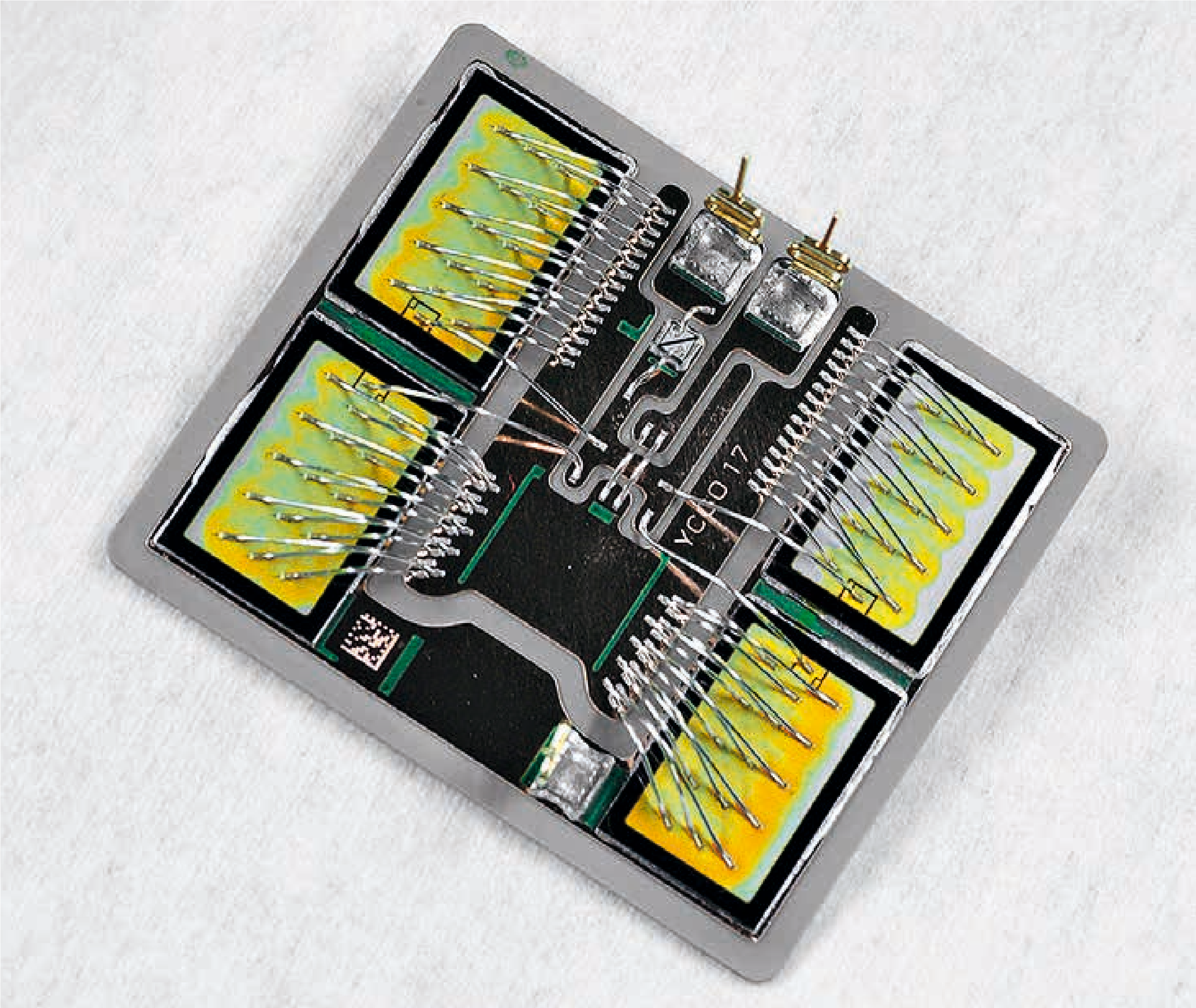
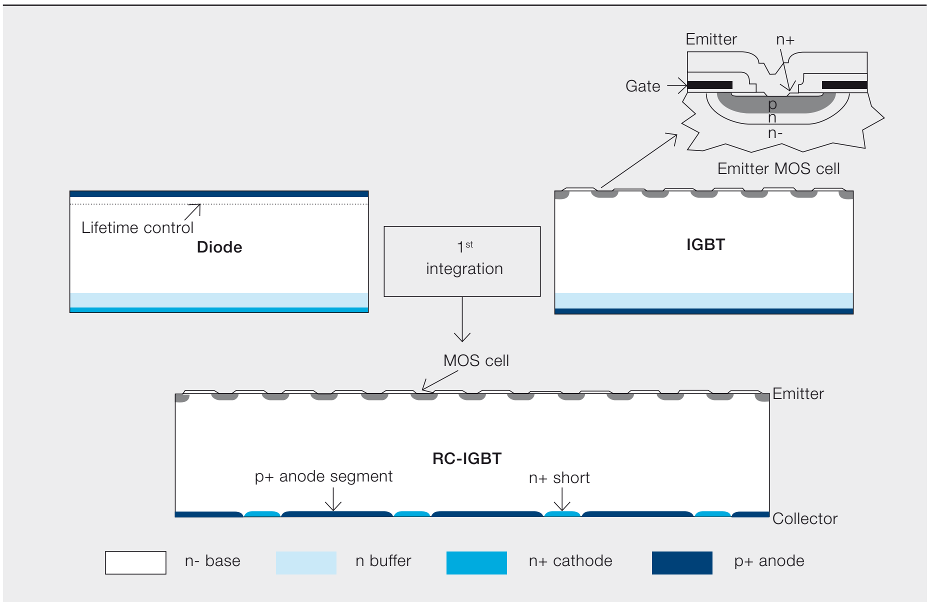


The two-in-one chip

The bimode insulated-gate transistor (BIGT)

MUNAF RAHIMO, LIUTAURAS STORASTA, CHIARA CORVASCE, ARNOST KOPTA – Power semiconductor devices employed in voltage source converter (VSC) applications typically carry current in one direction only. VSC circuit topologies with inductive loads, however, commonly pair switchable elements that conduct in one direction with (freewheeling) diodes that conduct in the other (reverse direction or anti-parallel). It has thus long been a goal of semiconductor manufacturing to achieve full integration of the two into a single device, and ideally, into a single silicon structure. Such integration opens the road to higher power densities and more compact systems while at the same time simplifying manufacture. In IGBT[1] technology, reverse-conducting switches integrated onto a single chip have typically been restricted to lower-power devices and special applications. ABB has achieved a breakthrough with its BIGT (bimode insulated-gate transistor), integrating a freewheeling diode into the switching device while achieving operating characteristics previously restricted to far larger devices.

1 First integration step: reverse conducting IGBT (RC-IGBT)



Due to the inherent technical challenges associated with the concept of integrating switching devices with anti-parallel diodes, such an approach has (in recent years) only been employed for lower power components such as IGBTs and MOSFETs[2] and for special applications. Furthermore, for large-area bipolar devices, such as the IGCT[3], monolithic integration has been utilized but with the IGCT and diode utilizing fully separated silicon regions.

Development efforts at ABB have over the past few years targeted a fully integrated high-power IGBT and diode structure on a single chip. The main target application was for hard-switching mainstream inverters[4]. The new power semiconductor device concept is referred to as the bimode insulated gate transistor (BIGT). The first prototype devices, with voltage ratings above 3,300 V demonstrated higher power densities than conventional chips, and improved over-all performance. The BIGT was designed in accordance with the latest IGBT design concepts while fully incorporating an optimised integrated anti-parallel diode in the same structure. In addition to the power and size impact of the BIGT, the device also provides improved turn-off softness in both operational modes, high operating temperature capability, higher fault condition performance under IGBT short circuit and diode surge current[5], and improved current sharing when devices are operating in parallel. In addition, by utilizing the same available silicon volume in both IGBT and diode modes, the device provides enhanced thermal utilization due to the absence of device inactive operational periods and hence, improved reliability.

The practical realization of the single chip BIGT technology will provide a potential solution for future high voltage applications, demanding compact systems with higher power levels, especially those with high diode current requirements which could prove to be beyond the capability of the standard two-chip approach.

Several existing and new technologies were employed for the BIGT in order to realize the integration of the IGBT and diode functionalities.

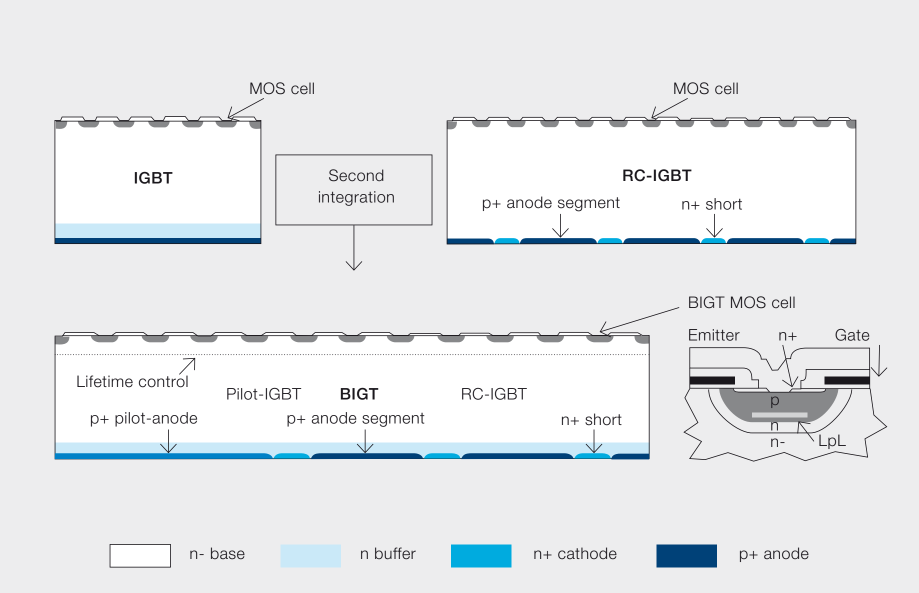
The integration challenge

In modern applications employing IGBT modules, the diode presents a major restriction with regard to its losses, performance and surge-current capability. Both limits are a result of the historically limited area available for the diode: a typical IGBT to diode area ratio is in the region of 2:1. These limits were essentially established after the introduction of modern low-loss IGBT designs. The approach of increasing the diode area is not a preferred solution, and in any case remains constrained by the footprint of the package designs. The demand for increased power densities of IGBT and diode components has thus shifted the focus to a solution integrating IGBT and diode, or what has normally been referred to as the reverse-conducting IGBT (RC-IGBT).

Until recently, the use of RC-IGBTs has been limited to voltage classes below 1,200 V for specialised soft switching applications with reduced diode requirements. Conventionally, the realization of such a device for high voltage and mainstream hard switching applications has always been hindered by design and process issues, resulting in a number of performance drawbacks and trade-offs summarized as follows:

Title picture
ABB's new BIGT integrates reverse-conducting diode functionaility into the structure of the semiconductor switch.

2 Second integration step: the bimode insulated gate transistor (BIGT)



– Snap-back[6] in the IGBT on-state I–V characteristics – the MOSFET shorting effect
– Trade-off of IGBT on-state versus diode reverse-recovery losses – the plasma shaping effect
– IGBT versus diode softness trade-off – the silicon design effect
– Safe operating area (SOA) – the charge uniformity effect

In the past few years, development efforts at ABB aimed at tackling the above issues have resulted in an advanced RC-IGBT concept, the BIGT.

The BIGT concept

The BIGT concept is based on two integration steps. The first of these is illustrated in ➔ 1. The IGBT and diode share a single structure. On the collector side, alternating n+ doped areas are introduced into an IGBT p+ anode layer. These then act as a cathode contact for the internal diode mode of operation. The area ratio between the IGBT anode (p+ regions) and the diode cathode (n+ regions) determines which part of the collector area is available in IGBT or diode modes respectively. During conduction in diode mode, the p+ regions are inactive and do not directly influence the diode conduction performance. However on the other hand, the n+ regions act as anode shorts in the IGBT mode of operation, strongly influencing IGBT conduction mode.

One of the implications of anode shorting is the voltage snapback referred to previously. This is observed as a region of negative resistance in the device's IGBT mode I–V characteristic. This effect will have a negative impact when devices are connected in parallel, especially at low temperature conditions. To resolve this issue, a second integration step was required. It has been shown that the initial snap-back can be controlled and eliminated by introducing wide p+ regions into the device, also referred to as a pilot-IGBT. This approach resulted in the BIGT concept which, in principle, is a hybrid structure consisting of an RC-IGBT and a standard IGBT in a single chip ➔ 2.

The pilot area is centralized on the chip to obtain better thermal distribution and reduced current non-uniformities. It is also designed to provide the outermost functional reach within the chip while ensuring a large RC-IGBT region. Alternating p+ and n+ regions are arranged in a striped structure with an optimized radial layout to ensure smooth and fast transition in the IGBT conduction mode from the pilot area to rest of the chip ➔ 3.

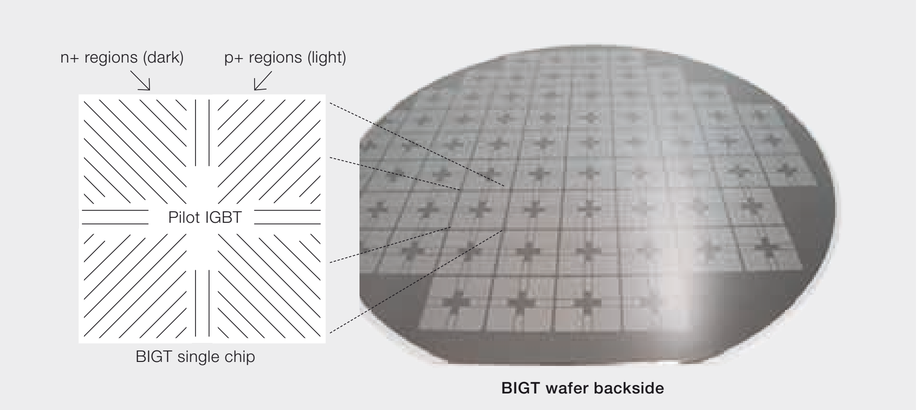
Several existing and new technologies were employed for the BIGT in order to realize the integration of the IGBT and diode functionalities. First, it is important to note that technology platforms already in use by ABB, such as the high voltage soft-punch-through (SPT) buffer and enhanced-planar cell concepts[7] have been

Development efforts over the past few years at ABB have targeted a fully integrated high power IGBT and diode structure on a single chip.

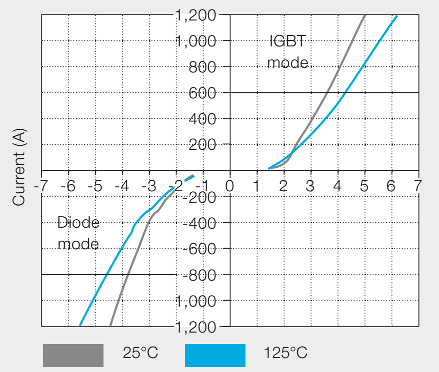
Footnotes

1 An IGBT (insulated-gate bipolar transistor) is a voltage-controlled semiconductor switch seeing widespread use in power electronics.
2 A MOSFET (metal-oxide-semiconductor field-effect transistor) is a semiconductor device used in both switching and amplification applications. It's switching applications are typically of lower power than IGBTs.
3 An IGCT (integrated gate-commutated thyristor) is a GTO (gate turn-off thyristor) optimized for hard switching and using a gate-drive integrated into the device. For more background on different semiconductor technologies, see "From mercury arc to hybrid breaker" on pages 70–78 of this edition of *ABB Review*.
4 Hard switching is a current turn-on / turn-off involving high dv/dt and di/dt during the switching.
5 Surge-current capability is a device's ability to accept a sudden and short current peak (far the device's its nominal current rating) without suffering damage.
6 Snap-back is an effect observed in IGBTs in which the on-state voltage can display a brief peak during turn-on, also shown in figure 9.
7 See "Switching to higher performance", pages 19–24, *ABB Review* 3/2008.

3 The BIGT backside design

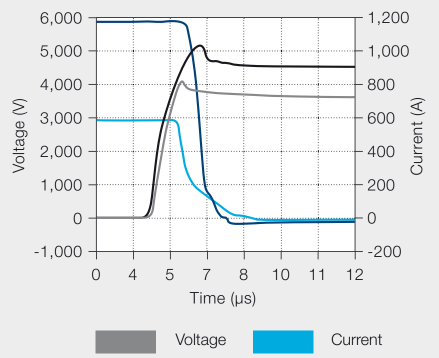


5 6.5 kV/600 A BIGT HiPak 1 on-state characteristics



4 The 6.5 kV/600A BIGT HiPak 1

6 6.5 kV/600 A BIGT HiPak 1 IGBT mode turn-off waveforms



The BIGT technology is initially being developed for high voltage devices and has been demonstrated at module level with voltage ratings ranging from 3.3 kV and up to 6.5 kV.

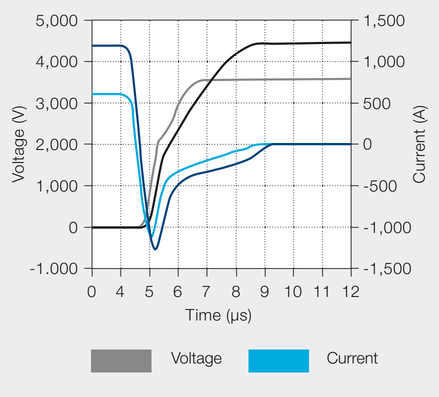
main enablers of this integration. In addition to their well known robustness and low loss properties, the SPT optimum doping profile contributes significantly to reducing the snap-back effect while the miniaturized enhanced-planar stripe cell design plays an important role in reducing the diode conduction and switching losses without having a negative impact on IGBT performance. Furthermore, in addition to a standard axial lifetime control, a precise local p-well lifetime (LPL) process was also devised (as shown in ➔ 2) to improve the trade-off of IGBT on-state versus diode reverse recovery losses. Finally, due to the anode shorts design, the BIGT has inherited a number of properties that have resulted in device performance advantages in both operation modes such as soft switching behavior under extreme conditions and very low leakage currents for operating at higher maximum junction temperatures.

BIGT performance

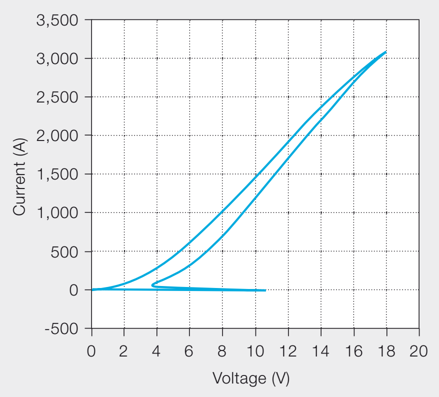
The BIGT technology is initially being developed for high voltage devices and has been demonstrated at module level with voltage ratings ranging from 3.3 kV and up to 6.5 kV. The test results presented here were carried out on the recently created 6.5 kV standard footprint HiPak 1 modules (140 × 130) with a current rating of 600 A ➔ 4.

A conventional IGBT/diode substrate will normally be occupied by four IGBTs and two diodes while the new substrate is now capable employing six BIGT chips all operating all in IGBT or diode mode. The BIGT advantage is clearly demonstrated her with the HiPak 1 module containing four BIGT substrates for a total of 24 BIGT chips being practically able to replace the larger HiPak 2 IGBT module (140 × 190) which normally contains six substrates having a total of 24 IGBTs and 12 diodes. The larger standard IGBT module has the further disadvantage of employing a much smaller diode area. This area is normally a limiting factor when in rectifier mode of operation and for the surge current capability. On the other hand, a larger HiPak 2 BIGT module is feasible with a total of 36 BIGT chips and its rating can potentially reach up to 900 A.

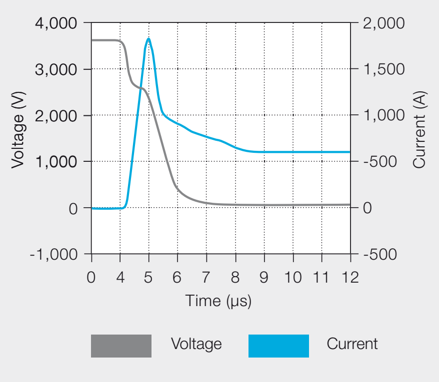
7 6.5 kV/600 A BIGT HiPak 1 diode mode reverse-recovery waveforms



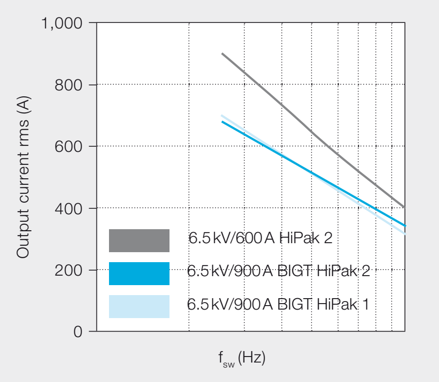
9 6.5 kV BIGT substrate diode mode surge-current capability



8 6.5 kV/600 A BIGT HiPak 1 IGBT mode turn-on waveforms



10 Output current capability of the 6.5 kV HiPak 1 and HiPak 2 modules in inverter modes



The BIGT HiPak 1 modules were tested under static and dynamic conditions, similar to those applied to state-of-the-art IGBT modules. The on-state characteristics of the BIGT in IGBT and diode modes are shown in ➔ 5. An on-state of approximately 4.2 V at 125 °C is shown at the 600 A nominal current for both operational modes. In addition, supporting the safe parallel connection of chips, the curves show a strong positive temperature coefficient even at very low currents and in both modes of operation. This is due to the optimum emitter injection efficiency and lifetime control employed in the BIGT structure.

For dynamic measurements at nominal conditions, the DC-link voltage was set to 3,600 V, while for SOA characterization it was increased to 4,500 V. All measurements were performed at 125 °C with a fixed gate resistor of 2.2 Ω, a gate emitter capacitance of 220 nF and a stray inductance of 300 nH. In ➔ 6 – 7, the module-level IGBT and diode turn-off waveforms are presented respectively under nominal and SOA conditions. BIGT turn-off waveforms have always displayed smoother performance than standard IGBT/diode modules. The BIGT did not show oscillations or snappy characteristics under any conditions. ➔ 8 also shows the BIGT turn-on behaviour under nominal conditions. The total IGBT and diode switching losses for the tested module were in the range of 10 Joules which is similar to that measured for the current standard 6.5 kV/600 A HiPak 2 IGBT module.

A HiPak 2 BIGT module is feasible with a total of 36 BIGT chips and its rating can potentially reach up to 900 A.

➔ 9 shows the last pass measurement of the BIGT diode mode surge current capability for one substrate (rated 150 A), reaching up to 3,000 A. It is clear that the BIGT HiPak 1 offers the uncompromised surge performance of a corresponding HiPak 2 IGBT/diode module, and the BIGT HiPak 2 module goes well beyond that. Finally, standard reliability verifications and frequency operation tests were carried out successfully on BIGT modules and chips.

Based on these results, The BIGT device is expected to outperform a present state-of-the-art IGBT and diode in both soft and hard switching conditions, and also fulfil the rigorous robustness standards required of power devices today. ➔ 10 shows the simulated output current performance in inverter mode for the 6.5 kV BIGT HiPak1 and HiPak 2 modules compared to today's HiPak 2 IGBT module at 125 °C. The BIGT rectifier mode output current simulations will provide even higher capability due to the large diode area available in the BIGT module. The BIGT technology will pave the way for future generations of system designs for providing higher power densities and exceptional overall performance without any limitations coming from diode performance.

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