RC-IGBT for Automotive Applications

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ABSTRACT

The number of hybrid electric vehicles and electric vehicles in use on the road has been increasing as a measure to reduce CO_2 emissions in order to protect the environment from phenomena such as global warming. In order to improve fuel efficiency for these types of vehicles, they need to reduce loss in mounted semiconductor devices, while also decreasing the size of the inverter. To meet these needs, Fuji Electric has been working to develop an RC-IGBT that integrates an IGBT and FWD into one chip. Moreover, we have optimized trench gate spacing, a field stop layer and lifetime control for the RC-IGBT for automotive applications. As a result, the inverter achieves an about 20% reduction in generated loss during the operation compared to using conventional RC-IGBTs for automotive applications.

1. Introduction

There has been an increase in global attention to environmental protection such as preventing global warming. Accompanying this, hybrid electric vehicles (HEVs), which use both an engine and motor to reduce CO_2 emissions, and electric vehicles (EVs), which are driven by a motor only, have been spreading.

There are also demands for automotive semiconductor devices that dissipate less power and smaller inverters to improve the fuel economy of HEVs and EVs. In response to this, Fuji Electric has developed a reverse conducting insulated-gate bipolar transistor (RC-IGBT) that integrates an IGBT and a free wheeling diode (FWD) on a single chip. RC-IGBTs have already been in practical use in small-capacity chips for home appliances. Their practical use in large-capacity chips for automotive applications, however, was difficult because of the high technological hurdle—for making them dissipate less power[1]. Fuji Electric overcame this technological hurdle and developed a low-loss chip using an RC-IGBT for mild hybrid vehicles[2][3].

We improved this RC-IGBT for mild hybrid vehicles (conventional RC-IGBT) and have developed an RC-IGBT for automotive applications that dissipates less power (improved RC-IGBT). This improved RC-IGBT can support various motor drive methods including full hybrid and mild hybrid.

2. Challenges and Measures

Figure 1 shows an schematic structure of an RC-IGBT. The RC-IGBT for an HEV has a structure that uses a field stop (FS) IGBT[4] mass-produced by Fuji Electric as a base. On it, IGBT units and FWD units are arranged alternately in stripes. The sizes of the IGBT units and FWD units are determined so that their characteristics are not negatively affected by mutual interference. Figure 2 shows a constitutive example of the losses generated in the inverter for an HEV. The generated losses are determined by the switching loss generated when a current is turned on/off (P_{on}, P_{off}, P_{rr}) and the steady-state loss of IGBT

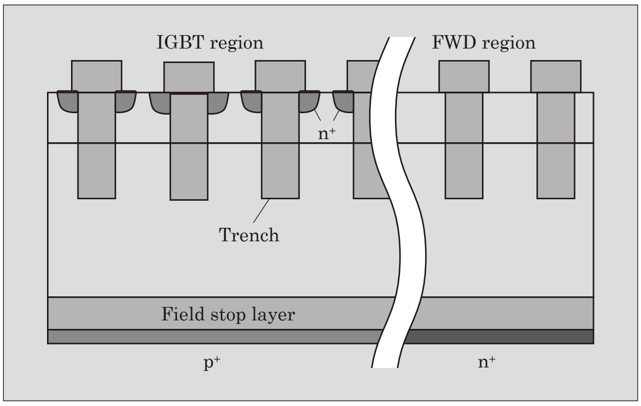

Fig. 1 Schematic structure of an RC-IGBT

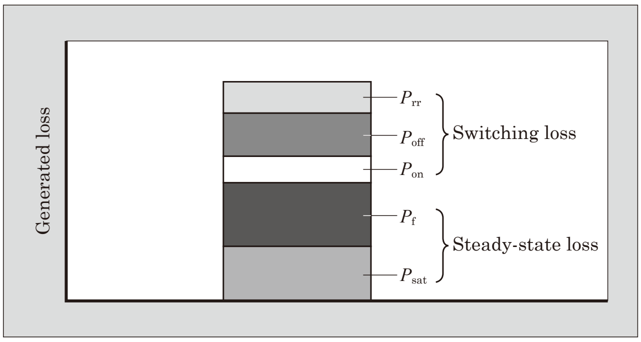

Fig. 2 Example of losses generated in an inverter

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and FWD (P_{sat}, P_f). Improving the fuel economy of HEVs requires a reduction in the steady-state loss. Consequently, we designed an improved RC-IGBT with the main objective of reducing the steady-state loss. When the loss is reduced, we can suppress the heat generated from the device and make the device smaller. As a result, IGBT modules and inverters can be miniaturized. The following describes the improvements made to the RC-IGBT.

(1) Reducing the conduction loss through the use of IE effect

It is known that the conduction loss of an IGBT can be reduced through a phenomenon called as injection enhanced (IE) effect. With this, a small number of carriers (holes for the case of n-channel IGBT) are accumulated in the drift layer and this reduces the saturation voltage $V_{CE(sat)}$. One effective way to enhance the IE effect is to make the spacing of the trench gates formed on the device surface smaller. For the improved RC-IGBT, we made improvements to enhance the IE effect. That is we optimized the trench gate spacing compared with conventional RC-IGBTs.

(2) Reducing the conduction loss by using a thinner wafer

It is desirable to make the chip as thin as possible. Because the thinner the chip is, the more the saturation voltage and forward voltage can be suppressed to reduce the steady-state loss. The thinner the chip is, however, the more often oscillation occurs when IGBT and FWD switch off. Consequently, we could not make the wafer sufficiently thin for the conventional RC-IGBT. But for the improved RC-IGBT, we were able to suppress the oscillation of both IGBT and FWD by optimizing the FS layer. This has led us to make the wafer sufficiently thin and achieve reduction in the conduction loss. The optimization of the FS layer also allowed for a reduction in the collector-emitter leak current I_{CES} at elevated temperatures.

(3) Reducing the conduction loss and switching loss through lifetime control

We added an improvement to optimize lifetime control, and reduce the conduction loss of IGBTs and switching loss of FWDs. This also reduced I_{CES} at elevated temperatures, resulting in better high-temperature characteristics.

3. Loss Characteristics

3.1 Electrical characteristics

RC-IGBT is a device made by integrating an IGBT and an FWD on a single chip. This section describes the IGBT characteristics and FWD characteristics of the RC-IGBTs respectively.

(1) IGBT characteristics

Figure 3 shows the IGBT saturation voltage output characteristics. The saturation voltage of the improved RC-IGBT is lower than that of the conventional RC-IGBT due to the measures described in Chapter 2.

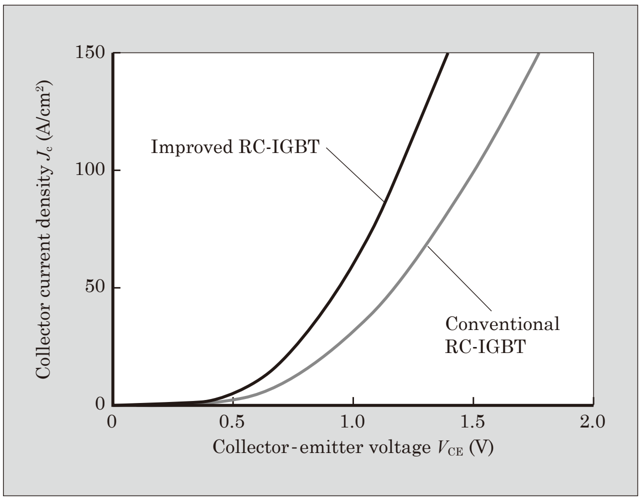

Fig. 3 IGBT Saturation voltage output characteristics

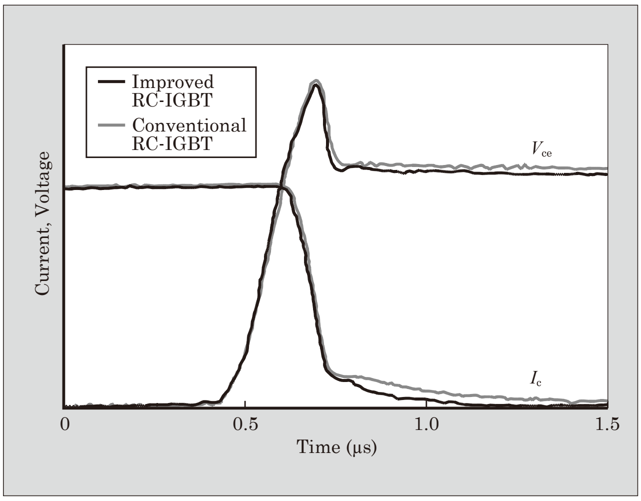

Fig. 4 IGBT turn-off characteristics

Figure 4 shows the IGBT turn-off characteristics. When the waveforms are compared, we notice that the tail current of the improved RC-IGBT at the time of turn-off is smaller and the turn-off time is also shorter than those of the conventional RC-IGBT. This indicates less turn-off loss. This is a result of the reduced saturation voltage and the optimized impurity concentration of the collector at the improved RC-IGBT. The oscillation at turn-off has also been suppressed by optimizing the collector section and FS layer.

As a result, we succeeded in significantly improving the trade-off characteristics of the improved RC-IGBT (see Fig. 5). This was achieved by taking advantage of its ability to maintain a low saturation voltage even when the turn-off loss is reduced. The values of the turn-off loss in the graph have been normalized with the loss of the conventional RC-IGBT being assumed as 1.

Figure 6 shows the I_{CES} characteristics under a high-temperature condition of the case (package) temperature T_C = 150 °C. As a result of optimizing the FS layer and lifetime control, the value of the improved

RC-IGBT has decreased to 30% or less of the conventional RC-IGBT.

(2) FWD characteristics

Figure 7 shows the FWD forward characteristics.

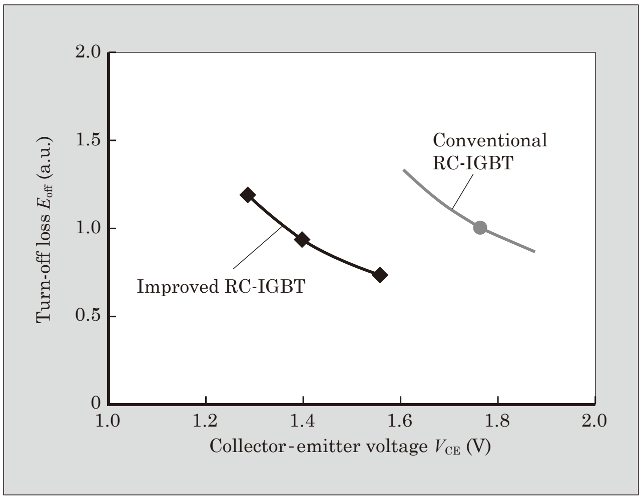

Fig. 5 IGBT trade-off characteristics

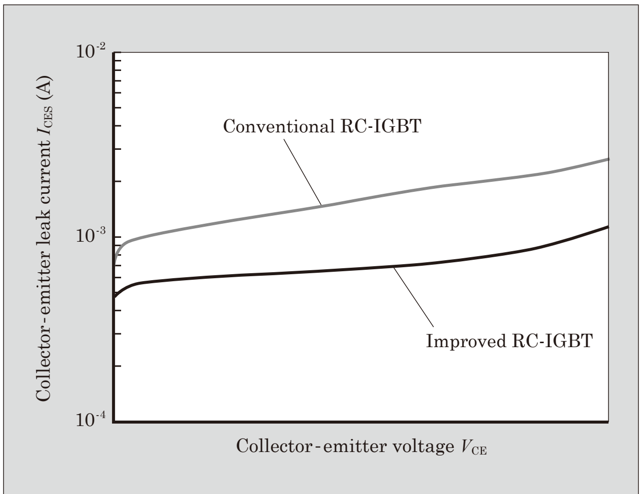

Fig. 6 I_{CES} characteristics (T_c = 150 °C)

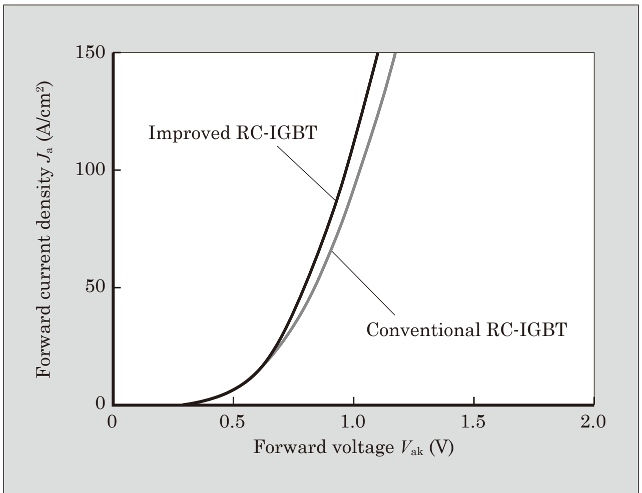

Fig. 7 FWD forward characteristics

The improved RC-IGBT has reduced the drop in the forward voltage compared with the conventional RC-IGBT due to the effect of using a thinner wafer.

Figure 8 shows the switching waveforms during reverse recovery operation. For the improved RC-IGBT, we have optimized the FS layer and lifetime control. This means that even the use of a thinner wafer can provide a soft-recovery characteristics to reduce the re-

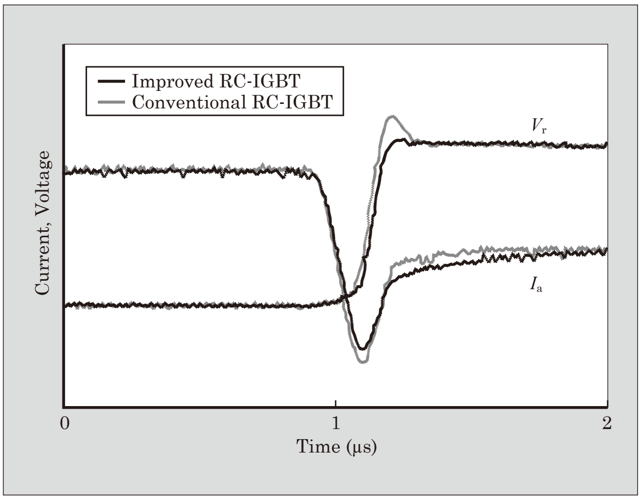

Fig. 8 Switching waveforms during reverse recovery operation

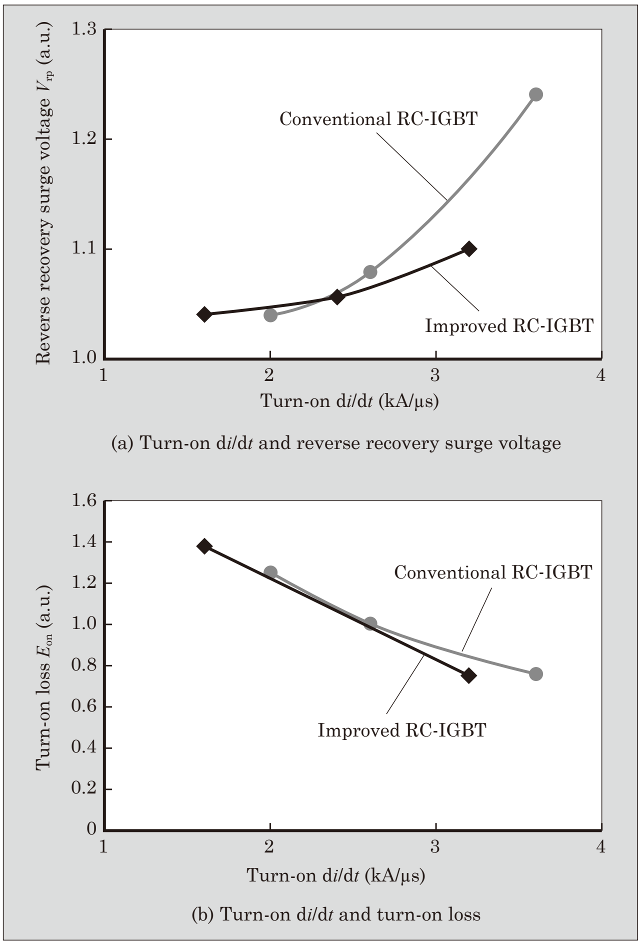

Fig. 9 Characteristics at turn-on

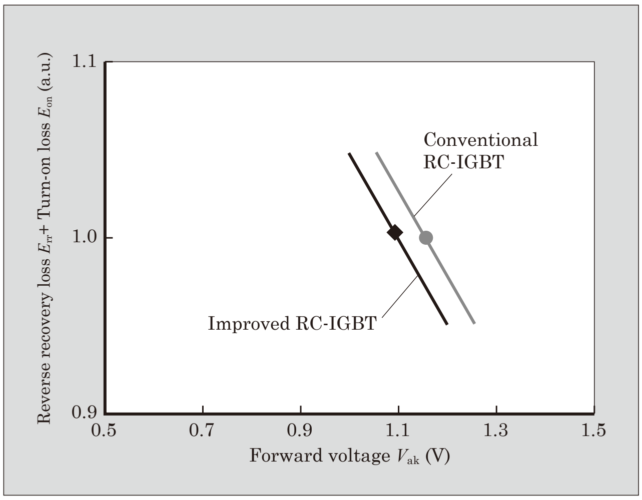

Fig. 10 FWD trade-off characteristics

verse recovery surge voltage.

Figure 9 shows the characteristics at turn-on. The reverse recovery surge voltage shown in Fig. 9(a) is a value normalized with the power supply voltage being assumed as 1. As the relationships between turn-on di/dt and reverse recovery surge voltage and between turn-on di/dt and turn-on loss show, the improved RC-IGBT can suppress the reverse recovery surge voltage at high-speed turn-on. A faster switching speed at turn-on can effectively improve the turn-on loss. Hence, we have reduced the turn-on loss at high-speed switching by driving with a lower gate resistance.

Figure 10 shows the trade-off characteristics between the forward voltage and reverse recovery loss + turn-on loss in an FWD. Reverse recovery characteristic and turn-on characteristic are phenomena that occur in the same transient period, and the amounts of them are determined by the difference in the voltage sharing ratio. For this reason, the Y-axis shows the added loss of two amounts. The values have been normalized with the loss in the conventional RC-IGBT being assumed as 1. The trade-off characteristic has been improved by reducing the loss that resulted from the drop in the forward voltage. We achieved this by using a thinner wafer and by reducing the turn-on loss through faster switching.

3.2 Loss generated during inverter operation

The losses generated during the inverter operation of the RC-IGBTs are shown in Fig. 11. A driving mode of a typical HEV is assumed as the condition for the loss calculation. With the improved RC-IGBT, the generated loss has been reduced by about 20% compared with the conventional RC-IGBT. This was due to the significant improvement of the IGBT characteristics. Reducing the generated loss leads to a decrease in the temperature caused by heat generated in the device. This enables the use of smaller devices, raising expectations for a lower inverter volume.

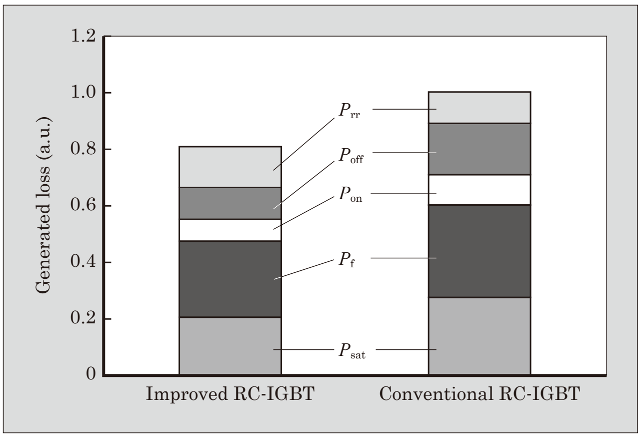

Fig. 11 Loss generated during inverter operation

4. Postscript

This paper described RC-IGBTs for automotive applications. From the need to solve environmental problems, major developments of hybrid electric vehicles and electric vehicles are expected to continue also in the future. The miniaturization of in-vehicle equipment seems to be one of the important challenges, and RC-IGBTs can be highly effective in achieving this objective. We will continue contributing to the improvement of devices and the development of devices using new materials.

References

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