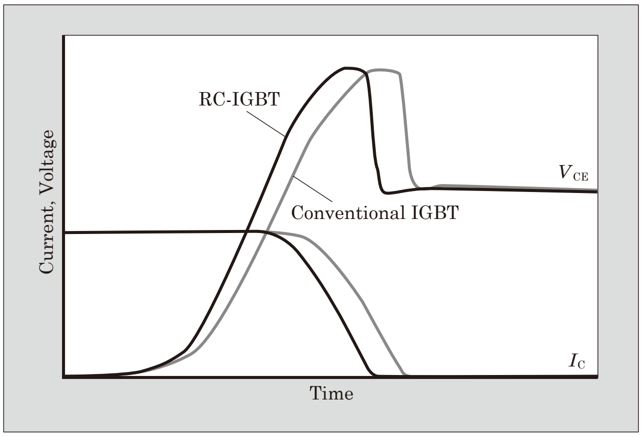

Fig.4 IGBT turn-off characteristics

switching losses (P_{on}, P_{off}, P_{rr}) are high, the steady-state losses of the IGBT and FWD (P_{sat}, P_f) are dominant. By using ingenuity in the design of the device surface, such as the trench pitch of the IGBT regions, for reducing the steady-state losses, the collector-emitter saturation voltage, which is a parameter that determines the steady-state losses, has been minimized[3]. With a thicker chip, the withstand voltage can be ensured more easily and manufacturing is easier but the saturation voltage and forward voltage increase, which worsen the steady-state losses, and a thinner chip is more desirable. Accordingly, Fuji Electric has been actively working on technology for fabricating thinner wafers since the early period.

We have now developed cutting-edge thin wafer processing technology, which has enabled us to make wafers thinner and achieve the thickness necessary and sufficient for a withstand voltage of 650 V, which was conventionally impossible, to realize reduced loss. In addition, we have also developed patterning technology suited for the back side of thin wafers and impurity layer formation technology to successfully form the IGBT collector p-type layer and FWD cathode n-type layer on the back side of one chip. The switching losses of IGBT and FWD have a trade-off relationship with steady-state losses. For that reason, we have performed carrier lifetime control for optimizing the trade-off.

3. Loss Characteristics

3.1 Electrical characteristics

This section presents the electrical characteristics of an RC-IGBT with the same active area as the conventional IGBT and FWD.

(1) IGBT characteristics

Figure 3 shows the saturation voltage output characteristics of the RC-IGBT and the conventional IGBT. The RC-IGBT has achieved a lower saturation voltage than that of the conventional IGBT by wafer thinning and surface structure optimization. In addition, electrons flow into the n-type layer, which is the back side cathode of an FWD region adjacent to an IGBT region, and hole injection from the p-type layer, or the IGBT collector, is suppressed to hinder conductivity modulation. For that reason, in the low saturation voltage region, snapback* has been reported to occur in the current-saturation voltage curve[4]. Occurrence of snapback causes the saturation voltage to increase, which may worsen the losses. To prevent this, we have optimized the structures of the IGBT and FWD regions respectively to facilitate conductivity modulation for suppressing snapback.

Figure 4 shows the turn-off characteristics of the RC-IGBT and the conventional IGBT. It indicates that the RC-IGBT offers larger dv/dt at turn-off than the conventional IGBT and a higher carrier emission rate. This is because the RC-IGBT has the collector p-type layer and cathode n-type layer short-circuited on the back side, which causes electrons to be emitted not only from collector p-type layer but also from the cathode n-type layer on the back side of the adjacent

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

FWD region. This results in a benefit of reduced turn-off loss with the RC-IGBT than the conventional IGBT. With the RC-IGBT, adjustment to the direction that improves steady-state losses (lower saturation voltage) allows reduced turn-off loss compared with that of the conventional IGBT, and this has made a significant improvement in the trade-off characteristics (see Fig. 5).

(2) FWD characteristics

Figure 6 shows the forward output characteristics of the RC-IGBT and conventional FWD. As with the steady-state loss of IGBT, the RC-IGBT has achieved less forward voltage reduction as compared with the conventional FWD by the effect of wafer thinning and surface structure optimization.

Figure 7 shows switching waveforms during RC-IGBT reverse recovery operation. With the RC-IGBT, there was an issue of electrons diffusing into IGBT as well as the FWD regions during FWD steady-state operation and the reverse recovery current I_{rp} becoming larger than the conventional FWD during reverse recovery operation, which made the reverse recovery loss Err larger, but the lifetime control technology has been used to successfully reduce I_{rp}.

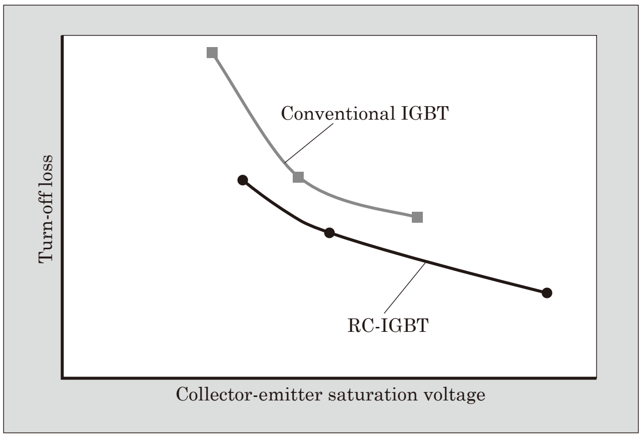

Fig.5 IGBT trade-off characteristics

3.2 Heat radiation characteristics

The RC-IGBT has achieved a reduction in the chip area and module area by integrating the IGBT and FWD. In addition, the RC-IGBT radiates heat from the FWD regions also via the IGBT regions, which makes the thermal resistance significantly lower than that of the conventional FWD. A module with a direct liquid cooling structure has been assumed to compare the thermal resistance between the RC-IGBT and the conventional IGBT and FWD with the same active

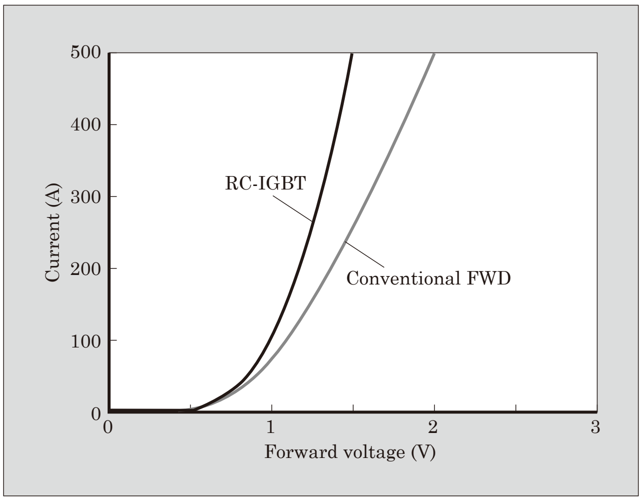

Fig.6 Forward output characteristics

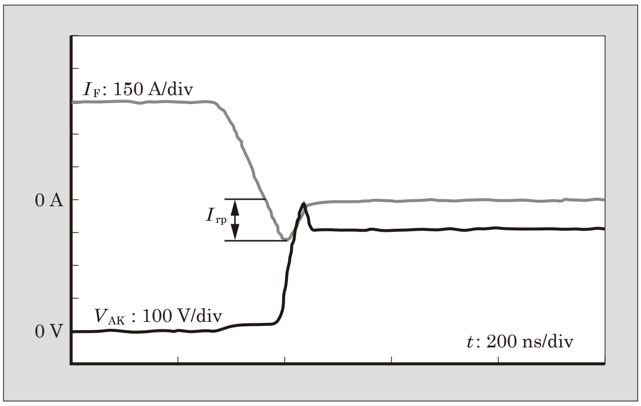

Fig.7 Switching waveforms during RC-IGBT reverse recovery operation

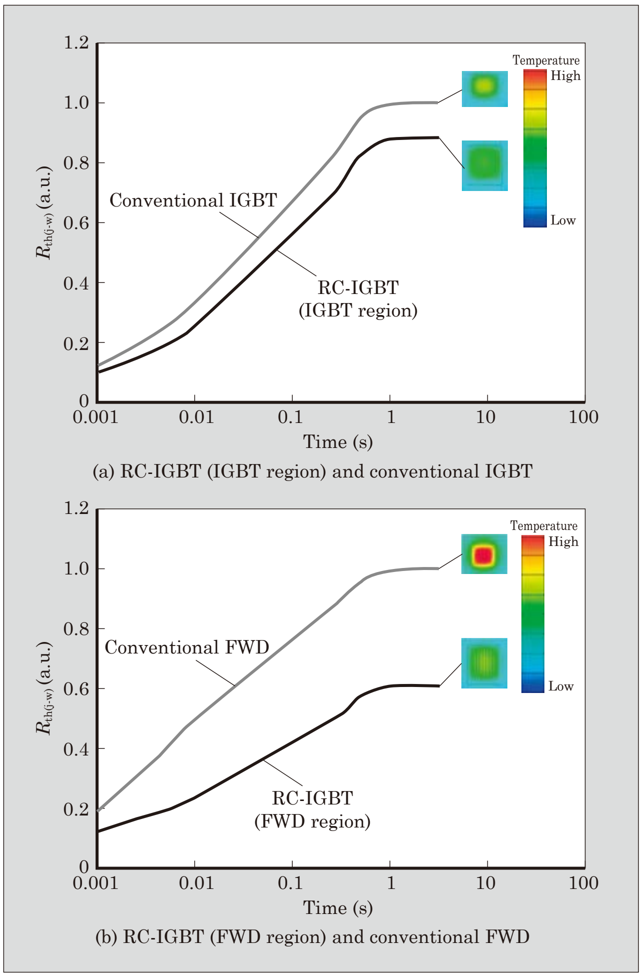

Fig.8 Thermal resistance based on same active area

area (see Fig. 8). The thermal resistance of the IGBT regions of the RC-IGBT is 12% lower than that of the conventional IGBT and the thermal resistance of the FWD regions is 40% lower than the conventional FWD.

4. Effect of Application to Module

This section describes the miniaturization effect of the RC-IGBT as it is applied to the IGBT module for mild HEVs.

Figure 9 shows the results of calculating loss and temperature during inverter operation with the RC-IGBT having the same active area as that of the conventional IGBT and FWD and miniaturized RC-IGBT. Table 1 shows a comparison of the chip active area and module area. As compared with the conventional IGBT, the RC-IGBT is capable of reducing power loss during inverter operation by 10% or more by reducing the saturation voltage, forward voltage and turn-off loss. In addition to reduced loss, the advantage of heat radiation described in Section 3.2 allows the chip's maximum temperature to be lowered by about 14 °C. The chip size of a module depends on the maximum temperature in operation and this result indicates that the RC-IGBT with smaller chip size can operate an inverter of the same rating. The RC-IGBT with the size reduced by 25% shows a temperature equivalent to the conventional IGBT and FWD, which means that the module area can be reduced by 20%.

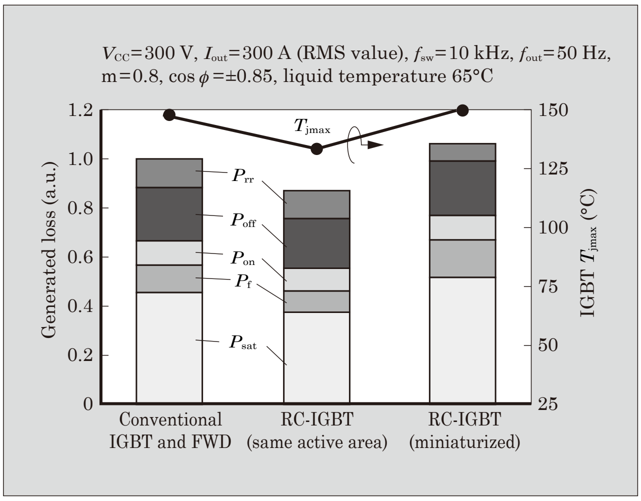

Fig.9 Generated loss of RC-IGBT and conventional IGBT and FWD

Table 1 Chip active area and module area

	Conventional IGBT and FWD	RC-IGBT (miniaturized)
Chip active area (a.u.)	1.00	0.75
Module area (a.u.)	1.00	0.80

5. Postscript

This paper has described the RC-IGBT for mild HEVs and the effect of its application to the module.

From the perspective of responding to environmental issues, HEVs and EVs are expected to continue to significantly evolve in the future. In that process, the importance of miniaturization of in-vehicle devices is estimated to further increase, and RC-IGBT that can realize miniaturization seems to be a very effective means to that end. In the future, we intend to make further contributions to this field by improving devices, developing devices using new materials, etc.

References

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