Improving the Short-Circuit Capability of RC-IEGT by Backside Double P-ring Structure

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***Abstract*— The reverse-conducting injection-enhanced gate transistor (RC-IEGT) is a device that has both p-type and n-type layers at the backside. It was found that the RC-IEGT has a weaker short-circuit capability compared to the conventional IEGT, which has a single p-type layer at the backside. We analyzed this issue using TCAD simulation and confirmed that the hole injection from the edge of the cell region is an important factor in suppressing the increase in the backside electric field. To improve the short-circuit capability without affecting the turn-off capability, we applied the backside double P-ring structure which injects the hole from the P-ring only at saturation current during short-circuit operation. As a result, the fabricated device showed an excellent short-circuit capability without any influence on other electrical characteristics, including the turn-off capability.**

***Keywords*— RC-IEGT, Short circuit, Double P-ring**

I. Introduction

To enhance the power density of high voltage devices, the RC insulated-gate-bipolar-transistor (IGBT) is widely researched [1]-[7]. Electron injection from a backside n-type layer is required for RC operation. However, the n-type layer does not inject holes from the backside, which can result in uneven carrier distribution around the backside compared to conventional IGBTs. This lateral carrier density variation can cause device failure due to local current crowding during switching operation. This effect is especially significant in the case of short circuits, when a huge current flows in a short time. In this report, we examine the effect of the backside structure on short-circuit operation.

II. Analyzing the Short-Circuit Capability

When evaluating the 4.5 kV conventional RC-IEGT shown in Figure 1 under the short-circuit conditions at room temperature, its capability was found to be inferior to that of the IEGT with only a p-type layer at the backside (Fig. 2). The RC-IEGT was destroyed despite the lower short-circuit current that was adjusted by the applied gate voltage, and its destruction mode was the turn-off period during short-circuit operation. This phenomenon has not been reported to the best of our knowledge [8]-[12]. The backside structure of this device consisted of n-type and p-type layers in stripes, so the type of the cell edge depended on its location. Hence, either the cell structure itself or the edge of the cell structure could cause the degradation of its capability due to the carrier unevenness during short-circuit operation. To investigate this, we performed TCAD simulation in both cases, with and without termination. Figure 3 shows the unit cell structure. It has only p-type and n-type striped patterns at the backside. Figure 4 shows the expanded structure to include the termination region. There was no p-type layer at the backside and no n-type emitter layer at the surface in the

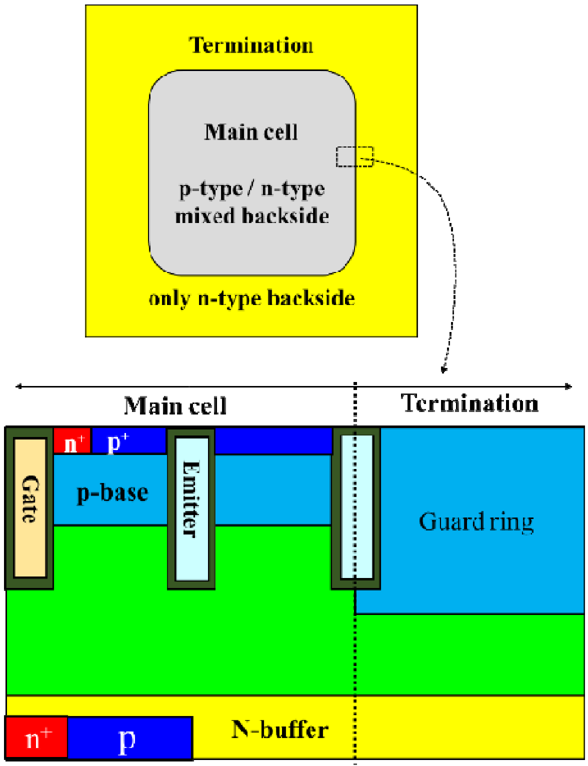

Fig. 1: Plane and cross-section views of the conventional RC-IEGT.

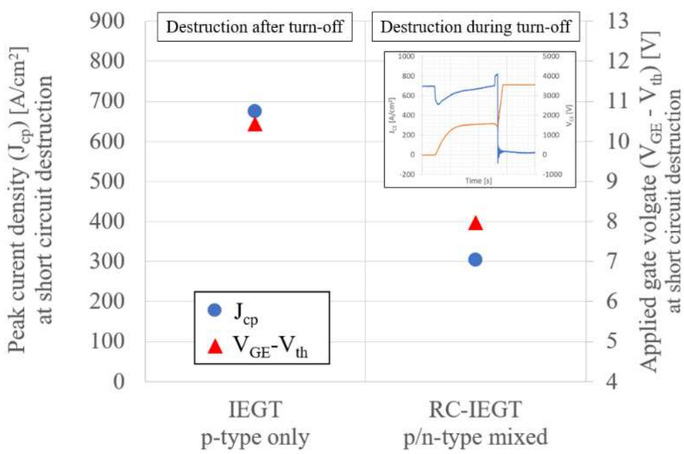

Fig. 2: Comparison of the peak current density and the applied gate voltage between IEGT and RC-IEGT at short-circuit destruction. The devices were evaluated under the fixed short-circuit time (10μs) and the gate voltage was increased until device destruction.

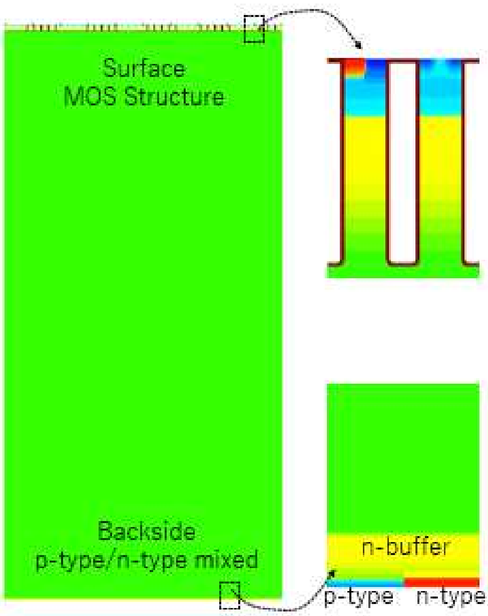

Fig. 3: The unit cell structure used for the short-circuit simulation.

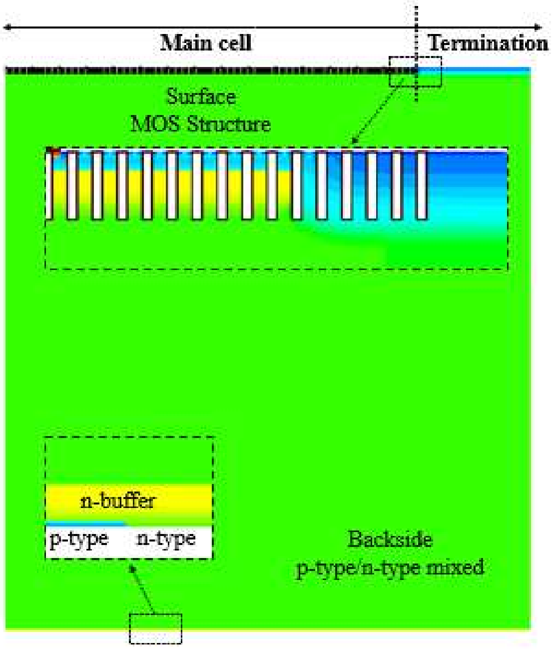

Fig. 4: The structure of the cell and termination combined for the short-circuit simulation.

termination region. We investigated the effect of these structures on short-circuit operation.

Figure 5 illustrates the electric field distribution of the unit cell under the short-circuit operation. The backside electric field did not increase even above the n-type layer. This result indicates that the injected hole from the p-type layer diffused well over the n-type layer, and the influence of the n-type layer at the cell was small. However, when the device structure was expanded to the termination region, the backside electric field at the termination was higher than that of the surface (Fig. 6). This result suggests that device destruction can occur when the backside electric field at the termination reaches the critical value. Based on these results, it is desirable to enhance the hole injection into the termination region.

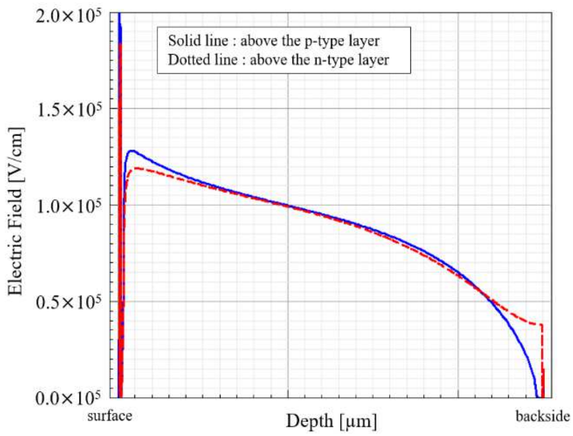

Fig. 5: Comparison of simulated electric field distributions above the p-type and n-type layers of the unit cell under the short-circuit operation.

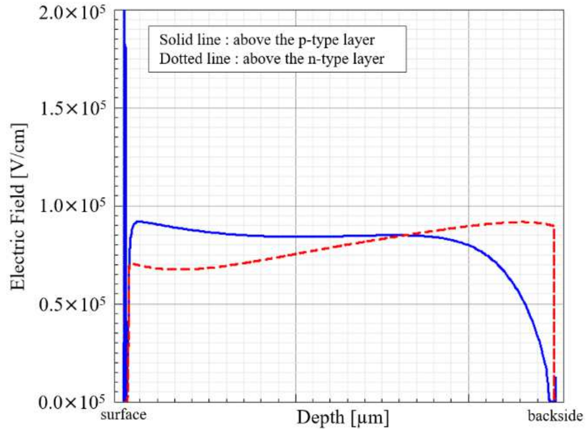

Fig. 6: Comparison of the simulated electric field distributions above the p-type and n-type layers of the cell and termination combined structure under the short-circuit operation.

However, the simple expansion of the p-type layer from the cell to the termination region weakens the turn-off capability due to an increase in carrier density around the termination region [13]. In order to achieve both the short-circuit ruggedness and the turn-off capability, we propose the backside double P-ring structure described below.

III. Improving the Short Circuit Capability

The backside double P-ring structure is shown in Figure 7. The first p-type ring surrounds the edge of the backside cell region, eliminating the n-type layer at the cell edge. It improves the balance between electron and hole density at the edge region. Moreover, the extra p-type ring is formed under the termination guard ring layer and is separated from the first p-ring. This extra p-type ring operates separately from the cell and it is preferable that its operation start current, which corresponds to the hole injection from the extra p-type ring, is beyond the reverse bias safe operating area (RBSOA). When the extra p-type ring width was wider than the appropriate value, the operation start current was low as shown in Figure 8 because the hole was easily injected from the extra p-type ring through the lateral resistance of the n-buffer layer. If the extra p-type ring operates within the RBSOA, it may weaken the turn-off capability due to the excess carrier accumulation around the termination region. Thus, the P-ring should operate only beyond the RBSOA. On the other hand, when the extra p-type ring width was set to a narrower value, it was difficult to operate and it led to the degradation of the short-circuit capability. Based on these concepts, we optimized the extra p-type ring width to the highest operation start current.

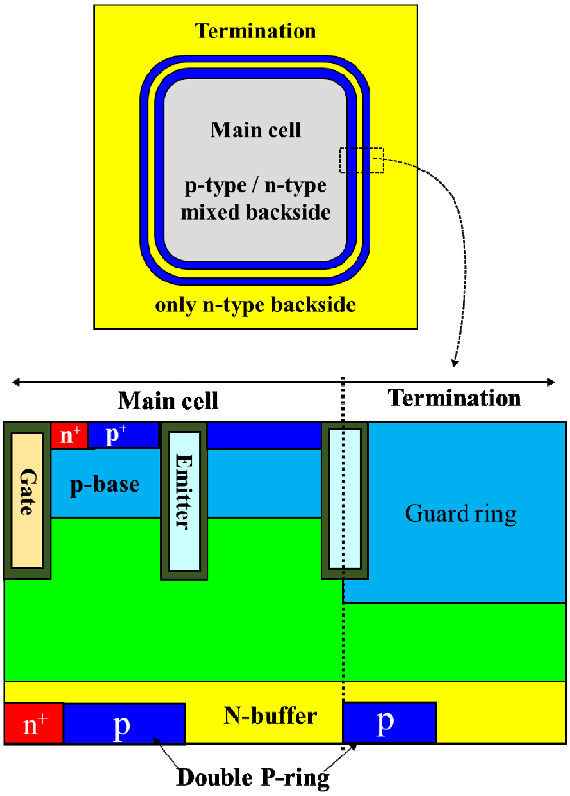

Fig. 7: Plane and cross-section views of the backside double P-ring RC-IEGT.

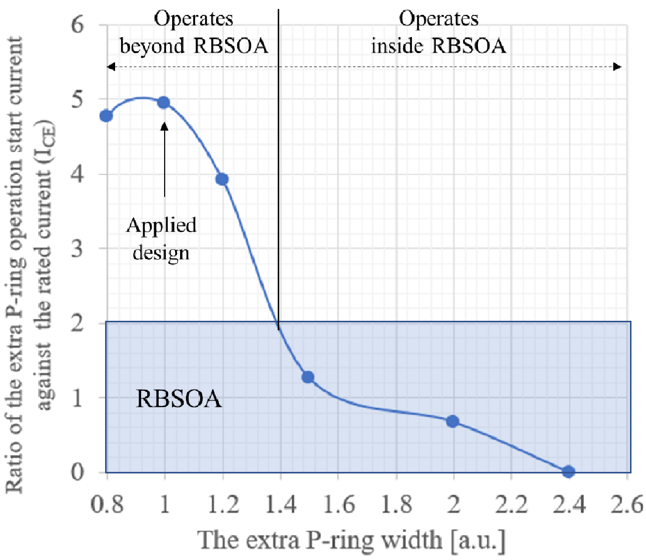

Fig. 8: Simulated relationship between the extra p-type ring width and the operation start current under short-circuit conditions.

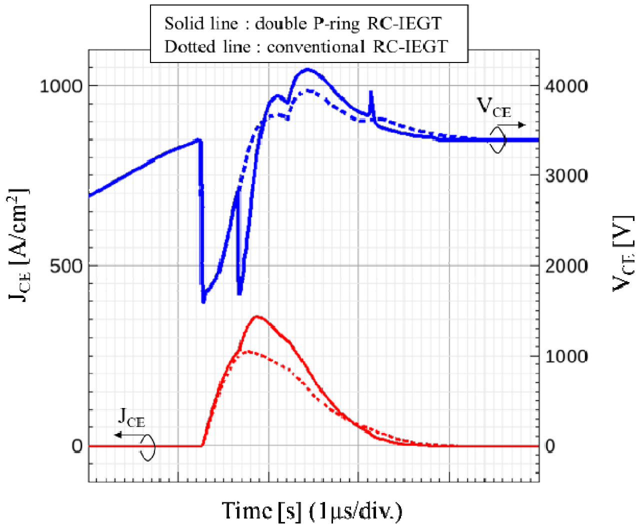

Fig. 9: Simulated short-circuit waveforms of the conventional RC-IEGT and the backside double P-ring RC-IEGT.

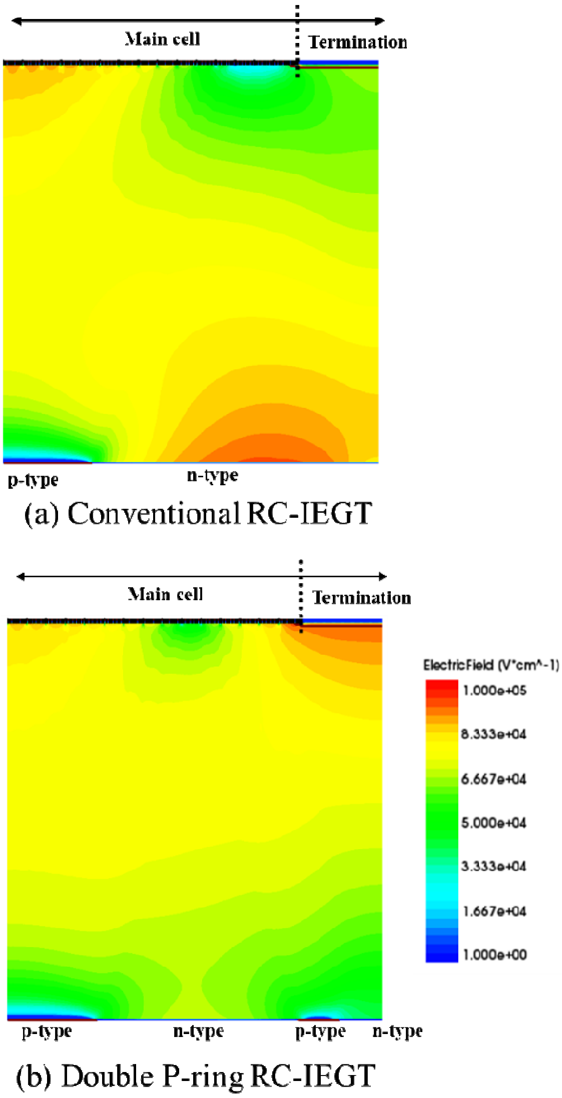

Fig. 10: Simulated electric field distributions of the conventional RC-IEGT and the backside double P-ring RC-IEGT at the peak current condition during short-circuit operation.

Figure 9 shows simulated short-circuit waveforms of the conventional RC-IEGT and the backside double P-ring RC-IEGT. The hole injection from the extra p-type ring increases the peak current of the short-circuit operation. Figure 10 illustrates simulated electric field distributions at the peak current condition. The backside electric field was relaxed by the hole injection from the extra p-type ring.

We then fabricated and evaluated the backside double P-ring RC-IEGT. The measured short-circuit waveform of the fabricated device is shown in Figure 11. The additional current from the double P-ring was observed around the saturation current. It had a significant impact on the short-circuit capability (Fig.12). The gate applied voltage of the double P-ring RC-IEGT at short-circuit destruction was improved and was almost equal to that of the conventional IEGT. The destruction mode also shifted from the turn-off period to thermal runaway after turn-off. Importantly, the turn-off capability was not deteriorate by applying the backside double P-ring structure. We have succeeded in improving the short-circuit capability without any influence on other electrical characteristics, including turn-off capability.

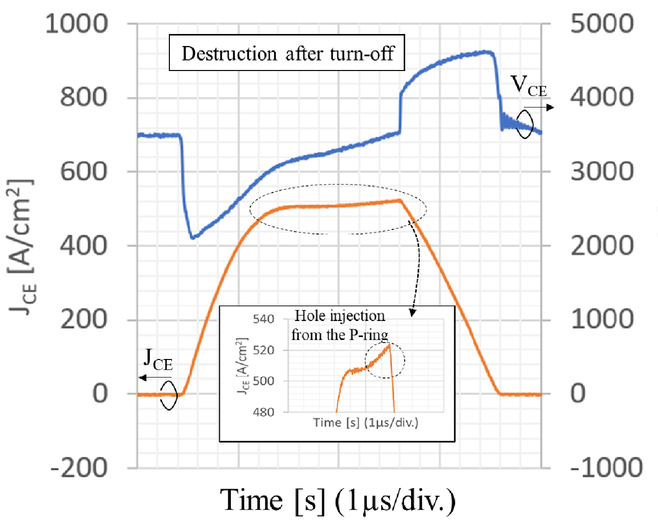

Fig. 11: Measured short-circuit waveform of the fabricated backside double P-ring RC-IEGT.

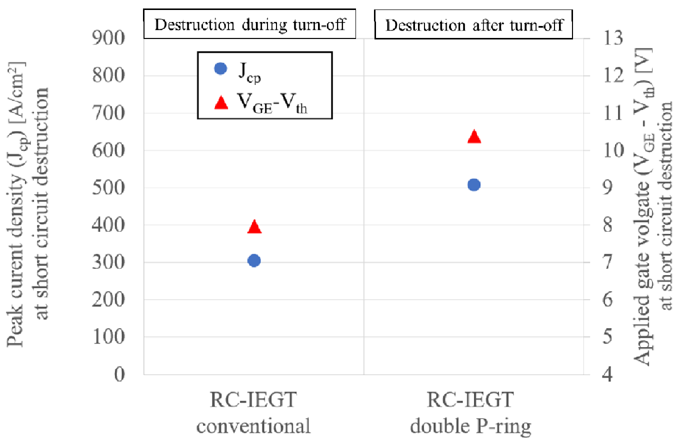

Fig. 12: Comparison of the evaluated peak current density and the applied gate voltage between the conventional RC-IEGT and the backside double P-ring RC-IEGT at short-circuit destruction.

IV. Conclusions

We simulated and fabricated the backside double P-ring RC-IEGT for improving the short-circuit capability. TCAD simulation revealed that the short-circuit capability was affected by the edge design of the cell region. The lack of holes caused an increase in the backside electric field. Therefore, the hole injection around the edge area is an important factor to decrease the backside electric field. To improve the short-circuit capability without affecting the turn-off capability, we applied the backside double P-ring structure to the RC-IEGT, which injected holes from the extra p-type ring only around saturation current during the short-circuit operation. As a result, we have confirmed that the short-circuit capability was improved without any influence on the turn-off capability by evaluating the fabricated device.

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