Experimental results of a Large Area (91mm) 4.5kV "Bi-mode Gate Commutated Thyristor" (BGCT)

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Abstract

In this paper, we present the experimental results of the 91mm, 4.5kV Bi-mode Gate Commutated Thyristor (BGCT). The BGCT is a new type of Reverse Conducting Integrated Gate Commutated Thyristor (RC-IGCT) [1]. In this work, we have also compared the results of the BGCT with that of the 91mm, 4.5kV conventional RC-IGCT both electrically (i.e. on-state and turn-off characteristics) and thermally (i.e. temperature distribution during the conduction of the device). The experimental results show that the BGCT has a better technology curve, improved safe operation area, soft reverse recovery behavior and lower leakage current compared to conventional RC-IGCT. The thermal simulation results performed with Abaqus show that BGCT has a better thermal distribution i.e. more uniform temperature distribution throughout the wafer in both GCT- and diode-modes of operation.

1. Introduction

The IGCT has been established as the device of choice for high power applications such as medium voltage drives, pumped hydro, STATCOMs, railway interties and power quality applications [2-3]. The main features of the IGCT are:

- It conducts like a Thyristor in the on-state resulting in low conduction losses.
- Turns-off like an Insulated Gate Bipolar Transistor (IGBT) in open base pnp transistor mode (i.e. hard switching turn-off capability due to the integration of the low inductive gate unit).
- Good device scalability for increased current rating [4-5] and increased blocking voltage rating [6].
- Its hermetic press pack design for good reliability in the field with respect to the power-semiconductor device protection and load cycling capability.

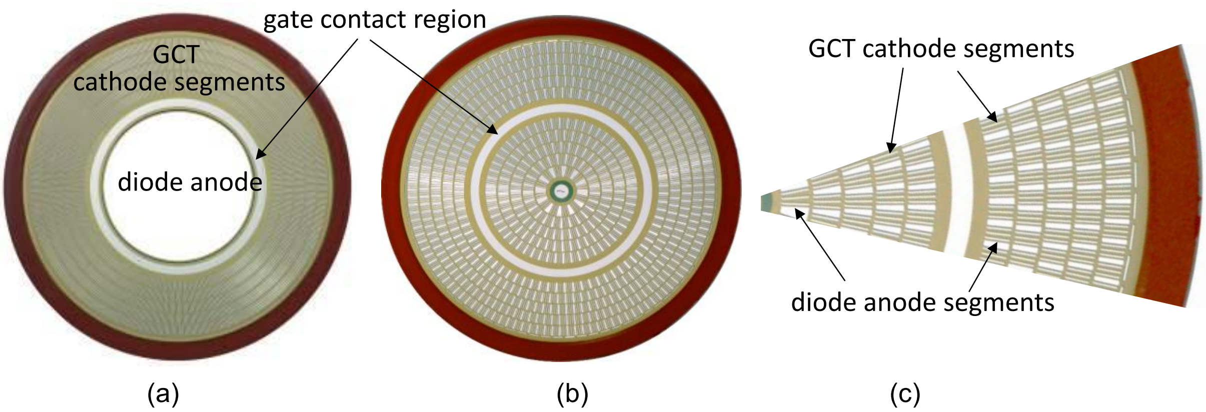
Today, IGCTs have been optimized for Voltage Source Inverter (VSI), Current Source Inverter (CSI) and event switching (solid state circuit breaker) applications and are available as Asymmetric, Symmetric (Reverse Blocking), and Reverse Conducting devices. The paper [7] reports the major developments of the IGCT technology, such as high power technology (to increase safe operation area), high temperature operation (140°C), and lower losses towards 1V on-state.

For VSI topologies, the Asymmetric IGCT has the highest power level for a given wafer size while the RC-IGCT provides compactness by integrating a diode on the same GCT wafer [8]. However, in the state-of-the-art RC-IGCTs, the GCT and diode are integrated into a single wafer but they are fully separated from each other as shown in Fig. 1a. Consequently, in the RC-IGCT, the utilization of the silicon area is limited in the GCT region when operating in GCT-mode and in the diode region when operating in the diode-mode. The BGCT, on the other hand, features an interdigitated integration of diode- and GCT-areas as shown in Fig. 1b to Fig. 1d. The interdigitated integration of the GCT- and diode- in the BGCT offers the following advantages over conventional RC-IGCT:

- An improved diode as well as GCT area.
- Better thermal distribution.
- Soft turn-off/reverse recovery behavior
- Lower leakage current.

The BGCT concept has been demonstrated first experimentally with 38mm, 4.5kV devices [9]. The experimental results show that the BGCT has a better technology curve in GCT-mode and almost matches the technology curve of the RC-IGCT in diode-mode while maintaining other advantages such as soft reverse recovery behavior and significantly lower leakage current (about 4 times lower leakage current at 2.8kV, 125°C) due to the distributed anode shorts at the backside as shown in Fig. 1d.

In this paper, we demonstrate the BGCT concept with a large area i.e. 91mm, 4.5kV BGCT for high power electronics applications (the current handling capability increases with enlarged device area).



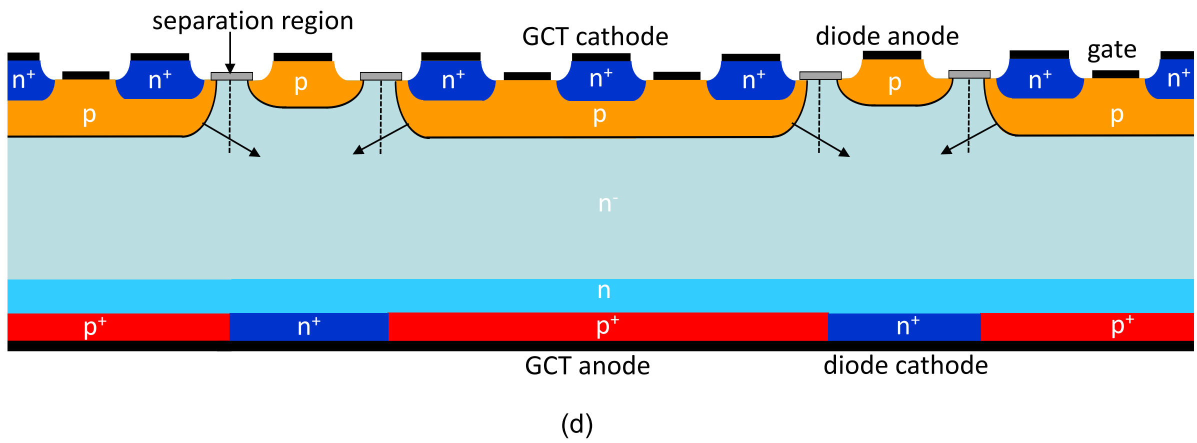


Fig. 1. (a) top-view of conventional 91mm, 4.5kV RC-IGCT, (b) top-view of 91mm, 4.5kV BGCT, (c) zoomed part of the BGCT; the wide white rectangular/triangular regions are the diode anode segments and the ones between the diode anode segments are the GCT cathode segments, (d) schematic cross section of a BGCT with shallow diode anode.

2. Experimental Results in GCT-mode

2.1. On-state Characteristics

The on-state characteristics of a 91mm, 4.5kV BGCT at 25°C & 125°C after carrier lifetime engineering are as shown in Fig. 2. For the carrier lifetime engineering, the combination of both homogenous lifetime control and local lifetime control techniques is used to improve the technology curves of the BGCT both in GCT- and diode-modes. It is worth mentioning that, the local lifetime control is applied only at the backside of the device (diode cathode side).

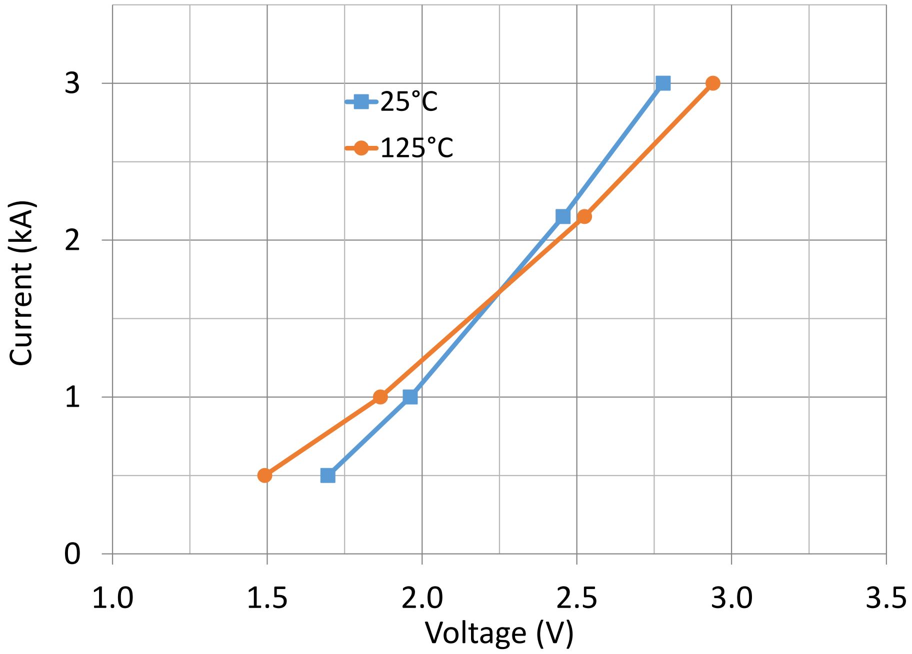


Fig. 2. The measured on-state characteristics of a 91mm, 4.5kV BGCT in GCT-mode at 25°C & 125°C.

2.2. Turn-off Characteristics

The switching circuit shown in Fig. 3 is used to test the turn-off behavior of the BGCT and RC-IGCT. We have used the same gate control unit for both cases. The comparison of the turn-off waveforms between BGCT and RC-IGCT is shown in Fig. 4. It can be seen from Fig. 4 that the BGCT shows soft turn-off behavior (around 4μs) compared to RC-IGCT.

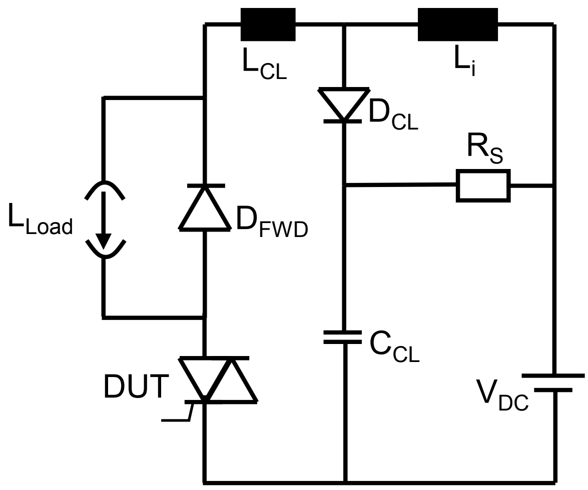


Fig. 3. The switching circuit used to test the turn-off behavior of the BGCT and RC-IGCT.

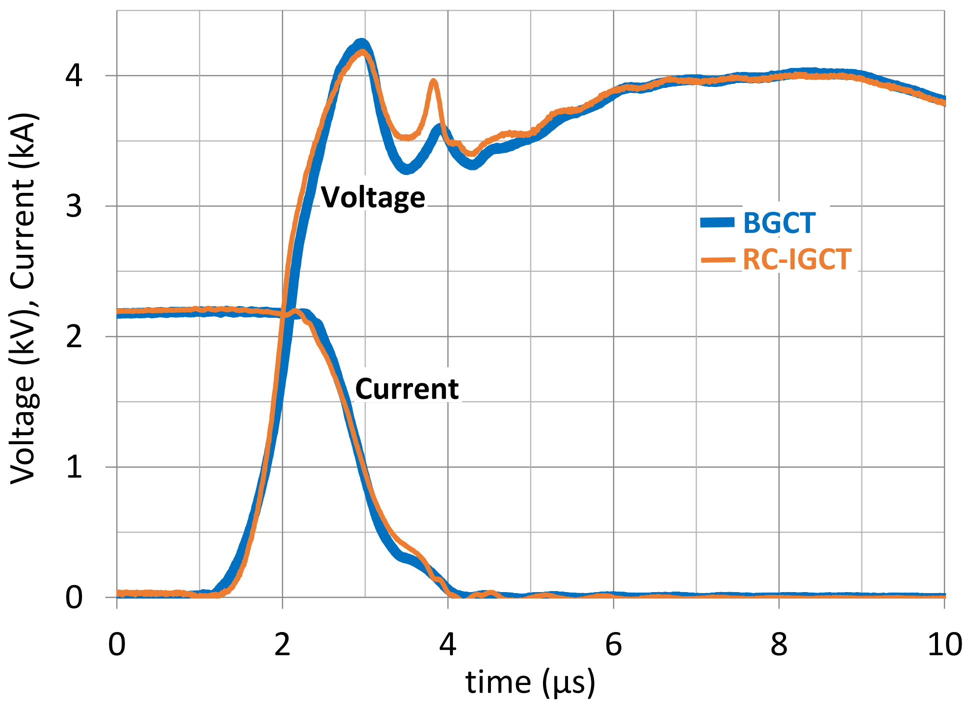


Fig. 4. The measured turn-off waveforms of a 91mm, 4.5kV BGCT and 91mm, 4.5kV RC-IGCT at 2.2kA, 2.8kV and 115°C.

2.3. Maximum Turn-off Current Capability

The 91mm, 4.5kV BGCT offers significantly higher safe operation area (SOA) i.e. higher maximum controllable turn-off current capability compared to the conventional RC-IGCT at a given dc-link voltage. Fig. 5 illustrates that the BGCT is able to successfully turn-off the currents as high as 4.4kA at 2.8V and 115°C, which is more than 1.3 times higher than the maximum turn-off current capability of the RC-IGCT.

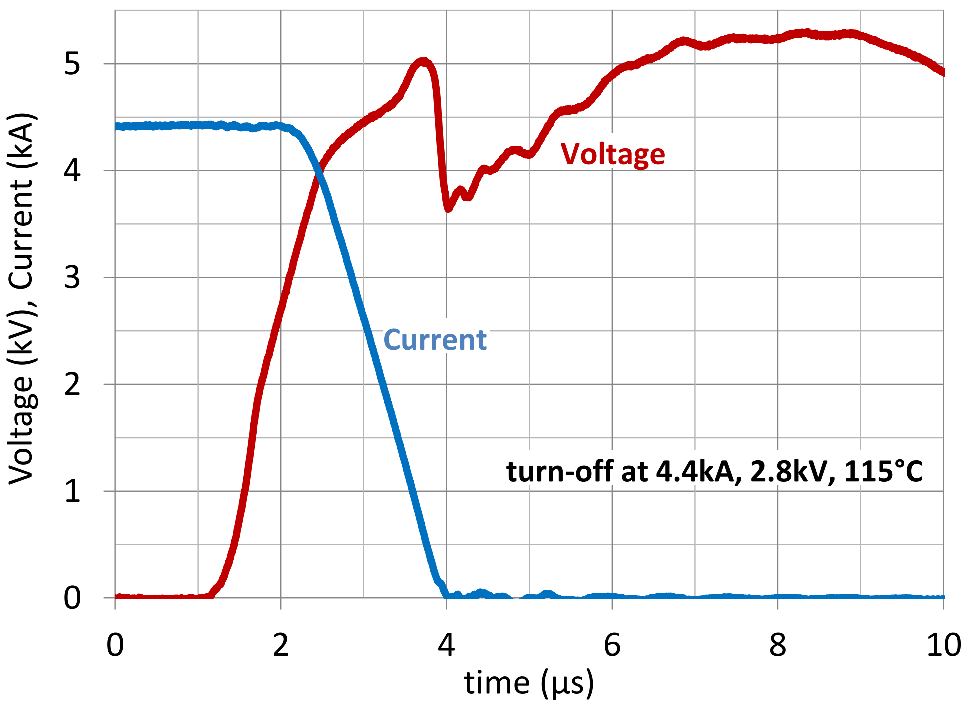


Fig. 5. The measured SOA turn-off waveforms of a 91mm, 4.5kV BGCT. The measurement results showing successful turn-off current capability up to 4.4kA at 2.8kV and 115°C, which is 1.3 times higher than the RC-IGCT.

3. Experimental Results in Diode-mode

3.1. On-state Characteristics

The on-state characteristics of a 91mm, 4.5kV BGCT at 25°C & 125°C after carrier lifetime engineering are as shown in Fig. 6. As explained before, for the carrier lifetime engineering, the combination of both homogenous lifetime control and local lifetime control techniques is used in BGCT. In the RC-IGCT case, local lifetime control is used on both sides of the device only in the diode part (i.e. anode and cathode sides of the diode) along with the homogeneous lifetime control. The main reason to use local lifetime control at the anode side of the diode in conventional RC-IGCT is to reduce the reverse recovery peak current, I_{RM} and hence limit the high power dissipation (I_{RM} * V_{DC}) and thereby protect the diodes from high power failures [10].

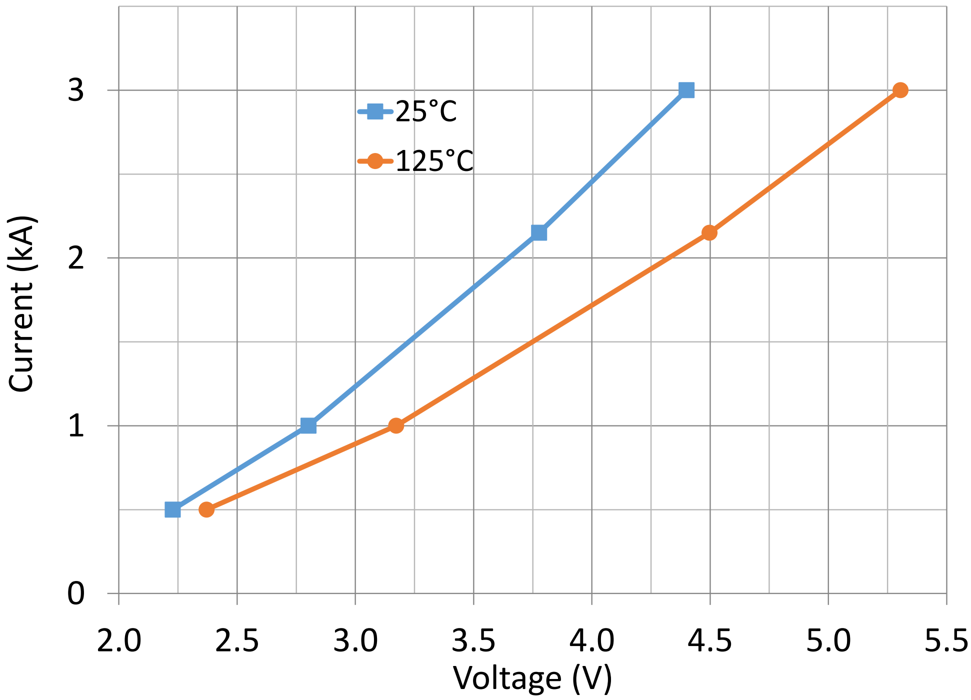


Fig. 6. The measured on-state characteristics of a 91mm, 4.5kV BGCT in diode-mode at 25°C & 125°C.

3.2. Reverse Recovery Characteristics

In this section, the reverse recovery characteristics of a 91mm, 4.5 kV BGCT are compared with that of the conventional RC-IGCT in diode-mode. It can be seen from Fig. 7 that, the BGCT shows a softer reverse recovery behavior compared to RC-IGCT. The main reason is the distributed p^+- and n^+-regions on the backside i.e. the diode cathode side (see Fig. 1d) as explained in [9]. It is worth noting that the BGCT in diode-mode is tested only up to dc-link voltages of 2kV to avoid destruction of the device from high power failure as no local lifetime is used at the front side of the device (i.e. diode anode side).

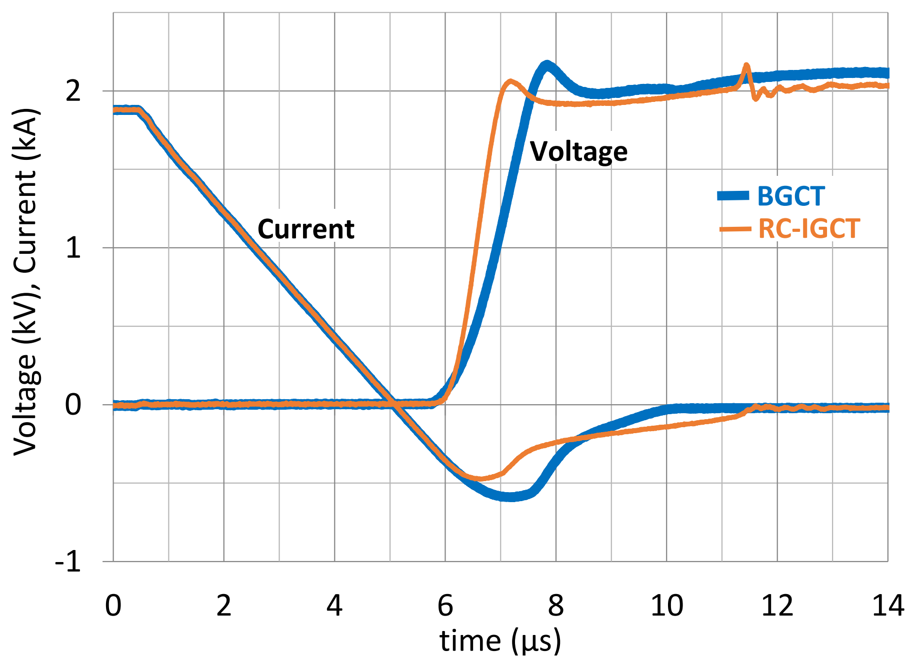


Fig. 7. The measured reverse recovery characteristics of a 91mm, 4.5kV BGCT and 91mm, 4.5kV RC-IGCT at 2kA, 1.9kV and 115°C.

4. Technology Trade-Off of BGCT and RC-IGCT

4.1. GCT-mode

Like in 38mm, 4.5kV BGCT [9], the 91mm, 4.5kV BGCT has a better technology curve (turn-off losses vs. on-state voltage drop) than that of the RC-IGCT in GCT-mode. For the same turn-off losses, the on-state voltage drop of the BGCT is more than 100mV (5%) lower compared to that of the RC-IGCT. This is likely due to more available area in BGCT compared to that of the GCT in RC-IGCT.

4.2. Diode-mode

The 91mm, 4.5kV BGCT has a better technology curve (reverse recovery losses vs. on-state voltage drop) than that of the RC-IGCT also in diode-mode. Like in 38mm, 4.5kV BGCT [9], the technology curve of the 91mm, 4.5kV BGCT in diode-mode improves with increasing diode anode efficiency. For the same reverse recovery losses, the on-state voltage drop of the BGCT is more than 200mV (6%) lower compared to that of the RC-IGCT.

5. Thermal behavior of BGCT and RC-IGCT

Fully coupled (i.e. electrical, thermal, mechanical) simulations have been performed with Abaqus to analyze the thermal behavior of the BGCT and RC-IGCT in both GCT- and diode-modes of operation. As expected, the simulation results show that BGCT has a better thermal distribution (i.e. more uniform temperature distribution throughout the wafer) due to the interdigitated integration of GCT- and diode-areas in the BGCT (utilization of whole silicon volume in both GCT- and diode-modes of operation), compared to that of the RC-IGCT as shown in Fig. 8. The better thermal distribution leads to both lower losses and enhanced reliability.

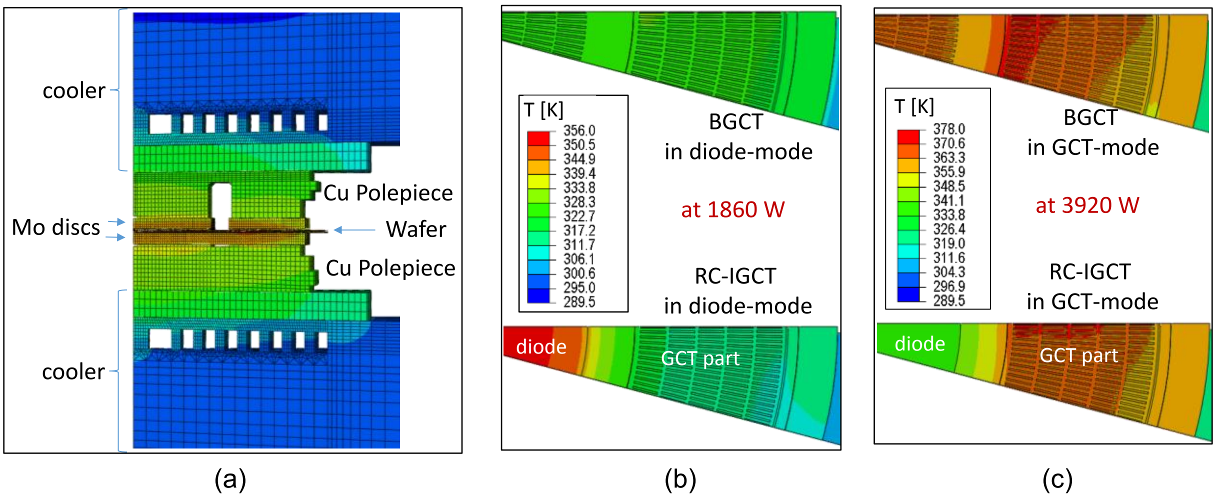


Fig. 8. Thermal simulations of BGCT and RC-IGCT (a) simulation setup (b) temperature distribution in diode-mode (c) temperature distribution in GCT-mode. The temperature is more uniformly distributed throughout the wafer in BGCT and as a result, the maximum junction temperature is lower in BGCT.

6. Conclusions

We have presented the experimental results of a 91mm, 4.5kV BGCT. The BGCT is a new type of reverse conducting IGCT with improved performance (i.e. better technology curve, soft reverse recovery/turn-off behavior and lower leakage current) than that of the conventional RC-IGCT. Furthermore, the experimental results show that the 91mm, 4.5kV BGCT has significantly higher turn-off current capability (i.e. >1.3 times) compared to RC-IGCT. The thermal simulation results show that the BGCT has a better thermal distribution compared to RC-IGCT due to utilization of whole silicon volume in both GCT- and diode-modes of operation.

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