

## 3.3kV RC-IGCTs Optimized for Multi-Level Topologies

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### Abstract

The Integrated Gate Commutated Thyristor (IGCT) is a high power semiconductor device with hard switching turn-off capability and thyristor-like conduction. Hence IGCTs can be optimized for lowest conduction losses. Today however, IGCTs have voltage ratings ranging from 4.5kV up to 6.5kV and are optimized normally for state-of-the-art two to five level inverters, which are usually operating at relatively high switching frequencies. With the recent trend towards employing multi-level topologies in many power electronics applications, efforts are being made to develop devices towards lower conduction losses and lower voltage ratings for operating efficiently at lower switching frequencies with higher power capabilities. Therefore, in this paper, we demonstrate by simulation and experiment the feasibility of designing 3.3kV Reverse Conducting (RC)-IGCTs with very low conduction losses for multi-level topologies.

### 1. Introduction

The IGCT established since its evolution from the Gate Turn-Off Thyristor (GTO) in the mid 1990's [1], as the device of choice for industrial medium voltage drives (MVD) and also for other applications such as wind-power conversion, STATCOMS, power quality and railway interties, to name a few. The IGCT conducts like a thyristor in the on-state resulting in low on-state voltage drops and turns-off like a transistor in open base transistor mode (hard switching turn-off capability due to the integration of the low inductive gate unit). Therefore, the IGCTs have optimum plasma distribution in the conduction mode to achieve low on-state voltage drop compared to that of the Insulated Gate Bipolar Transistors (IGBT) as shown in Fig. 1. Today however, IGCTs have voltage ratings ranging from 4.5kV up to 6.5kV for enabling two to five level voltage source inverters (VSI). Hence, such devices are normally optimized for relatively high switching frequencies in the range of few 100Hz.

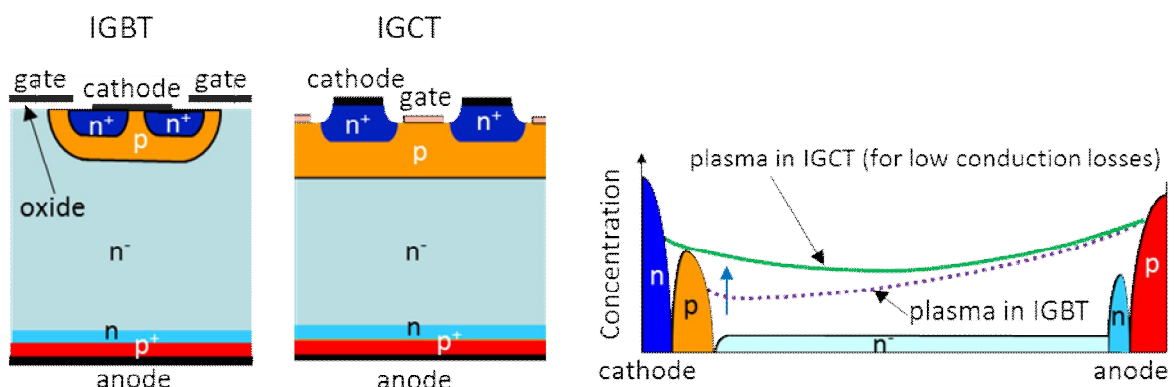


Fig. 1. Schematic structures of IGBT and IGCT and their plasma distribution during conduction

With the recent trend towards employing multi-level topologies in many power electronics applications [2-4], demands are now being made for more application specific devices with a shift in focus towards lower conduction losses for operating efficiently at lower switching frequencies with higher power capabilities. The authors [5] demonstrated by simulation and experiment the feasibility of designing a wide range of high voltage IGCTs (2.5kV up to 6.5kV) towards lower on-state voltage drop through anode engineering to achieve values approaching 1V while maintaining good overall performance (e.g. high turn-off current capability, blocking etc.).

In most of the VSI applications, the freewheeling diode has to be connected anti-parallel to the IGCT to conduct currents in the reverse direction during freewheeling mode. In an RC-IGCT shown in Fig. 2, the IGCT and Diode are integrated into a single wafer and this approach is advantageous because the diode i.e. an extra component can be eliminated. The monolithic integration of the IGCT and freewheeling diode leads to better component integration in terms of processing and reduced parts count at the system level, therefore improved assembly and reliability [6]. Therefore, in this paper, we demonstrate by simulation and experiment the feasibility of designing 3.3kV RC-IGCTs towards lower conduction losses for very low frequency applications (e.g. multi-level topologies where the operating switching frequency is less than 200Hz).

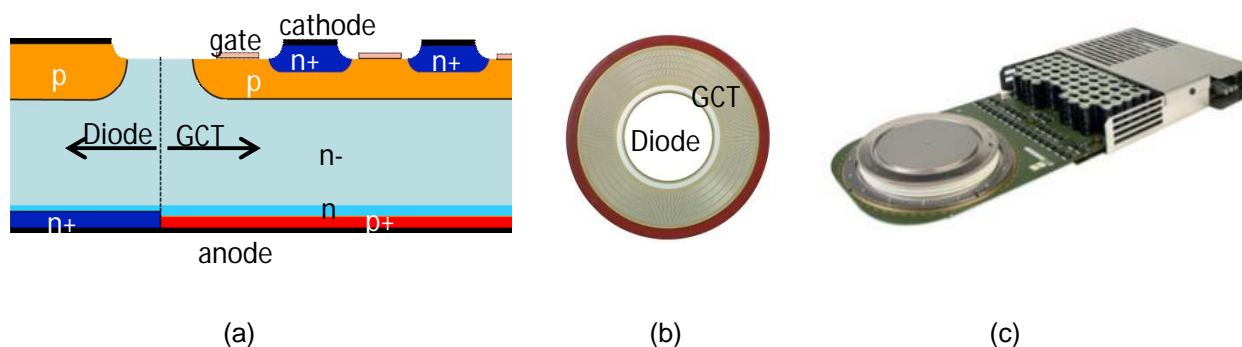


Fig. 2. (a) Schematic structure of an RC-IGCT (b) 91mm, 3.3kV RC-IGCT wafer (c) 3.3kV RC-IGCT with integrated gate unit

## 2. Simulation Results of 3.3kV RC-IGCT

The aim of the simulation study (Sentaurus TCAD device simulations) was to investigate the potential of a new voltage class (3.3kV) RC-IGCT towards lower conduction losses for very low frequency applications. In addition, to find out the right silicon specs i.e. the resistivity & thickness of the n-base and anode doping profiles in order to fabricate the devices to achieve required blocking capability and very low conduction losses.

Here in the GCT part, the technology curve is tailored by anode engineering (adjustment of the p<sup>+</sup>-anode doping of the GCT) whereas in the diode part, it is achieved by lifetime control (LC) i.e. with the single particle peak and/or double particle peak as shown in Fig. 3. The on-state simulation results of 91mm, 3.3kV RC-IGCTs at 400K are illustrated in Fig. 4 for both GCT and Diode modes. The simulation results show the potential of a 3.3kV RC-IGCT to achieve very low on-state voltage drop below 1.3V up to currents of 2.0kA in GCT conduction mode. For comparison, the typical on-state voltage drop is about 2.5V at 2.0kA, 400K for existing 4.5kV RC-IGCT in GCT conduction mode which is optimized for two to five level inverters. The Diode part of the device is optimized with lifetime control to reduce the reverse recovery current peak,  $I_{rr}$  thereby reverse recovery losses,  $E_{rec}$  and hence protect the diode from high power failures.

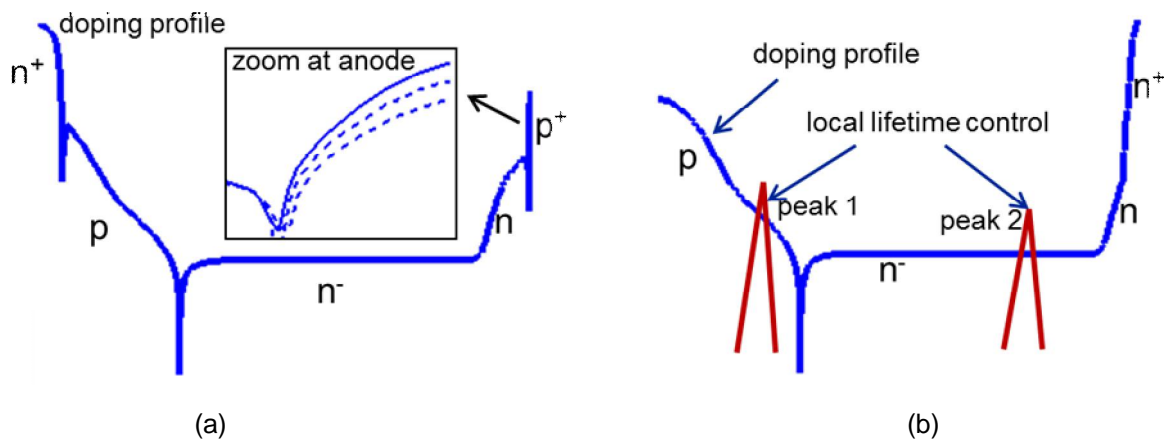


Fig. 3. Doping profiles of 91mm, 3.3kV RC-IGCT (a) GCT part: the technology curve is tailored by anode engineering (varying the p<sup>+</sup>-anode doping of the GCT) (b) Diode part: the technology curve is tailored by lifetime control

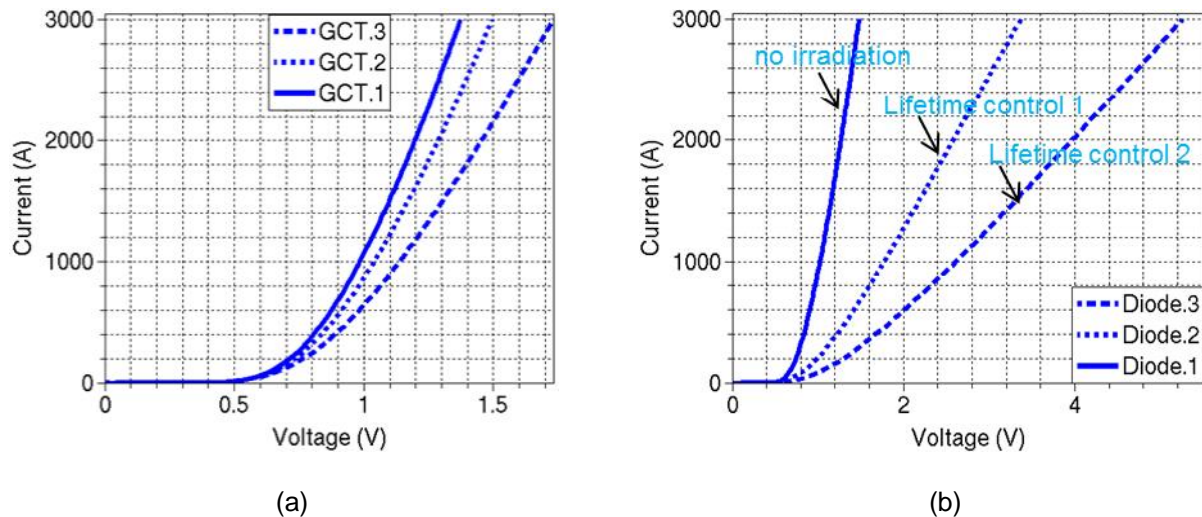


Fig. 4. On-State simulation results of 91mm, 3.3kV RC-IGCT at 400K (a) GCT mode: p<sup>+</sup>-anode doping of the GCT.1 > GCT.2 > GCT.3 (b) Diode mode: lifetime killing in Diode.3 > Diode.2 > Diode.1

### 3. Measurement Results of 3.3kV RC-IGCT

To demonstrate the potential of 3.3kV RC-IGCTs towards very low conduction losses, 91mm devices on 4" silicon wafers were manufactured and the blocking capability and the on-state & turn-off characteristics were tested both in GCT and Diode modes. In the GCT part, the design variation was done by three different anode doses (i.e. in GCT part, the technology curve was tailored by anode engineering) whereas in the diode part, it was achieved by lifetime control (the diode anode was the same for all the devices). The simulation and measurement results demonstrate the potential of 3.3kV RC-IGCTs to achieve very low conduction losses and required blocking capability as well as high turn-off current capability.

### 3.1. On-State Characteristics

Fig. 5 illustrates the on-state characteristics of the fabricated 91mm, 3.3kV RC-IGCTs at 400K both in GCT and Diode modes. In GCT part, p<sup>+</sup>-anode dose was varied towards higher levels (A3 > A2 > A1) for providing higher injection efficiency and subsequently lower conduction losses, albeit at the expense of higher switching losses. The measurement results show the potential of 3.3kV RC-IGCTs to achieve a very low on-state voltage drop, V<sub>T</sub> below 1.3V up to currents of 2.0kA in GCT conduction mode.

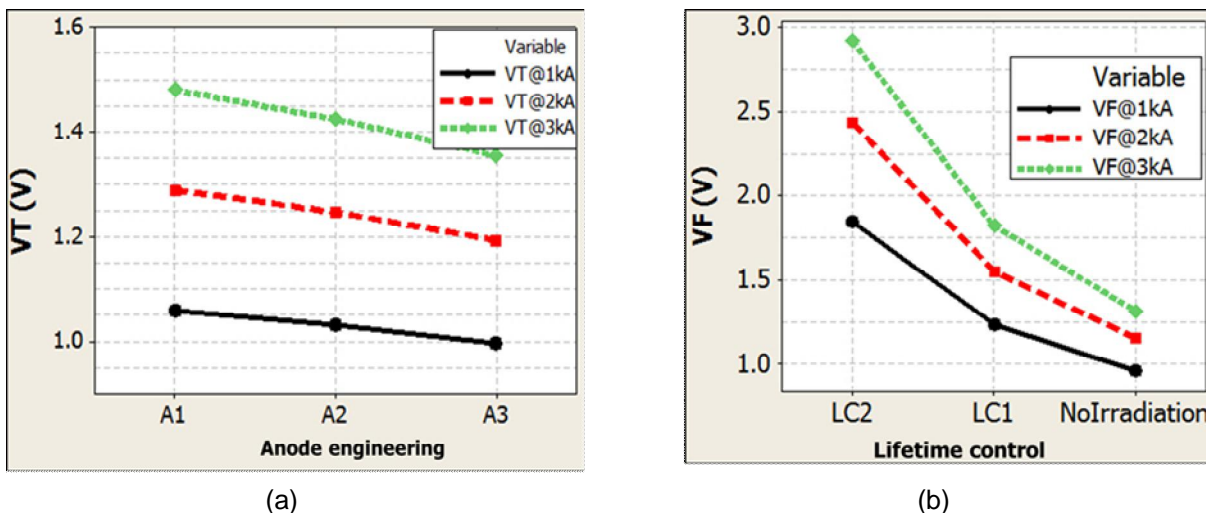


Fig. 5. On-State measurement results of 91mm, 3.3kV RC-IGCT at 400K (a) GCT mode: variation of the GCT p<sup>+</sup>-anode dose (A3 > A2 > A1) (b) Diode mode: variation of the lifetime control (LC)

The Diode part of the device was optimized with lifetime control (LC2<sub>Dose</sub> > LC1<sub>Dose</sub>) to reduce the reverse recovery current peak, I<sub>rr</sub> thereby reverse recovery losses, E<sub>rec</sub>. As shown in Fig. 5(b), the on-state voltage drop, V<sub>F</sub> is below 2.5V up to currents of 2kA in diode conduction mode. For comparison, the typical on-state voltage drop is about 4.1V at 2.0kA, 400K for existing 4.5kV RC-IGCT in diode conduction mode.

### 3.2. Blocking Characteristics

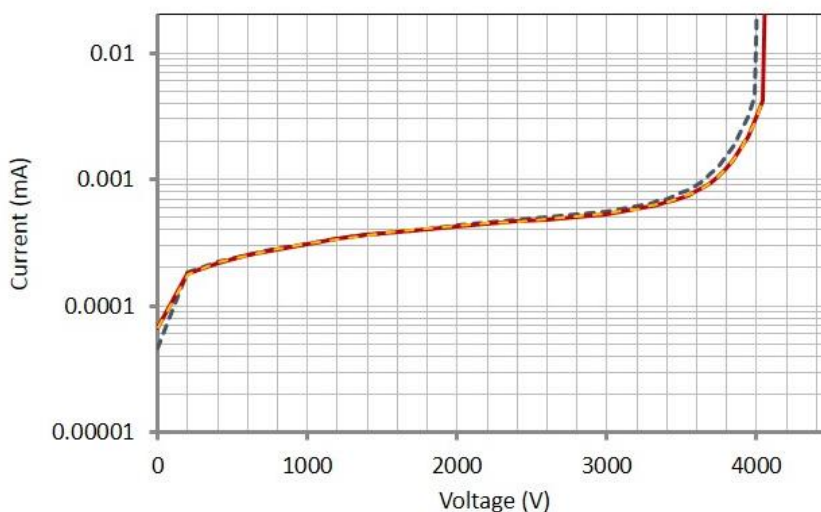


Fig. 6. Measured blocking characteristics of the fabricated 91mm, 3.3kV RC-IGCTs at 300K

Fig. 6 illustrates the blocking characteristics of the fabricated 91mm, 3.3kV RC-IGCTs at 300K. The measurement results show that the devices can block about 4kV which is more than the required blocking capability (~ 3.6kV) at 300K. Usually these devices operate at dc-link voltages of 1.8kV and the leakage currents at 1.8kV are about 0.4 $\mu$ A and 0.5mA at 300K and 400K, respectively.

### 3.3. GCT Turn-Off Characteristics

Fig. 7 illustrates the turn-off waveforms of the fabricated 91mm, 3.3kV RC-IGCTs (for three different designs of the GCT anode) at 2.2kA, 2kV and 400K. The measurement results show that the devices can maintain “**high levels of hard switching turn-off current capability despite of having very low conduction losses**” [5]. It can be seen from Fig. 7 that the tail current is larger for higher anode dose device and hence higher switching losses. Fig. 8 illustrates the technology trade-off curve between turn-off losses and on-state voltage drop of the 3.3kV RC-IGCTs in GCT mode.

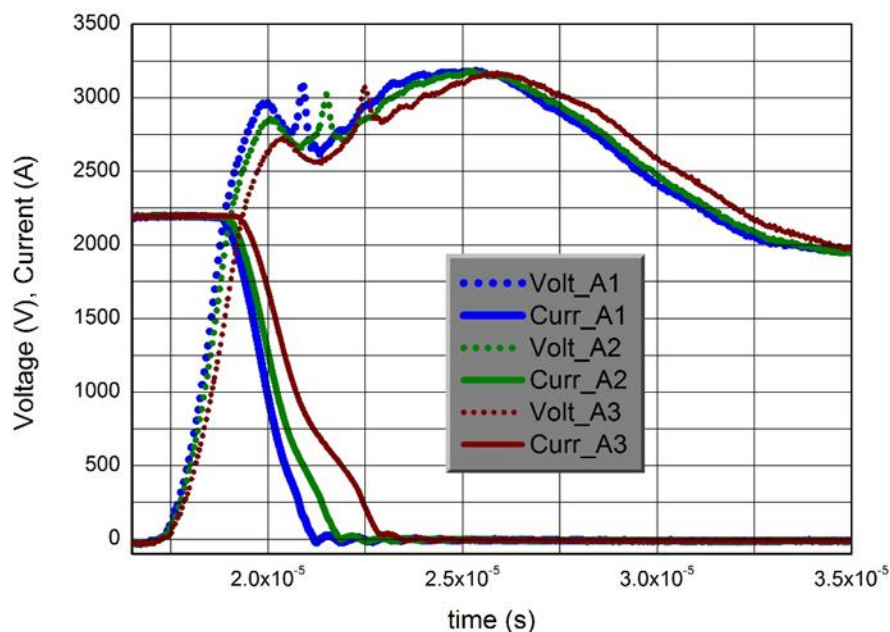


Fig. 7. Turn-off waveforms of the fabricated 91mm, 3.3kV RC-IGCTs at 2.2kA, 2kV, 400K in GCT mode. The difference between A1, A2 and A3 is the GCT p<sup>+</sup>-anode dose (A3 > A2 > A1).

We have observed from the simulations as well as from the experiments that after certain anode doping/dose, the reduction in the on-state voltage drop with further increase of the anode dose is small but the increase of the switching losses are high. **It is worth mentioning that in applications where the switching losses are of least concern, with the IGCTs one could achieve the ultimate potential of reaching the on-state voltage drop,  $V_T$  goal of 1V at reasonably high currents (>1kA).**

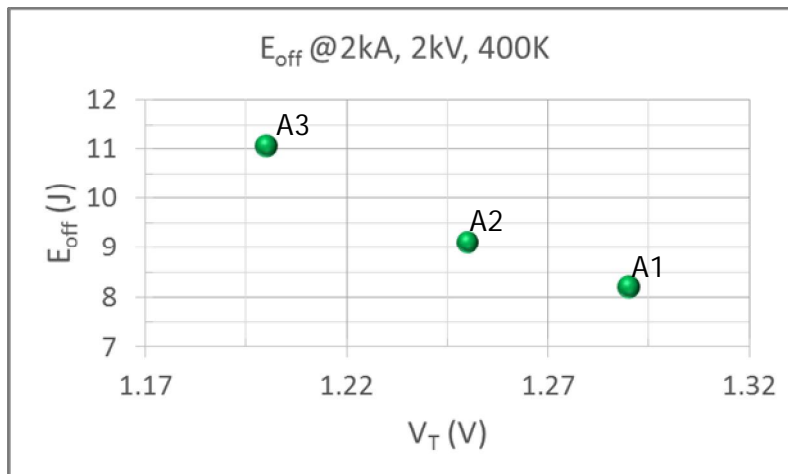


Fig. 8. Technology trade-off curve between turn-off losses and on-state voltage drop of the fabricated 91mm, 3.3kV RC-IGCTs in GCT mode (GCT anode dose: A3 > A2 > A1).

### 3.4. Diode Reverse Recovery Characteristics

Fig. 9 illustrates the reverse recovery waveforms of the fabricated 91mm, 3.3kV RC-IGCTs (with different lifetime control) in diode mode at 2.2kA, 2kV and 400K. Fig. 10 illustrates the technology trade-off curve between reverse recovery losses and on-state voltage drop of the 3.3kV RC-IGCTs in diode mode.

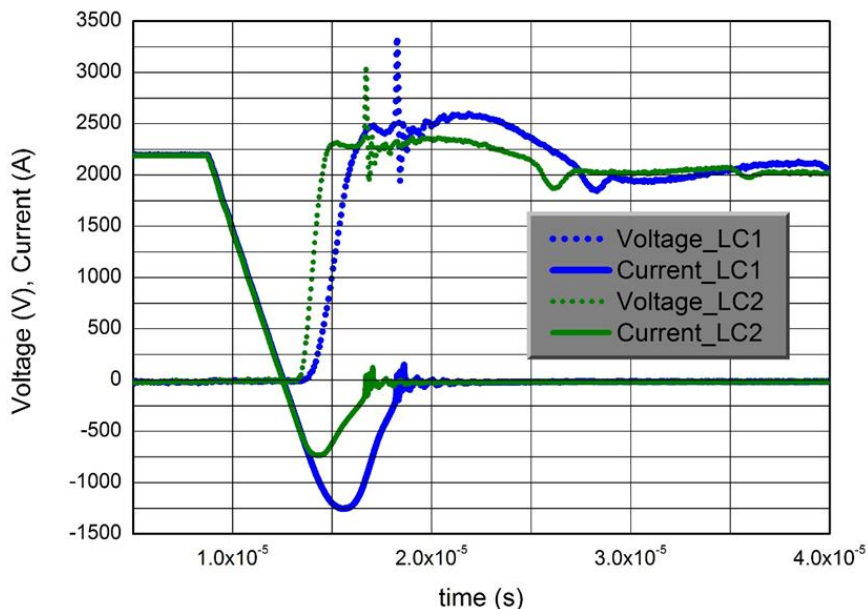


Fig. 9. Reverse recovery waveforms of the fabricated 91mm, 3.3kV RC-IGCTs at 2.2kA, 2kV, 400K in diode mode (harsh turn-off conditions i.e. tested the turn-off capability at higher dc-link voltage). The difference between LC1 and LC2 is the lifetime control in diode part (high lifetime killing in LC2 compared to LC1)

It can be observed from Fig. 9 and Fig. 10 that the  $I_{rr}$  and hence  $E_{rec}$  can be reduced with LC2 (double particle peak as shown in Fig. 3) compared to that of the LC1 (single particle peak as shown in Fig. 3) at the expense of high on-state voltage drop. **The second irradiation makes the diode also softer [7] as one can see from the lower  $di/dt$  at the tail time. As a result the voltage overshoot is lower for the LC2 process.** The slight snappiness appear due to the harsh turn-off conditions used, e.g. high dc-link voltage. This can be reduced or eliminated with a further optimization of the lifetime control.

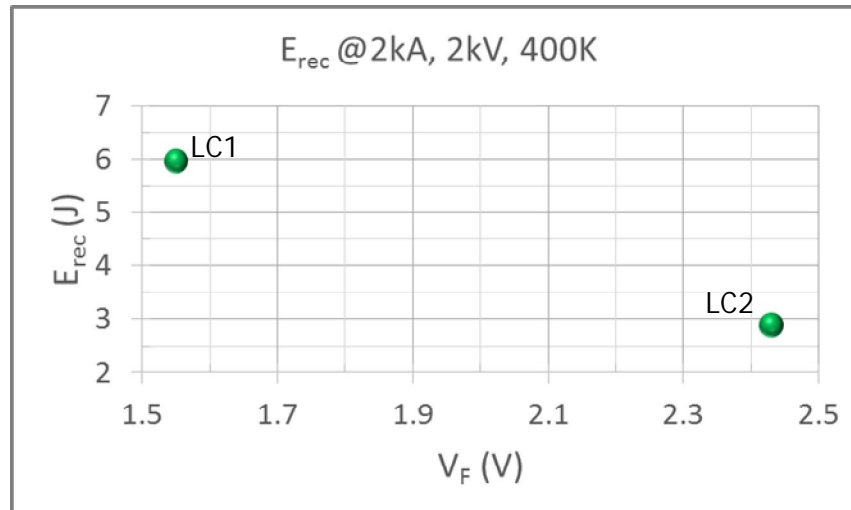


Fig. 10. Technology trade-off curve between reverse recovery losses and on-state voltage drop of the fabricated 91mm, 3.3kV RC-IGCTs in Diode mode

## 4. Summary

The results obtained from this investigation will provide an overall outlook with regard to the potential of 3.3kV RC-IGCTs to achieve very low conduction losses even at higher currents i.e. to achieve the ultimate potential of reaching the  $V_T$  goal of 1V at reasonably high currents. The main aim is to assess the suitability of such optimized IGCTs for modern power electronics applications having the main focus on lowering the conduction losses for operating at lower switching frequencies.

## 5. References

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