Recent Advancements in IGCT Technologies for High Power Electronics Applications

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Abstract

In this paper, we review the progress made recently for further developing the Integrated Gate Commutated Thyristor (IGCT) device concept for high power electronics applications. A wide range of newly introduced IGCT technologies are discussed and recent prototype experimental results as well as novel structures and future trends of the IGCT technology are presented. This will provide system designers with a comprehensive overview of the potentials possible with this device concept.

Introduction

The IGCT is in principle a thyristor based device concept which has since its evolution from the Gate turn-off Thyristor (GTO) in the mid 1990`s [1-6] established itself as the device of choice for industrial Medium Voltage Drives (MVD) and has also been used in many other systems such as wind-power conversion, STATCOMs, and interties to name a few. Due to the integration with a low inductive gate unit, this hard driven device conducts like a thyristor (i.e. low on-state losses) and turns-off like a transistor (i.e. hard switching). The basic Asymmetric IGCT structure cross section, wafer and integrated package / gate unit components are shown in Fig. 1.

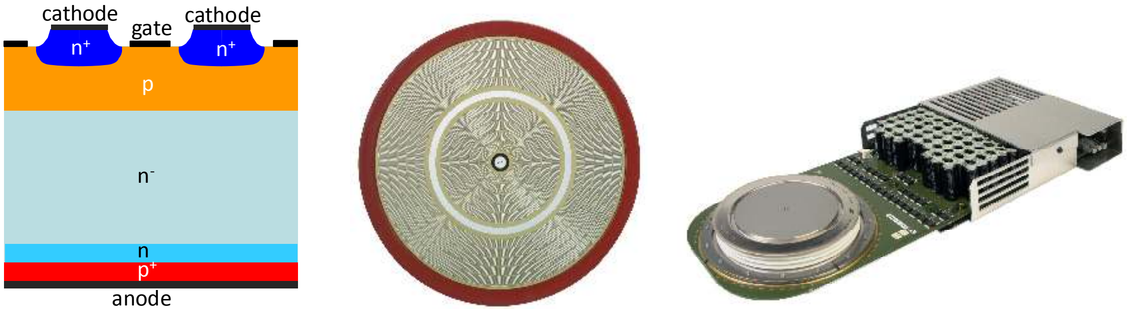


Fig. 1: IGCT device. Left: schematic cross section of Asymmetric IGCT. Middle: top view of 91mm IGCT wafer. Right: the IGCT wafer in a hermetic package and with its integrated gate unit.

Today, IGCTs have been optimized for current source inverter (CSI) and voltage source inverter (VSI) applications with state-of-the-art devices having voltage ratings ranging from 4.5kV up to 6.5kV and are today available as Asymmetric, Symmetric (Reverse Blocking), and Reverse Conducting devices as shown in Fig. 2.

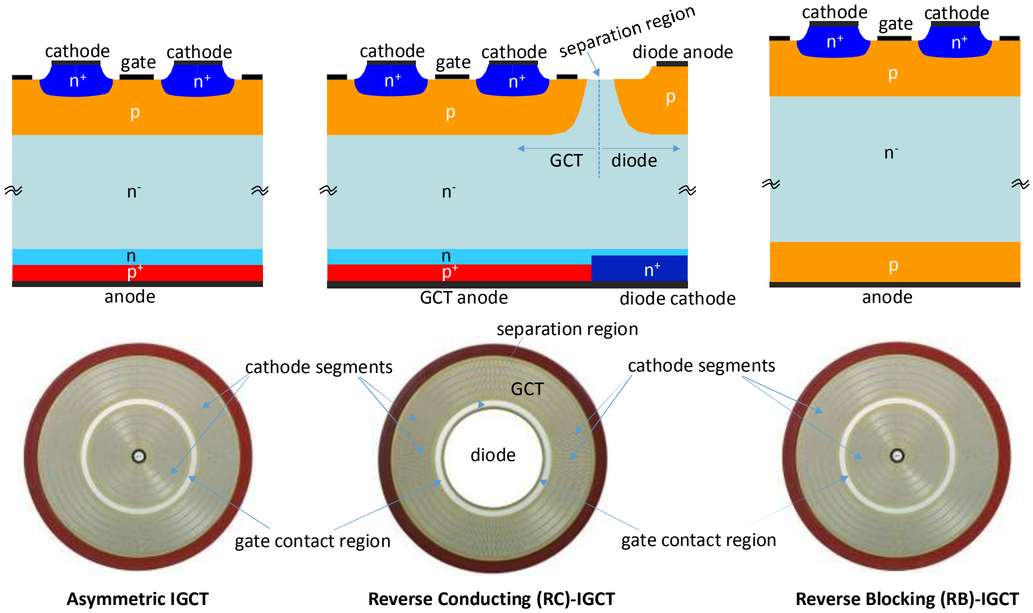


Fig. 2: State-of-the-art IGCT device types and their schematic cross sections from top side to bottom side (vertical cross section).

For VSI topologies, the Asymmetric IGCT has the highest power level for a given wafer size while Reverse Conducting IGCT (RC-IGCT) provides compactness by integrating a diode on the same GCT wafer [7-9]. However, the main drawback for the RC-IGCT is due to less available GCT area for a given wafer size. Inherent to the IGCT concept, the gate unit is critical for the device switching performance and is therefore an integral part of the device for proving a low inductive gate path [2], [10-11]. The hermetic press-pack design of the IGCT has for years proven its reliability in the field with respect to the power semiconductor device protection and load cycling capability. Consisting of a few layers of well-designed materials there are no issues with solder voids or bond lift off as other technologies experience [12].

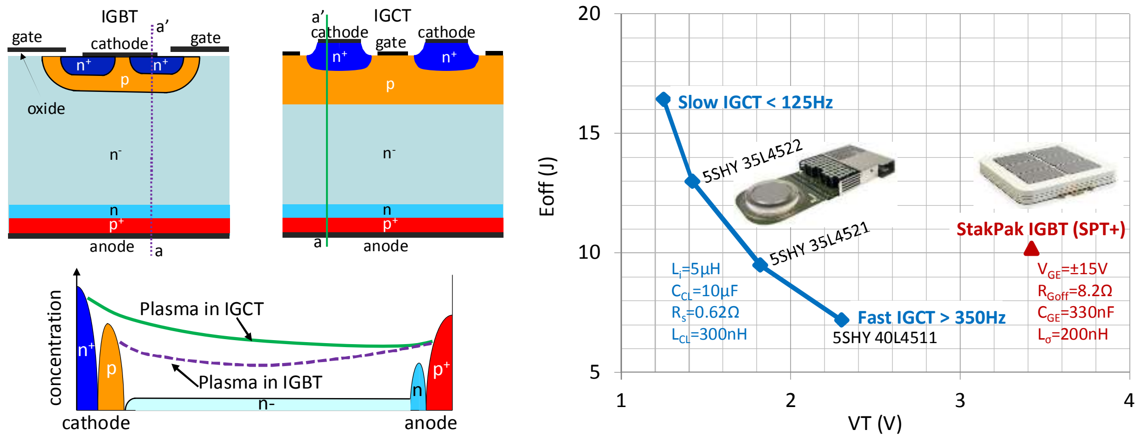


Fig. 3: IGCT vs. IGBT. Left: schematic structures of IGCT and IGBT and their plasma distribution during conduction. Right: technology curve comparison between 4.5kV Asymmetric IGCT and StakPak IGBT module at 2.8kV, 2kA, 125°C.

Therefore, the IGCT is the ideal device of choice for many high power electronics applications due to its thyristor like conduction (i.e. optimum plasma distribution to achieve low conduction losses for example compared to Insulated Gate Bipolar Transistors (IGBT) as shown in Fig. 3), transistor like turn-off and hermetic press-pack design. Fig. 3 also compares the losses performance of the state-of-the-art 4.5kV SPT+ IGBT and Asymmetric IGCT in a press-pack design at 2kA, 2.8kV and 125°C (both devices have nearly the same active area i.e. 40cm^2). It can be seen from Fig. 3 that the IGCT has clearly a better technology curve (turn-off losses vs. on-state voltage drop) compared to that of the IGBT i.e. for the same switching losses, the on-state voltage drop is close to half in the IGCT compared to an equivalent IGBT [13]. However, IGCTs need a clamp circuit to protect the anti-parallel diode from high power failures in the circuit topology [14] and this clamp circuit contribute to additional losses during switching and depends on the clamp inductance and switching current.

IGCT performance trends

In the past 10 years, the IGCT technology has experienced major development trends to further exploit the main advantages in terms of lower conduction losses and higher power densities offered by this device design/process concept. Fig. 4 shows a basic illustration summarizing the basic IGCT performance trends for achieving higher power densities with new technology platforms. The increase in power has been divided into two categories, the first is related to an increase in power density through lower losses and/or higher operating temperatures. Furthermore, the main enabling factor for achieving these trends is linked strongly with a high current turn-off current capability for increasing the safe operation area (SOA) of the device. The second trend target an increase in absolute power by either an increase in device size from the state-of-the-art 91mm to 150mm and/or through integration concepts which in principle provides the full targeted functionalities as per application requirement with a single wafer device instead of employing two devices (IGCT and diode).

In this article we will discuss the main features which makes the IGCT an attractive option for high power applications with respect to the technology developments outlined above. Each of the technology platforms will be presented with regard to the device design and targeted performance while providing static and dynamic results from fabricated prototypes samples.

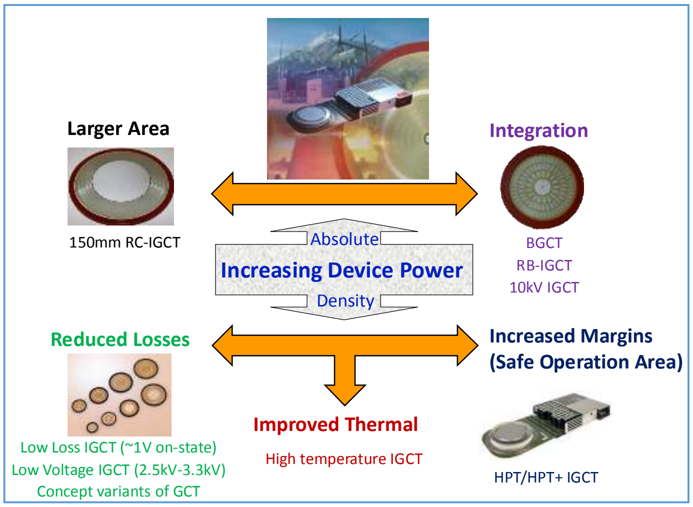


Fig. 4: IGCT development trends for achieving lower losses and/or higher power handling capabilities.

Current technologies

Increased margins: High Power Technology

The main limiting factor to conventional IGCTs has been related to the maximum controllable turn-off current capability and not due to losses or thermal constrains. Therefore, the introduction of the High Power Technology (HPT) platform [11] is hailed as a major step for improving the IGCT SOA performance while providing an enabling platform for future development trends as discussed below. The HPT-IGCT gives an increase in the maximum turn-off current of up to 40% at 125°C, incorporating an advanced corrugated p-base design compared to a standard uniform p-base junction as shown in Fig. 5 that ensures controlled and uniform dynamic avalanche operation with better homogeneity over the diameter of the wafer during device turn-off. The HPT has been proven for IGCT products with voltage ratings up to 6.5kV. Fig. 6 shows the comparison of the maximum turn-off current capability between conventional (standard p-base) IGCT and HPT-IGCT. Fig. 6 shows also an example of the powerful turn-off switching capability of the 4.5kV, 91mm HPT-IGCT generation. The test was performed in a circuit without a snubber and was carried out to establish the SOA limits of the device which means that the conditions were set outside the boundaries given in the device data sheet. The IGCT was capable of turning off in excess of 5kA by withstanding extreme conditions with a large stray inductance. We can clearly observe that the IGCT was also able to reach and sustain a high stress transient mode referred to as the Switching-Self-Clamping-Mode (SSCM) [15] as the overshoot voltage reaches levels close to that of the static breakdown voltage.

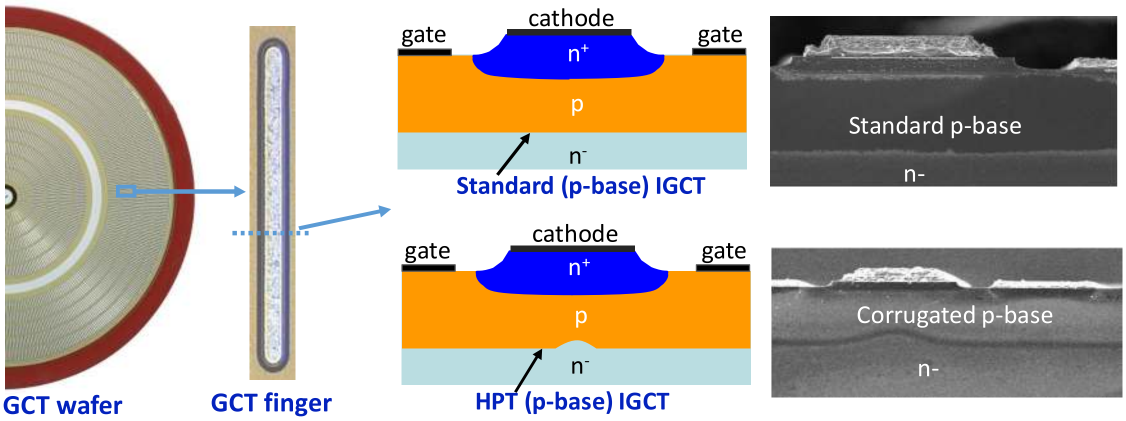


Fig. 5: Schematic structures and SEM pictures of the standard p-base IGCT and HPT-IGCT.

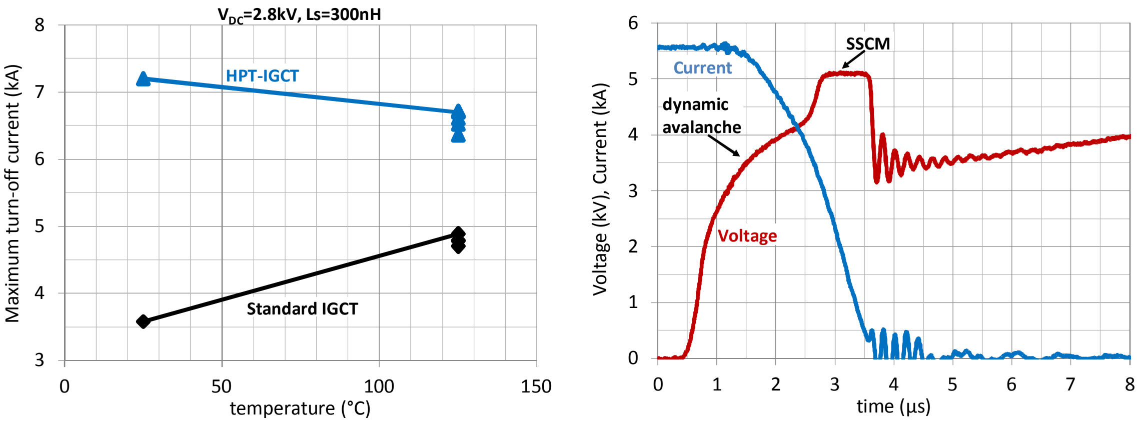


Fig. 6: Experimental results of the HPT-IGCT. Left: the comparison of the maximum controllable turn-off current capability between HPT-IGCT and standard (conventional p-base) IGCT. Right: the SOA turn-off waveforms of a 4.5kV, 91mm HPT-IGCT with SSCM (switching-self-clamping-mode).

Integration: Reverse Blocking IGCT (6.5kV and 2.5kV)

In certain applications such as the solid state DC breaker, AC-applications and in current source inverters (CSI), a symmetrical blocking switching device is required. Although this technically could be accomplished by using an Asymmetric IGCT connected in series with a fast diode, the preferred solution is a Symmetric IGCT in a single wafer [16]. Since the required performance and some modes of operation are different from the other IGCT, device design optimization is needed to achieve the reverse blocking performance along with low losses and robust switching performance. Both 6.5kV

RB-IGCTs [17] for CSI applications and 2.5kV RB-IGCTs [18] for bi-directional DC breaker applications have been developed. Fig. 7 shows the on-state characteristics and switching waveforms of a 91mm, 2.5kV RB-IGCT showing on-state voltage drop as low as 0.9V at rated current i.e. 1kA, 125°C and a maximum controllable turn-off current capability up to 6.8kA at 1.6kV, 125°C [18].

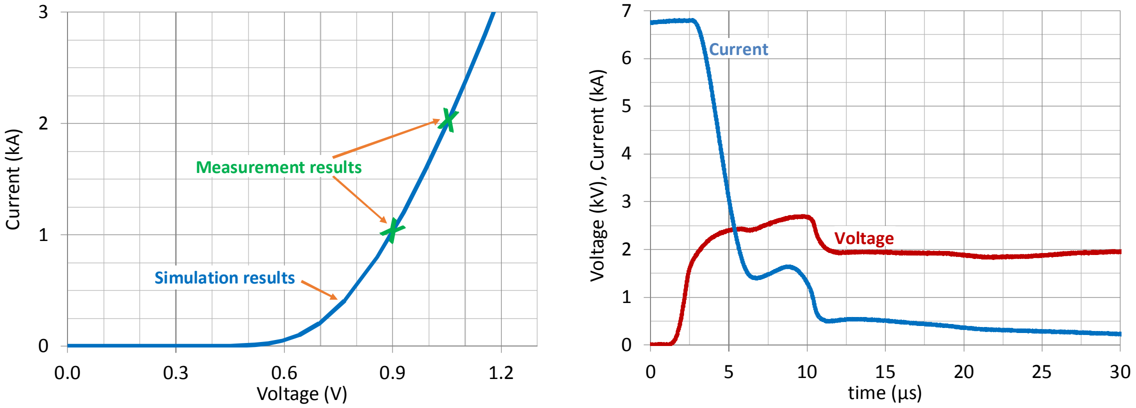


Fig. 7: 91mm, 2.5kV RB-IGCT at 125°C. Left: on-state simulation and measurement results. Right: turn-off measurement results showing successful turn-off current capability up to 6.8kA at 1.6kV.

Recent developments

Integration: High Voltage Ratings (10kV IGCT)

It is possible to make a 3-level inverter without series connection for line voltages of 6kV – 6.9kV if IGCTs with a voltage rating in the range of 8.5kV – 10kV were available. These high voltage devices offer several advantages such as simple mechanical design, less control complexity and high reliability compared to series connection of two 4.5kV or 5.5kV devices for line voltages of 6 – 6.9kV. Therefore, 10kV rated devices have been manufactured with the HPT platform to prove the feasibility of higher voltage ratings for IGCTs [19-20]. The turn-off waveforms of 91mm, 10kV IGCT are shown in Fig. 8 along with the manufactured prototype with the special high insulated press-pack.

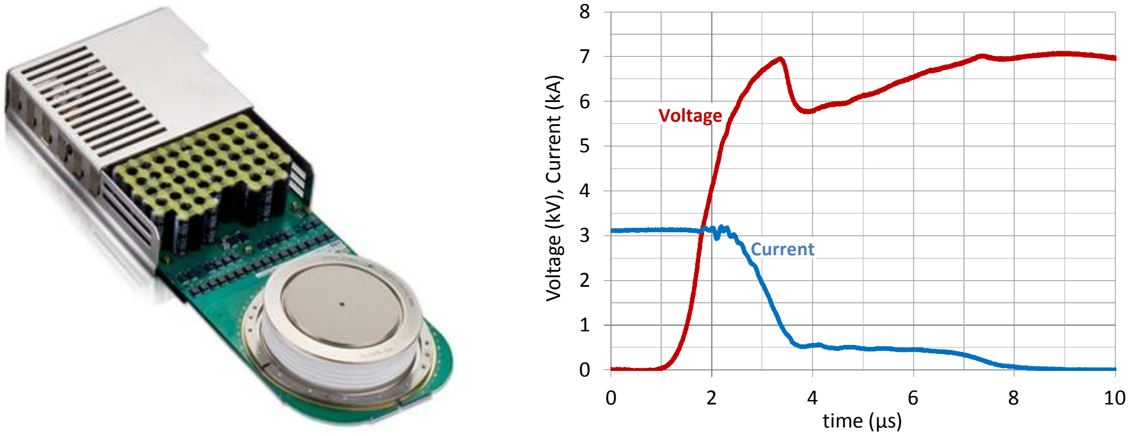


Fig. 8: 91mm, 10kV IGCT. Left: the device in a hermetic package and with its integrated gate unit. Right: turn-off measurements up to 3.3kA at 5.5kV and 125°C.

Improved thermal performance: High Temperature IGCT (HPT+)

A feasible way to increase the output power of an existing converter design is to increase the temperature rating of the used power semiconductor device. For continuous operation the cooling system may set a limit for the additional losses that the increased temperature allows. For intermittent operation though, the temperature increase is a valid option due to the increase in average power and since the requirements on the cooling system are limited. It is important that the device can handle a high load for a limited amount of time thus avoiding having to use a converter one size larger due to just one critical operating point. To accomplish this, a number of improvements to the HPT-IGCT are being implemented with the goal to allow a temperature increase to 140°C. Further optimization of the corrugated p-base doping profiles were introduced for the next generation HPT+ platform to allow full SOA in the whole temperature range up to 140°C as shown in Fig. 9 [21]. In addition, the internal interfaces such as the metallization on the wafer have been improved to reach a higher thermo-mechanical wear resistance. This is done to allow the higher temperature excursions that the intermittent operation up to 140°C can experience compared to the current devices that are rated 125°C. The verification of these improvements have started and the first results look promising. It can be seen also from Fig. 9 that the HPT+ technology has a clearly improved technology curve compared to HPT-IGCT due to its optimized corrugated p-base design.

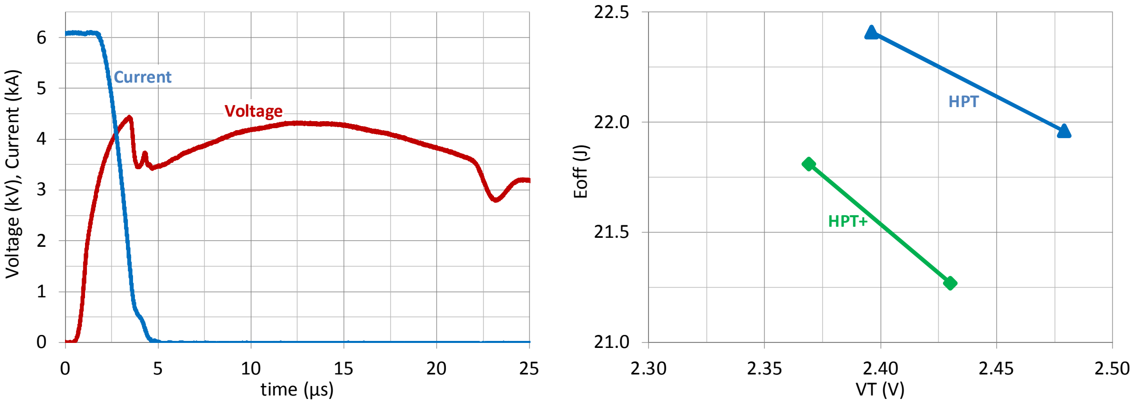


Fig. 9: Left: the SOA turn-off waveforms of a 4.5kV, 91mm HPT+ IGCT up to 6.1kA at 2.8kV, 140°C. Right: technology curves for HPT and HPT+ IGCTs at 4kA, 2.8kV, 125°C.

Reduced conduction losses: Towards 1 Volt on-state, 3.3kV IGCT demonstration

In recent years there is a clear trend towards using multilevel topologies in many power electronics applications [22]. These converters are operating at fairly low switching frequencies but at the same time they require high current carrying capabilities and/or high efficiency. Due to its inherent low conduction loss thyristor properties and the hard switched functionality, the IGCT is predestined for these applications. Therefore, further optimization is required for the IGCT towards very low on-state voltages (~1V) through anode engineering as shown in Fig. 10 while maintaining good overall performance.

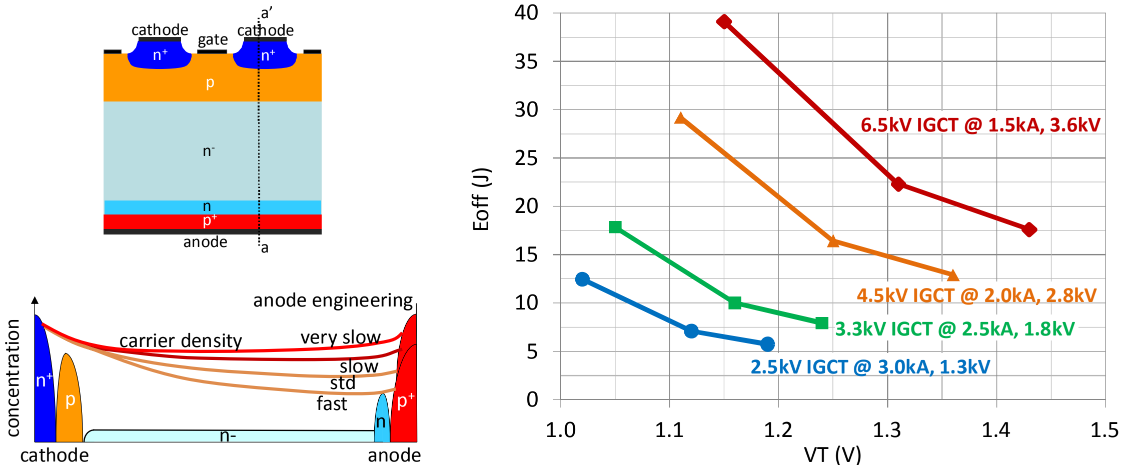


Fig. 10: Left: IGCT structure and its doping & anode engineering carrier profiles along the cutline a'-a. Right: technology curves of different voltage class 91mm IGCTs at 125°C achieved through anode engineering (i.e., with three different anode doping concentrations).

Since there is a certain amount of freedom in selecting the device voltage for a multilevel system a number of simulations and experiments have been performed for a wide range of voltage classes to see what performance can be achieved [13]. The available results are summarized in Fig. 10 and give an input to the designers of multilevel converters to see how the systems can be optimized with respect to the minimum total inverter losses for a given topology, voltage rating and current rating.

Furthermore, first prototype samples of 3.3kV RC-IGCTs were manufactured to verify the simulation results. Three different anode injection trials were carried out (A1, A2 and A3) with regard to the potential of 3.3kV RC-IGCTs to achieve very low conduction losses even at higher currents with reasonable switching losses. Fig. 11 illustrates the technology curve and turn-off waveforms of 3.3kV RC-IGCT prototype samples [23].

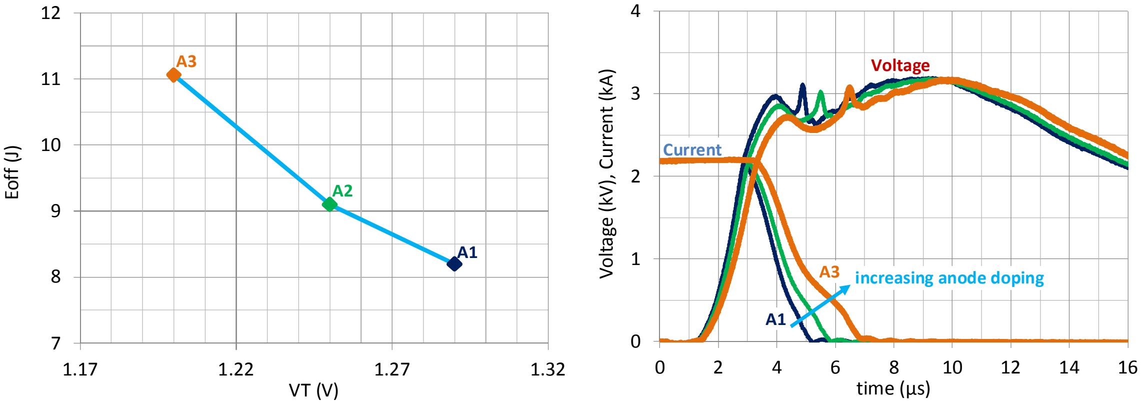
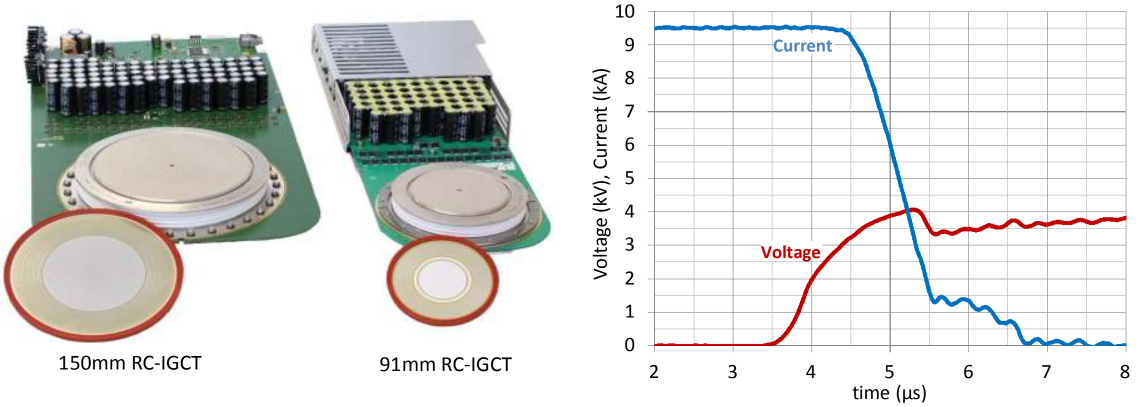


Fig. 11: 91mm, 3.3kV RC-IGCT. Left: technology curve at 2kA, 2kV and 125°C achieved through the anode engineering (anode doping A3>A2>A1). Right: measured turn-off waveforms at 2.2kA, 2kV and 125°C for three different anodes A3, A2, A1.

Larger area: 150mm RC-IGCT

The quest for ever-growing power ratings makes the option of expanding into larger silicon diameters viable [9]. Compared to the previous technology, the HPT has an improved scalability that enables the design of devices beyond the standard 91mm wafer size IGCT products that are available today. The first 150mm Reverse Conducting 4.5kV IGCT prototypes based on HPT+ technology have recently been manufactured and a prototype with gate unit is shown in Fig. 12 along with the SOA turn-off waveforms in GCT-mode [24]. Such high current capability gives a strong indication that the wafer, housing and gate unit have the targeted performance with respect to uniformity and absolute inductance. With this device, it will be possible to make 3-level inverters up to about 20MW without the need for series or parallel connection of power semiconductor devices.


150mm RC-IGCT

91mm RC-IGCT

Fig. 12: 150mm, 4.5kV RC-IGCT. Left: its package and gate unit compared to 91mm device. Right: measured turn-off waveforms of the 150mm RC-IGCT in GCT-mode up to 9.5kA at 2.8kV, 125°C.

Future trends / novel concepts

Full integration: Bi-mode Gate Commutated Thyristor

The conventional RC-IGCT enables better component integration in terms of process and reduced parts count at the system level, therefore improved reliability. As explained before, in a RC-IGCT the GCT and diode are integrated into a single wafer but they are fully separated from each other as shown in Fig. 2. 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. Therefore, a new fully integrated device (interdigitated integration) concept was developed referred to as the Bi-mode Gate Commutated Thyristor (BGCT) for integrating an IGCT and Diode into a single structure while utilizing the same silicon volume in both GCT and Diode modes [25]. Each individual segment acts either as GCT cathode or Diode anode as shown in Fig. 13.

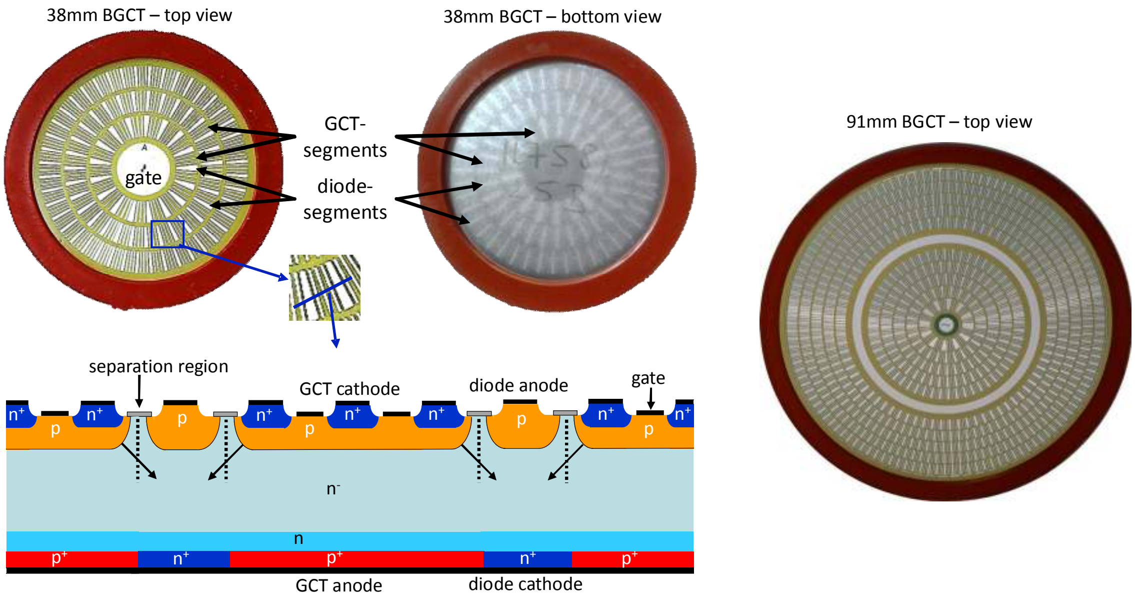


Fig. 13: The fabricated 4.5kV BGCTs. Top left: 38mm BGCT prototype (top view and bottom view). Bottom left: the schematic cross section of the BGCT from top side to bottom side. Right: recently fabricated 91mm BGCT prototype.

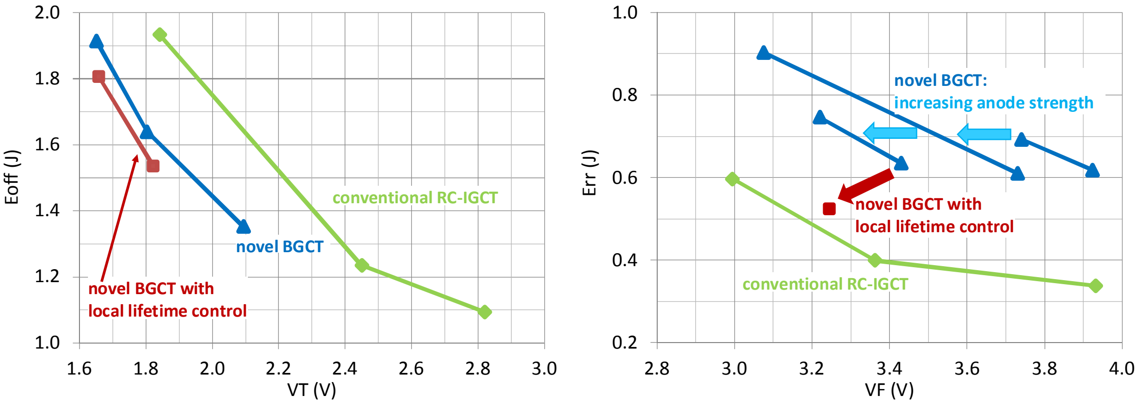


Fig. 14: Comparison of the experimental technology curve (turn-off losses vs. on-state voltage drop) between BGCT and conventional RC-IGCT at T = 115°C. VT and VF are at 300A and Eoff and Err are at 340A, 2700V. Left: GCT-mode. Right: diode-mode.

This interdigitated integration results in an improved diode as well as GCT area, better thermal distribution, softer reverse recovery and lower leakage current compared to conventional RC-IGCTs. The BGCT concept has been demonstrated first experimentally with 38mm, 4.5kV prototypes [26] and extended to 91mm size (recently fabricated 91mm, 4.5kV BGCT prototype can be seen in Fig. 13). The experimental results show that the BGCT has considerably lower leakage current (~ 4 times lower leakage at 2.8kV, 125°C) compared to that of the conventional RC-IGCT due the presence of anode shorts leading to a lower bipolar gain effect. This would enable the device to operate at higher junction temperatures ($T_{jmax} > 125°C$) and hence higher power rating of the converters. As shown in Fig. 14, the experimental results also demonstrated 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 significantly lower leakage current and soft reverse recovery behaviour. Fig. 15 illustrates the turn-off waveforms of the 38mm, 4.5kV BGCT compared to that of the 38mm, 4.5kV RC-IGCT both in GCT- and diode-modes. In GCT-mode, both BGCT and RC-IGCT show similar turn-off waveforms (same turn-off losses), while the on-state of the BGCT is 150mV lower compared to RC-IGCT due to more available area in BGCT. Also in diode-mode, the BGCT shows a softer reverse recovery behaviour compared to RC-IGCT due to the distributed p^+- and n^+-regions on the backside (diode cathode side).

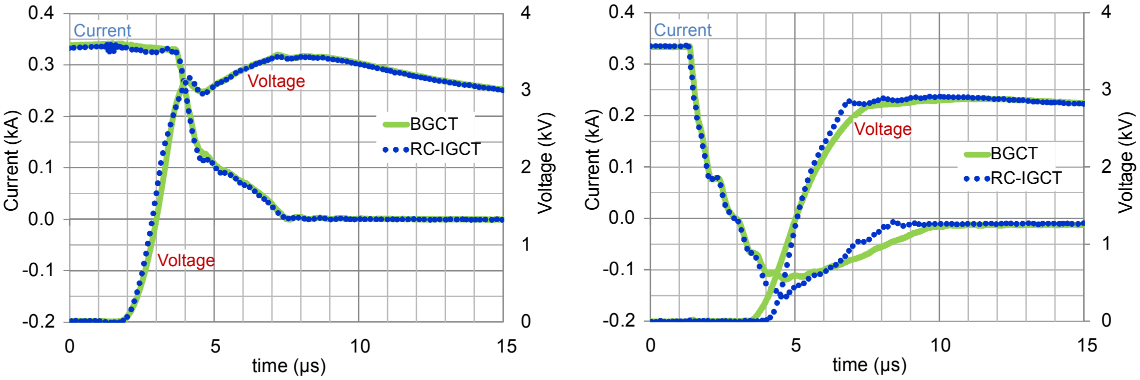


Fig. 15: Measured turn-off waveforms of the 38mm, 4.5kV BGCT and RC-IGCT at 115°C, 0.34kA, 2.7kV. Left: in GCT-mode. Right: in diode mode.

Reduced losses: Concept variants of GCT (IGDT, Dual GCT)

A number of IGCT concept variations were proposed and demonstrated to reduce the switching losses of the IGCT such as the Integrated-Gate Dual Transistor (IGDT) and Dual GCT. The IGDT or also called dual-gate GCT has two gate-units with one on cathode side and another one on the anode side [27]. With this dual-gate technology, the tail losses can be completely eliminated thereby switching losses can be reduced significantly compared to conventional IGCT. The dual-gate technology can be an attractive solution especially for high voltage devices such as 10kV where the switching losses are a main concern. One the other hand, the concept of the Dual GCT is to integrate monolithically two GCTs on a single wafer, in which one is optimized for low conduction losses and the other one for low switching losses to improve the performance of the device compared to a single IGCT [28]. In order to be switched independently (to minimize the switching losses, the device with lower conduction losses has to be switched-off first compared to the other one), separate gate connections have to be provided. The concept has been investigated by numerical simulations and verified experimentally using two discrete IGCT devices.

Conclusion

In this paper, a review of recently introduced IGCT technologies with improved performance and functionalities have been presented along with experimental results obtained from manufactured prototype samples. This paper will provide a full and comprehensive review for power electronics systems designers willing to explore the potential performance advantages of the IGCT latest technologies for future high power applications. These include devices having higher operational temperatures, reverse blocking and reverse conducting functionalities, lower losses towards 1V on-state, wider range of voltage ratings (2.5kV – 10kV), larger areas up to 150mm (up to 10kA), and the BGCT.

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