Prospects of Bipolar Power Devices in Silicon Carbide

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Abstract: There has been a rapid improvement in SiC materials and power devices during the last few years. SiC unipolar devices such as Schottky diodes, JFETs and MOSFETs have been developed extensively and advantages of insertion such devices in the power systems have been demonstrated. However, for high power systems such as high voltage converters, bipolar devices are preferable due to their low on-resistance. In this work, a detailed review of the current situation and future trends in SiC power switches, especially BJTs, IGBTs, and GTOs, is given with an emphasis on the device designs and characterization. On the contrary to Silicon BJTs, SiC BJTs exhibit a positive temperature coefficient for the on-state voltage drop, which makes SiC BJTs easily paralleled. In addition, a current gain of 50-70 has been routinely achieved on SiC BJTs which can significantly simplify the gate drive circuits. SiC IGBTs are suitable as the power switches in the range of 10 – 20 kV due to the conductivity modulation and simple gate driver. SiC GTOs have shown superior high current handling capabity even at high temperatures making the preferable device for high power pulse applications. This paper discusses the state-of-the-art achievements on these devices and identifies the key issues in SiC materials and device processing which will influence the future SiC power bipolar device commercialization.

INTRODUCTION

With the recent progress, power electronic interfaces to power systems such as static VAR compensators, high voltage dc (HVDC) transmission, and flexible ac transmission systems (FACTS), are getting more and more attention. These systems require power semiconductor devices with high voltage (>10 kV) and fast switching characteristics. Since the ratings of currently available Silicon Insulated Gate Bipolar Transistors (IGBTs) and Integrated Gate Commutated Thyristors (IGCTs) are limited to 6.5 kV, a series connection of power devices is necessary which increases complexity and cost of the systems. In addition the operating temperature of Silicon devices are limited by 150°C.

Power devices in silicon carbide (SiC) offer numerous benefits in high power systems due to high critical field and wide band gap of SiC [1]. Extensive research has been conducted on 4H-SiC power MOSFETs for blocking voltages up to 10 kV [2]. The high voltage power MOSFETs suffer from a dramatic increase of the on-resistance at high temperature due to reduction in bulk mobility. The bipolar devices in SiC such as Bipolar Junction Transistors (BJTs), IGBTs and Gate Turn-Off (GTO) Thyristors have a potential for achieving 1.2-20 kV rated single switches with sub-microsecond switching as well as higher junction temperature (300 °C) operation. In this paper, we examine the current status and technical issues which need to be addressed.

SiC BJT

SiC power bipolar junction transistors (BJTs) have been developed in recent years due to the unique properties such as low on-resistance, normally-off, positive temperature coefficient of the resistance, and fast switching speed. SiC BJTs can address the requirements in the 600 V to 10 kV range [4-5]. It is the only normally-off device in SiC which could achieve a comparable on-resistance to silicon CoolMOS, but exhibit superior high temperature operation.

A represenative device structure for 1200 V is shown in Fig. 1.

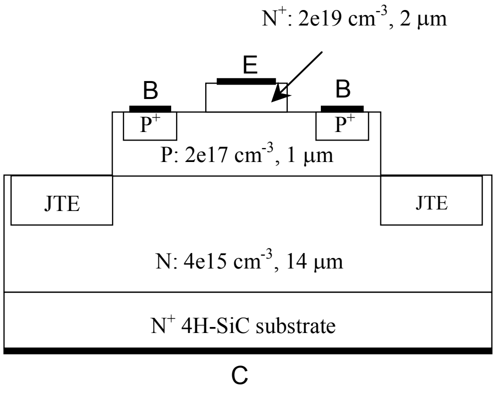


Figure 1: Cross section of a SiC BJT.

First important feature of the structure to note is the complete epitaxial construction of the device. It was shown by Agarwal et al [3] that implanted emitter structure which is common in silicon technology didn't work as well in SiC technology. The reason behind the poor performance of implanted emitter structure lies in the fact that there is considerable damage caused by ion-implantation of impurities in SiC which result in low life-time and consequently low current gain. The base contact regions have to be implanted for ease in fabrication and are kept at least 5 micron away from the emitter edge so as to keep the influence of implant-induced defects on current gain to a minimum.

The other remarkable features of BJT characteristics are that the current gain reduces with temperature and the on-resistance increases with temperature as shown in Fig. 2. This feature is very different from silicon devices and is extremely useful for stable operation of many devices in parallel or one large device. The reduction of current gain with temperature is explained by the deep acceptor levels in the base. At room temperature, the acceptors are only 10-20% ionized. However, at elevated temperure, ionization of acceptors increases and therefore the current gain reduces.

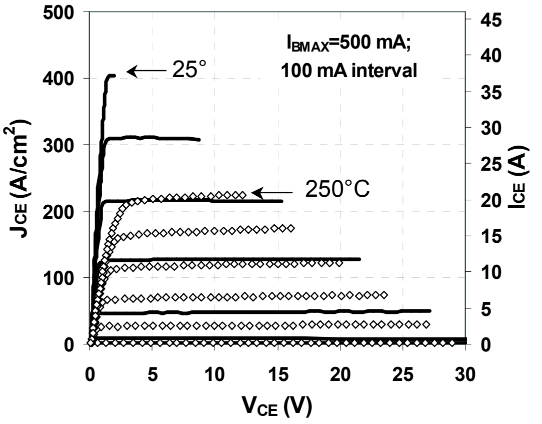


Figure 2: Output characteristics of SiC BJT at 25°C and 250°C.

The increase in on-resistance of the BJT with temperature can be explained by the fact that there is weak conductivity modulation of the collector region in saturation. The lack of strong conductivity modulation in collector is explained by the fact that the doping density the collector is relatively high compared to silicon for a given breakdown voltage due to the higher breakdown field strength of SiC. Therefore, the SiC BJT behaves essentially like a majority carrier device which also leads to faster switching as compared to silicon BJTs. The current gain of 70 in the active region at room temperature can be routinely achieved as shown in Fig. 2. The open-emitter breakdown voltage, BV_{CBO}, and the open base breakdown voltage, BV_{CEO}, are shown in Fig. 3. Due to the high bandgap of SiC, the leakage currents are relatively small even at elevated temperatures.

The on-characteristics of similar size, 1.2 kV SiC BJTs and MOSFETs are compared in Fig. 4. As one can clearly see, the on-resistnce of SiC BJT is approximately half of that of MOSFET. The SiC MOSFETs are limited by the low inversion layer electron mobility whereas no such limitation exists for BJTs.

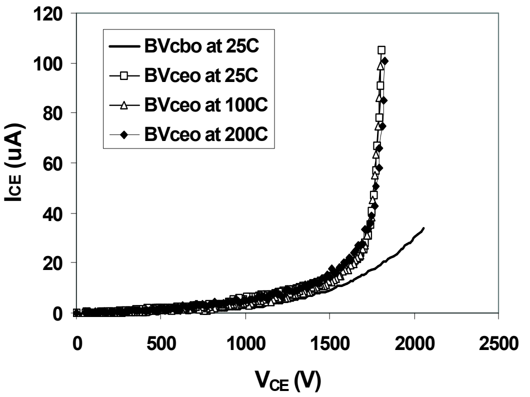


Figure 3: BV_{CEO} and BV_{CBO} at different temperatures for SiC BJT.

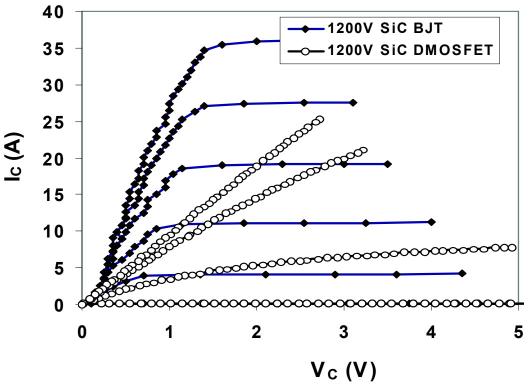


Figure 4: Comparison of output characteristics of BJTs and MOSFETs at 25°C. Device active area of both the devices: 0.16 cm^2. BJTs: I_{BMAX}=500 mA with 100 mA interval; MOSFETs: V_{GMAX}=16 V with 2 V interval.

As mentioned before, due to the lack of conductivity modulation, SiC BJTs switch extremely fast. In Figs. 5 and 6, we show turn-on and turn-off performance into a resistive load with 600 V power supply voltage and 57 A using a 1 ohm load resistance. The turn-off and turn-on times are approximately 25 ns indicating an ultrafast response of these devices.

SiC P-CHANNEL IGBT

While SiC BJTs do not show substantial conductivity modulation, SiC IGBTs depend upon it for a low forward drop in the range of 10 – 20 kV switches. IGBTs are a desirable device structure due to its simple gate drive interface and the great success in the silicon world. Technically, SiC MOS structure has been demonstrated with high breakdown strength and low interface charge density in recent years, paving the way for possible demonstration of IGBTs on this material.

A typical p-IGBT structure for 12 kV blocking is shown in Fig. 7 [6].

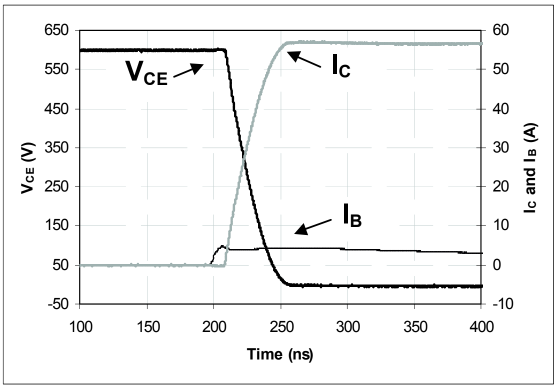
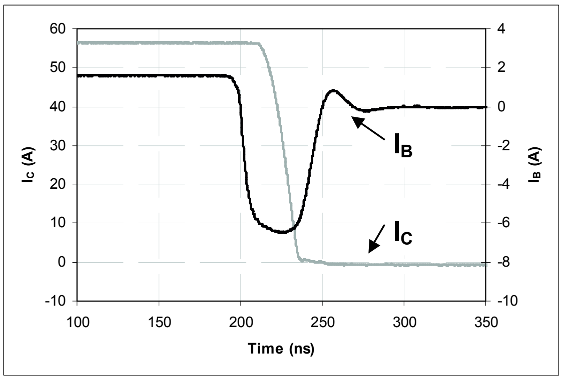


Figure 5: Resistive swtiching turn-on waveforms of the SiC BJT. V_{CE}=600 V; I_C=60 A.



Figur 6: Turn-off waveforms of the SiC BJT. V_{CE}=600 V; I_C=57 A.

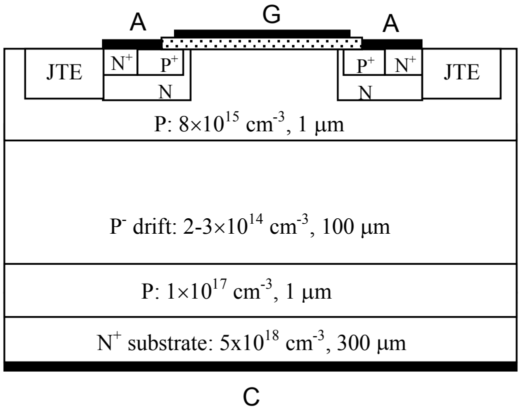


Figure 7: Cross section of a 12 kV SiC p-IGBT.

The first interesting feature to note is that the SiC IGBT has been constructed on an n^+ substrate due to approximately 50× higher conductivity of n-type substrates as compared to p-type substrates in 4H-SiC. This fact neccesiates the fabrication of p-channel IGBT. A hole surface mobility for p-channel mosfets of 12 cm^2/V-s has been demonstrated which was comparable to 15 cm^2/V-s for the electrons in n-channel mosfets. However, for higher voltage devices, the contribution of the MOSFET channel to the overall resistance is relatively small when compared to the resistance of the conductivity modulated drift layer. The n-channel IGBTs can be made starting out with n^+ substrates but the final performance of the both types of IGBTs is similar with 12 kV blocking voltage [7]. The p-channel IGBTs are much easier to build and therefore represent the device of choice.

The forward characteristics of the 12 kV p-channel SiC IGBT are compared with the 12 kV SiC n-channel MOSFETs and a series connection of two Si, 6.5 kV IGBTs at room temperature in Fig. 8. For sake of comparison, a constant power dissipation curve at 300 W/cm^2 has been drawn. At room temperature, a differential on-resistance of 18.6 mΩ·cm^2 at a gate bias of –16 V on p-IGBTs provides an evidence of strong conductivity modulation in the 100 μm p-type drift layer. It can be seen that the SiC p-IGBT has the highest current density and therefore the lowest conduction losses at a given forward drop.

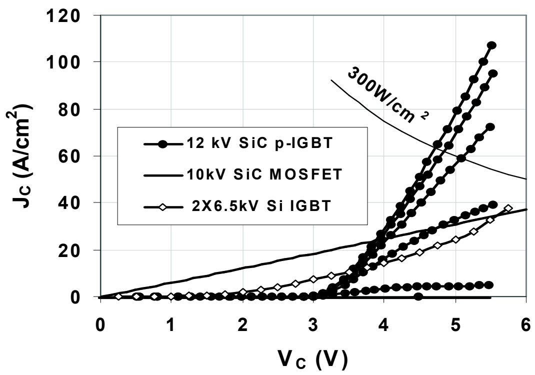


Figure 8: Output characteristics of the 12 kV SiC p-IGBT at 25ºC compared with a 10 kV SiC MOSFET and two Si 6.5 kV IGBT connected in series. V_{GMAX}=16 V with 2 V interval.

At elevated temperature, the forward drop of SiC IGBT remains relatively constant (Fig. 9) whereas the forward drop of SiC MOSFET increases by ~100% at 150°C. This phenomenon can be explained by the negative temperature dependence of the ambipolar diffusion coefficient and the positive temperature dependence of inversion layer mobility.

The blocking voltage of approximately 12 kV is shown in Fig. 10. The case for using SiC IGBTs at even higher voltages, up to 20 kV, can be easily justified based on the performance shown here. For higher voltage applications requiring 20 kV devices, a single SiC p-IGBT should be developed.

Devices were tested in a standard clamped inductive test circuit with a gate resistance of 10 Ω. A 10 kV, 1 A SiC JBS diode was used as free wheeling diode. The inductor was an air-core design with a measured inductance of 14 mH. An inductive switching test was done at 1.5 kV and 1.2 A (300 A/cm^2) for the p-IGBT. The turn-off waveforms are shown in Fig. 11.

The device shows a fast turn on speed of 40 ns. A turn off time of ~2.8 µs was measured. A long turn-off tail indicates the minority injection in the drift region resulting in a long turn-off time.

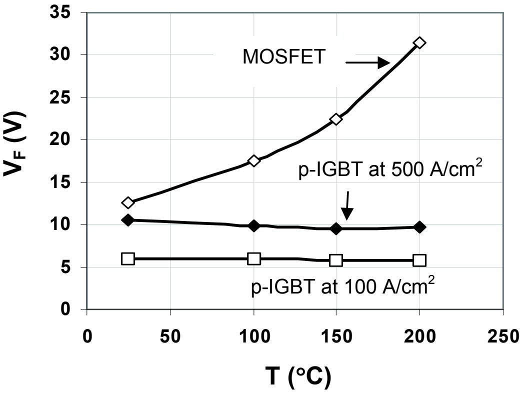


Figure 9. Dependence of forward voltage drop on operating temperature for 12 kV SiC p-IGBTs and SiC MOSFETs.

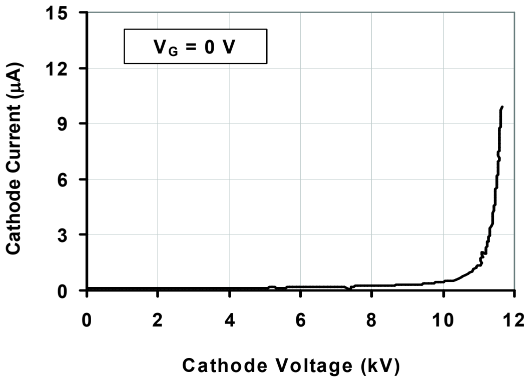


Figure 10: Blocking characteristic of p-IGBTs at 25°C.

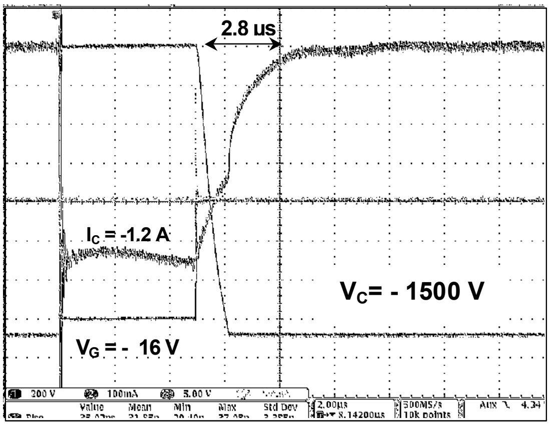


Figure 11: Inductive switching characteristics of the 12 kV SiC p-IGBT at 25°C. R_G=10 Ω; L=14 mH; a 10 kV, 1 A SiC JBS diode was used as free wheeling diode.

SiC SUPER GTO

Power thyristors offer a low forward voltage drop even at high on-state curretn densities due to strong conductivity moduclaiton from both anode and cathode. SiC Super GTOs (S-GTO) are being developed for very high voltage applications in utility (for example - Fault Current Limiters) and pulse power applications (for example - Rail Guns). These devices can be developed up to 20 kV in blocking voltage to reduce the number of devices in series and can work at high junction temperatures. The combination of reduced size of the series stack and lower cooling requirements due to higher junction temperature operation will lead to a large reduction in system volume and weight. In addition, when fully developed, the reliability of SiC devices will be much greater than Si devices due to very low reverse leakage currents. The higher speed of these devices compared to the silicon counterparts (due to a 10x lower minority carrier charge) will especially be handy for Fault Current Limiters and Pulse Power applications where speed is essential.

A typical device cross-section of an 8-10 kV SiC S-GTO is shown in Fig. 12. This device is also built on n^+ SiC substrate for the same reasons described earlier for SiC p-IGBT. As a result, unlike silicon GTOs, SiC GTOs have Anode on the top and Cathode on the bottom. The Gate is referred to the Anode. The cell-pitch is kept short (40 microns) to facilitate rapid turn-on and turn-off. The blocking layer is only 75 micron thick compared to a silicon device which will require a 750 micron thick blocking layer (and therefore impractical). A picture of the 7 mm x 7 mm SiC S-GTO is shown in Fig. 13. It has five gate pads to evenly distribute the gate current during turn-on and turn-off. With suitable double-sided packaging, these devices have shown turn-on di/dt of ~30 kA/µs-cm².

The DC forward blocking characteristic at room temperature are shown in Fig. 14. The device blocks approximately 9 kV in the forward direction. It blocks less than 150 V in the reverse direction due to the assymetrical design.

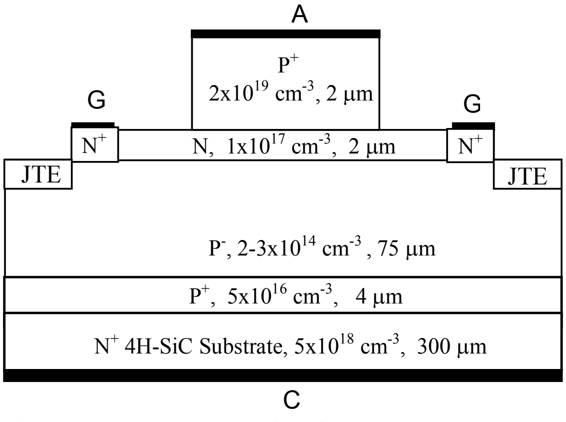


Figure 12: Cross section of a 9 kV SiC GTO.

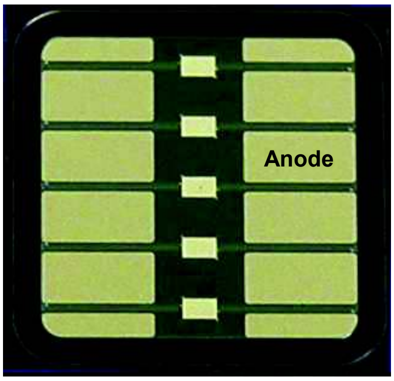


Figure 13: A picture of the 7 mm x 7 mm SiC S-GTO.

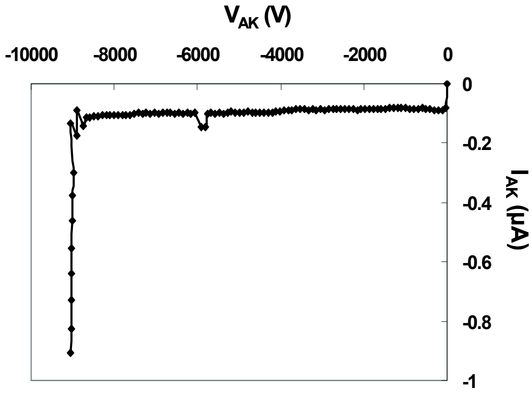


Figure 14: Blocking characteristic of the SiC GTO at 25°C.

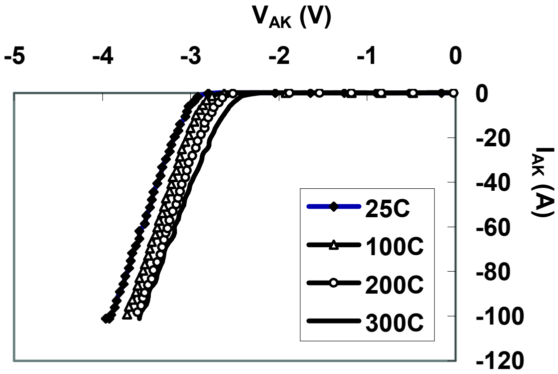


Figure 15: Output characteristics of a 9 kV SiC GTO at different temperatures. I_G=25 mA. Device active area: 36 mm^2.

The forward blocking is not a strong function of temperature due to very low leakage currents up to 300°C. The forward conduction characteristics are shown in Fig. 15 as a function of temperature. A forward drop of 3.6 V can be obtained at 300°C at 100 A as shown in Fig. 16. A very useful feature of this device is that at high current densities (>300 A/cm^2), a positive temperature coeffiecient in differential on-resistance is obtained which allows for stable parallel operation for pulsed power applications which typically operate at ~20 kA/cm^2.

Technical Issues

Reliability tests have shown that all the above devices currently suffer from a degradation of forward drop due to recombination-induced stacking faults in the drift layer [8]. Essentially, the defects known as stacking faults are created in a forward biased SiC bipola device wherever there is a recombination of electrons and holes. This phenomenon has been attributed to a particular dislocation called 'Basal plane Dislocation (BPD)'. When a SiC bipolar device is forward biased, the drift region is flooded with electron-hole pairs during operation. Stacking Faults (SFs) are formed by the energy released via carrier recombination. These SFs reduce the lifetime of the minority carriers, which in turn results in an increase in the forward voltage drop. SFs also result in a reduced current gain for BJTs and an increased holding current for GTOs. Over the last few years, tremendous progress has been made in reducing the density of BPDs in SiC epilayers. Today, this problem has been greatly reduced. However, further work is needed to completely eliminate the influence of BPDs in SiC bipolar devices.

The second important issue (applicable to IGBTs and GTOs) has to do with the fact that an ambipolar lifetime of at least 5 μs with better than 5% uniformity across the device is required for 20 kV class of bipolar devices in SiC. In silicon, one would typically need 1 ms of lifetime for 6 kV devices. Today, the mean lifetime in thick SiC epilayers, is approximately 1.5 μs but it is highly non-uniform across the wafer. The defects limiting the life-time need to be identified, eliminated and then a means of obtaining a uniform lifetime (for example, irradiation) needs to be established. Already, a significant technical research has been taking place in this area. Lastly, there is a need to reduce the doping of thick epilayers to below 10^{14} cm^{-3} for 20 kV class of devices (IGBTs and GTOs). Today, we can routinely obtain a doping of $2x10^{14}$ cm^{-3}.

SUMMARY

High power applications such as heavy duty traction motor drives and power distribution systems require power devices with a blocking voltage of > 6.5 kV and current capacity >1 kA. SiC power bipolar devices cater very well to these high power applications. SiC BJTs can routinely be made in 1.2 kV to 10 kV voltage range with current gains of 50-100. The 1.2 kV BJTs can operate up to 300°C with sub 50 ns switching and extremely low conduction and switching losses. The reduction in current gain and increase in on-resistance with temperature provide stable operation over a wide range of temperatures unlike silicon BJTs. For all practical purposes, SiC BJTs behave as majority carrier devices like SiC MOSFETs with added advantage of high temperature operation and twice the current density. Superior 4H-SiC power IGBTs derive great advantages by leveraging the unique material properties of SiC, with the efficiency of MOS control topology, and the on-state benefits of conductivity modulation of the drift layer. High voltage 4H-SiC IGBTs have been demonstrated to be superior to the DMOSFET counterparts with respect to the on-resistance and RBSOA. SiC p-IGBTs have shown 12 kV blocking, switching times of a few µs and low forward voltage drop – a significant improvement over 10 kV SiC MOSFETs and 6.5 kV Silicon IGBTs. They will dominate the applications requiring a breakdown voltage of 10-20 kV in future. Finally, SiC Super GTOs in the range of 10-20 kV will facilitate reduced series stack and cooling requirements in Fault Current Limiters and Rail Guns. In addition to faster switching, reduced conduction and switching losses and reduced cooling requirements, SiC bipolar devices will be less prone to thermal runaway owing to low leakage currents.

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