CoolSiC™ Automotive Discrete Schottky Diodes

Understanding the Benefits of SiC Diodes compared to Silicon Diodes

About this document

This application note explains the features and application benefits of Automotive CoolSiC™ Discrete Schottky Diodes.

Author: Ajay Poonjal Pai (IFAG ATV HP IET BDS)

Scope and purpose

This document aids the user to better understand the working principles of Silicon Carbide schottky diodes, and their fundamental differences compared to a Silicon diode. It shows how a silicon carbide can bring system benefits. This enables the user to make a wise decision while choosing diodes for the application.

Intended audience

Electrical engineers working on automotive power electronics.

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1 Introduction

There is a lot of research ongoing in making the power semiconductors, especially those used in automotive converters, more efficient. Conventional Silicon (Si) based devices are soon approaching their theoretical limit, and therefore, wide band-gap semiconductors such as Silicon Carbide (SiC) which offer higher efficiency, are becoming the subject of intense research. A SiC crystal consists of an equal number of carbon (C) and Si atoms, with each carbon atom covalently bonded to a Si atom. SiC occurs in more than 100 different crystal structures or poly-types and 4H-SiC is the most preferred in the industry.

The properties of SiC are compared to that of Si in Table 1. SiC offers the following advantages compared to Si:

- Compared to Si, SiC has a three times bigger band-gap, which is why, SiC is referred to as a wide band-gap material. Comparatively, three times higher energy is needed to move an electron in SiC from the valence band to the conduction band. As a result of this, SiC can sustain a ten times higher breakdown voltage compared to Si for the same thickness (breakdown voltage is related to the square of the band-gap). This makes it possible to build practical unipolar devices such as schottky diodes and MOSFETs in the kilo-volt range, which is not possible with Si. This also means that for the same breakdown voltage, SiC based devices can have a ten times thinner drift region compared to Si, which significantly reduces the drift-resistance, thereby reducing the conduction losses in SiC compared to Si.
- Another property of semiconductor materials is the saturated drift velocity, which is the maximum drift velocity acquired by the charge in a semiconductor device when subject to high electric field. This has an impact on the switching losses. As the saturation velocity of SiC is twice as high as that of Si, SiC based devices can switch significantly faster, thereby resulting in lower switching losses.
- SiC has a factor 2 better thermal conductivity compared to Si, which makes it thermally superior.

Property	Si	SiC
Band Gap E_G (eV)	1.1	3.26
Breakdown field E_B ($\mathrm{MVcm^{-1}}$)	0.3	2.5
Saturated drift velocity v_s ($10^7 \mathrm{cm\ s^{-1}}$)	1	2.7
Thermal Conductivity k (W $\mathrm{cm^{-1}K^{-1}}$)	1.5	3.7

Table 1: Comparison of Material Properties of Si and SiC

As a result of the above properties, SiC-based devices are interesting for designs that require higher efficiency and better performance, especially in automotive systems where size and volume of the converters are limited.

Infineon has several years of know-how with power semiconductor devices based on Silicon Carbide (SiC). Infineon released the first commercial SiC schottky diodes, way back in 2001. Since then Infineon has developed successive generations of the schottky diodes. These schottky diodes have made it possible to enhance the system efficiency of several applications like solar, industrial drives, server power supplies and so on. An increased efficiency means not only reduced energy consumption, but also reduced cooling efforts, a smaller foot print and, as a result, a smaller system. As the focus on electrification of automobiles is increasing, it is becoming more and more important to extend the benefits of SiC technology even to automotive systems.

Therefore Infineon has developed the CoolSiC™ Automotive Schottky Diodes Generation-5 (1), which is qualified as per AEC-Q100/101.

Figure 1 shows the timeline of SiC schottky diode development at Infineon[1]. The first version of diodes released were pure schottky diodes of the 600V class. In order to provide a better surge current robustness, without affecting the performance, the concept of merged pn-junction was introduced (which will be explained in the next paragraphs) into the successive generations. The third generation was optimized for thermal performance. In generation-5, the break-down voltage is increased to 650V, thereby making it possible to apply the diodes into systems operating at higher dc-link voltage, compared to the previous generations. The 'thin-wafer' technology is also introduced in Generation-5, where the bottom of the substrate is grinded from 350µm to 110µm. This results in a lower forward voltage drop, thereby resulting in a lower Figure of Merit (FoM). A lower figure of merit means lower power losses and therefore better electrical performance.

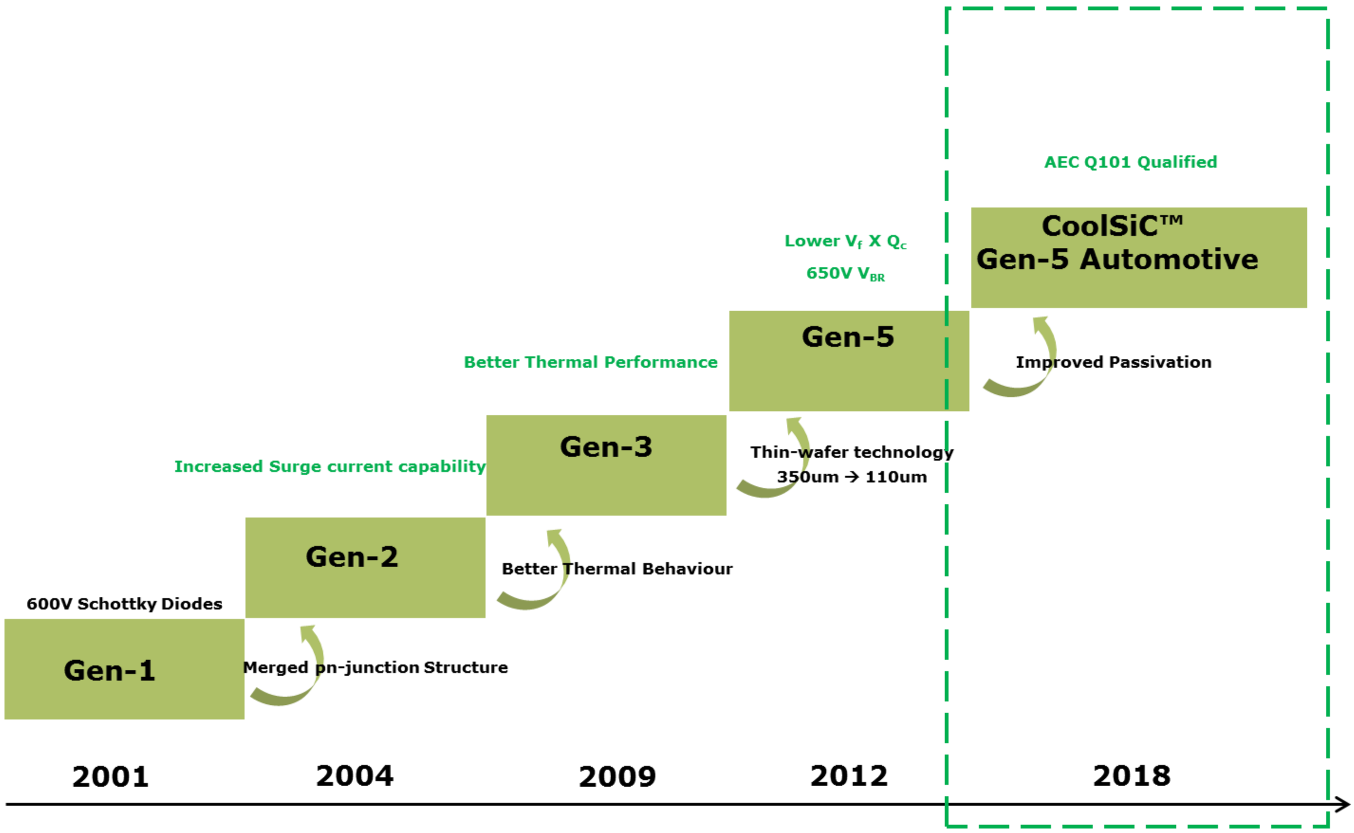

Figure 1: SiC Diodes- A timeline of development at Infineon

[1] The latest generation of SiC schottky diodes at Infineon is the Generation-6 diode, which is released for non-automotive applications. But it is not shown here.

2 CoolSiC™ Automotive Schottky Diode Generation-5 Technology

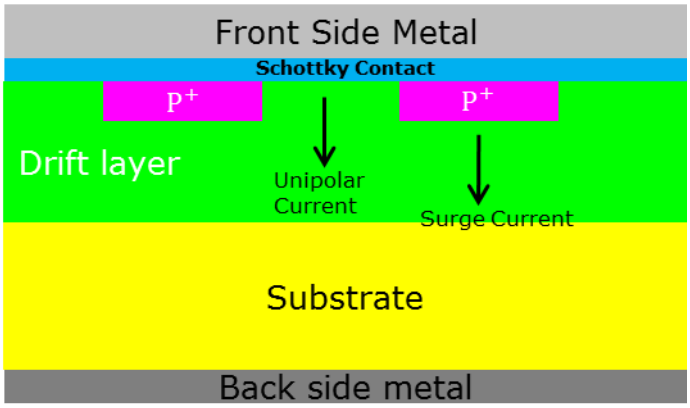

Figure 2: Principle structure of CoolSiC™ Generation-5 diodes showing the p+ islands in addition to the schottky junction

Figure 2 shows the principle structure of CoolSiC™ Generation-5 diodes. The drift layer that provides the blocking capability to the diode is formed by epitaxy on a highly doped SiC wafer which acts as the substrate and provides mechanical stability. The metal on the front and back side form the contacts for diode. The current flow would be from top to bottom as indicated by the arrows. The schottky junction is formed between the drift layer and the schottky metal, resulting in a unipolar current when forward biased. As such, the diode would have a high voltage drop at high currents which occur during surge operation (e.g., in-rush current when charging a capacitor), which would result in the destruction of the diode. In order to overcome this, the diode contains several p+ islands on the active area. These p+ islands which come into play only during surge currents, resulting in an additional current flow, making the diode behave as a pn diode during surge operation. The forward characteristics of the diode are shown in Figure 3, where the current branches due to the unipolar schottky region and the bipolar p+ islands are depicted.

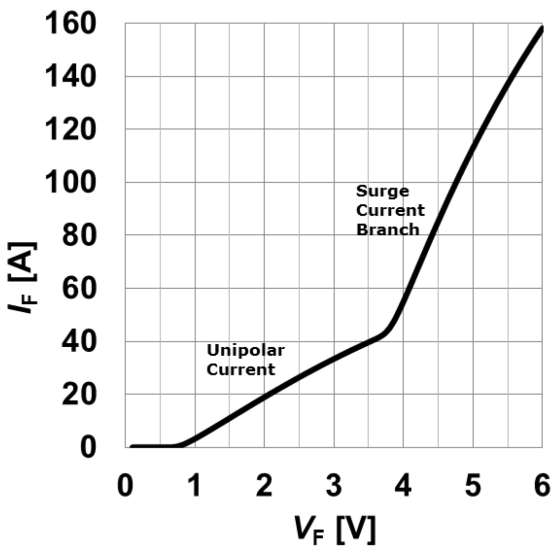

Figure 3: Forward characteristics of the diode showing the unipolar and the surge current regions

3 Features of the SiC Schottky Diodes

3.1 No Reverse Recovery

Si PiN diodes are bipolar devices, which depend on minority charge carriers (holes) for conduction. Some holes are stored in the drift layer during conduction, which have to be removed when the diode is turned off. As a result, the diode current does not simply fall to 0A, but rather goes in the negative direction to peak values which can be nearly as high as the forward current in the conduction state. This generates losses not only in the diode, but also in the complementary switch as will be discussed in the next paragraphs. SiC schottky diodes, on the other hand, being unipolar devices depend only on majority charge carriers for conduction. Therefore, turning them off does not require the removal of minority charge carriers. Hence, there is no reverse recovery in SiC schottky diodes.

Figure 4 compares the transient waveforms for the diode turn off for the SiC diode versus the Si diode. In each case, the active switch is a High-speed F5 IGBT. Clearly, the Si diode has a significantly higher reverse recovery current than the SiC diode. The residual overshoot in the SiC diode current waveform is purely due to capacitive effects. Here, the SiC diode has lower loss energy compared to the Si diode, due to two reasons (both are highlighted in the figure in green). Firstly- due to the lower current peak itself. The second is because the voltage in the SiC diode rises much earlier as there is no reverse recovery.

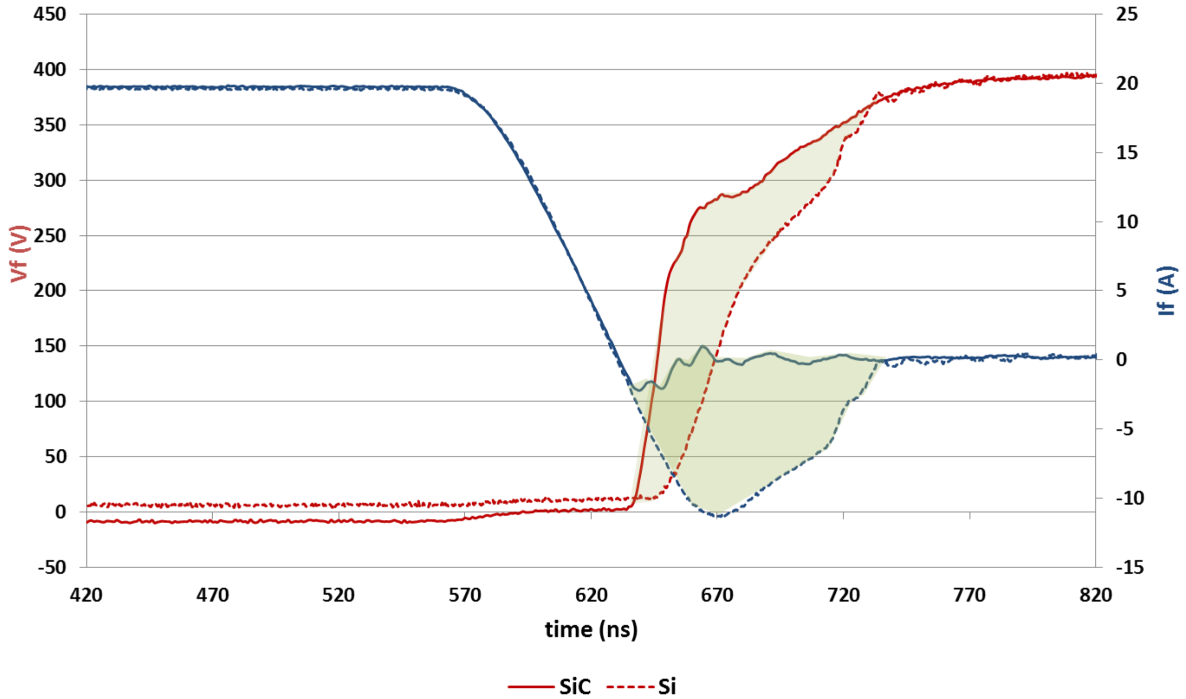

Figure 4: Comparison of switching waveforms at diode turn-off showing lower reverse recovery in the SiC diode compared to a Si diode

Figure 5 shows the corresponding transient waveforms at IGBT turn-on. The effect of reverse recovery can also been noticed here. Clearly, the IGBT produces a significantly higher peak current with the Si diode. With the SiC diode, this is nearly negligible. Therefore, SiC diodes result in energy savings not just in the diode itself, but also in the complementary active switch!

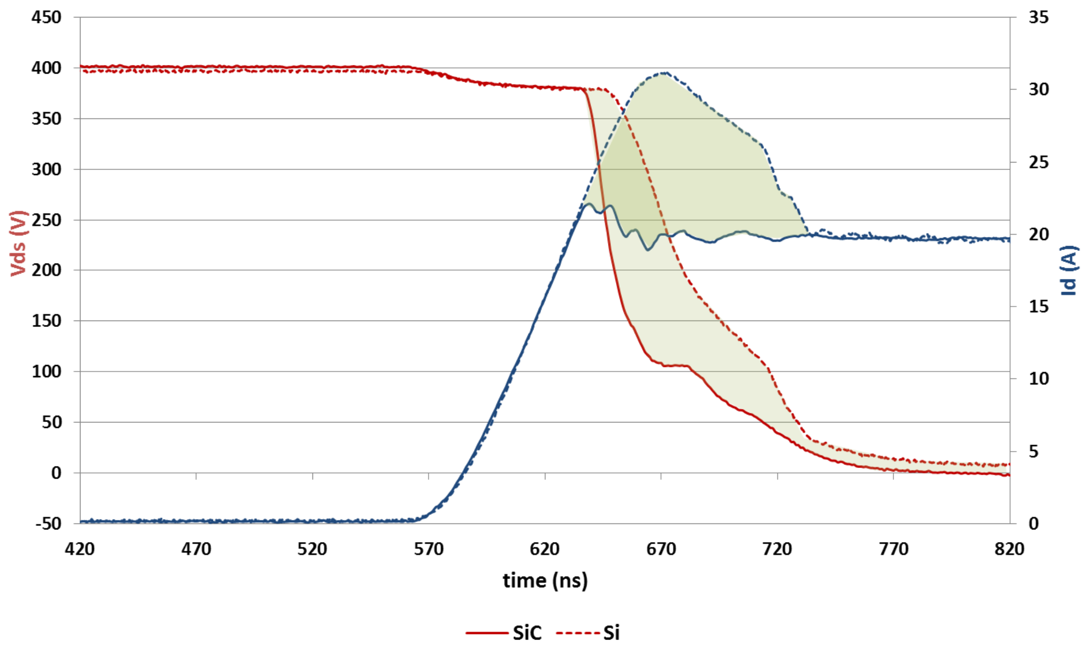

Figure 5: Comparison of switching waveforms at IGBT turn-on showing that a SiC diode results in lower current overshoot on the IGBT

Figure 6 compares the diode waveforms at turn-off for three different current classes- 8A, 10A and 12A. It can be seen that the reverse recovery peaks are increasing (the proportion of increase is quite small, though) with current class (chip area). This is because junction capacitance increases with chip area, resulting in a higher charge which has to be removed for diodes of higher current class.

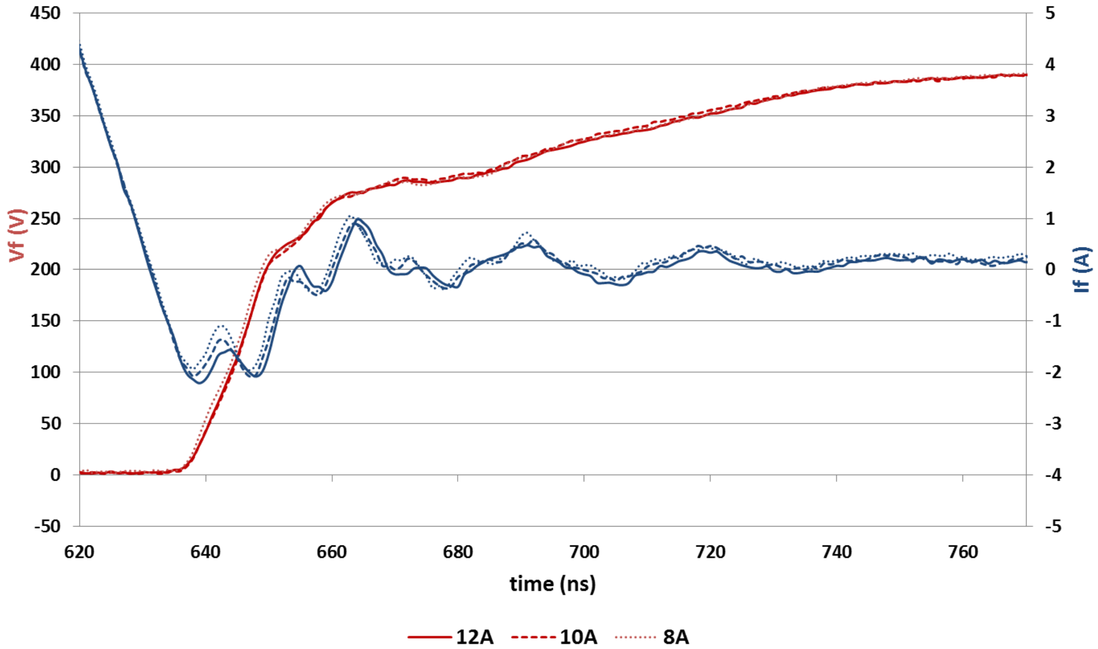

Figure 6: Comparison of switching waveforms at SiC diode turn-off for different current classes, showing that the reverse recovery peak is only slightly affected by the current class (purely due to capacitive effects)

3.2 No Forward Recovery

When a bipolar junction diode is put into conduction, it takes a finite amount of time before conductivity modulation sets in. Until this time, the voltage drop of the diode is significantly higher than its normal voltage drop, thereby resulting in higher losses during this time. This effect is called as forward recovery. This effect results in a higher voltage overshoot in the complementary active switch during its turn-off, resulting in higher turn-off losses in the complementary switch.

Figure 7 and Figure 8 show the transient waveforms at IGBT turn off, comparing the effect of the Si diode versus the SiC diode. The comparison is done at the same di/dt of the IGBT current waveform, to ensure that the voltage overshoot due to the stray inductance is the same. Thus, the difference in voltage overshoot between the two cases can be attributed to the diodes. It can be noted that the voltage overshoot is higher in the case of the Si diode compared to the SiC diode, confirming that the forward recovery of the Si diode is higher.

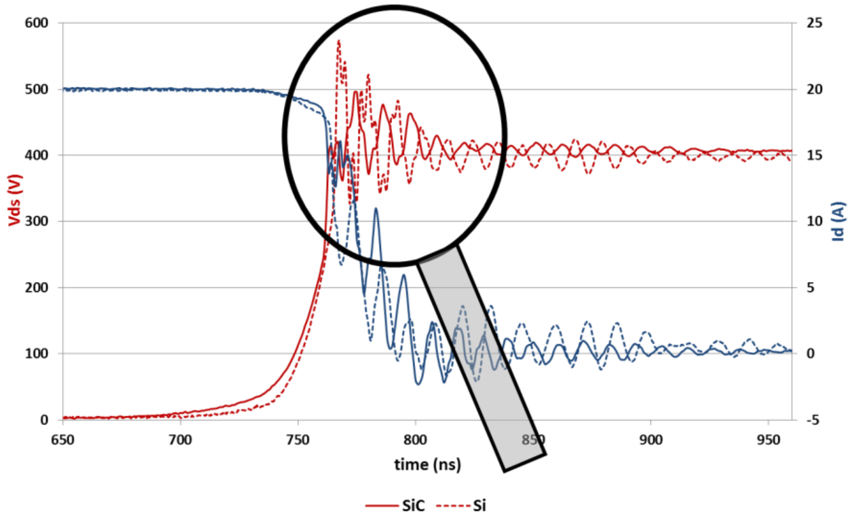

Figure 7: Comparison of switching waveforms at IGBT turn-off showing lower forward recovery voltage overshoot with the SiC diode compared to the Si diode

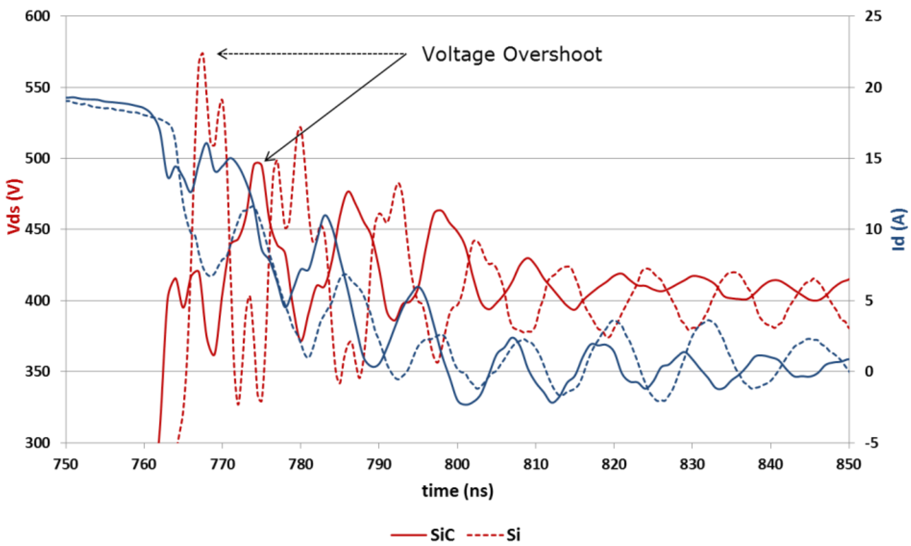

Figure 8: Comparison of switching waveforms at IGBT turn-off (Zoomed in region) showing lower forward recovery voltage overshoot with the SiC diode compared to the Si diode

3.3 Current-, Temperature- and di/dt-independent Switching Behavior

The switching behavior of bipolar devices is usually highly dependent on temperature, whereas that of unipolar devices is typically independent. This can be confirmed from Figure 9, which shows the switching waveforms of diode turn-off at two junction temperatures 25°C and 150°C. It can be seen that the waveforms are nearly identical. The same conclusion can be drawn also for the dependency on diode current as shown in Figure 10 where it can be confirmed that the reverse recovery current is independent of the device current.

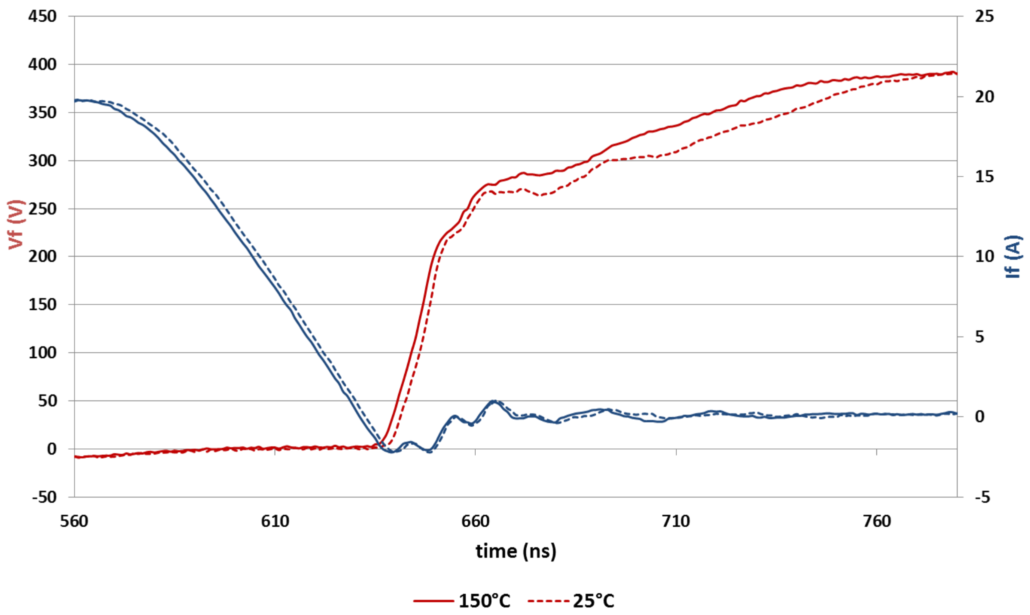

Figure 9: Switching waveforms at turn-off of SiC diodes showing independency of Temperature

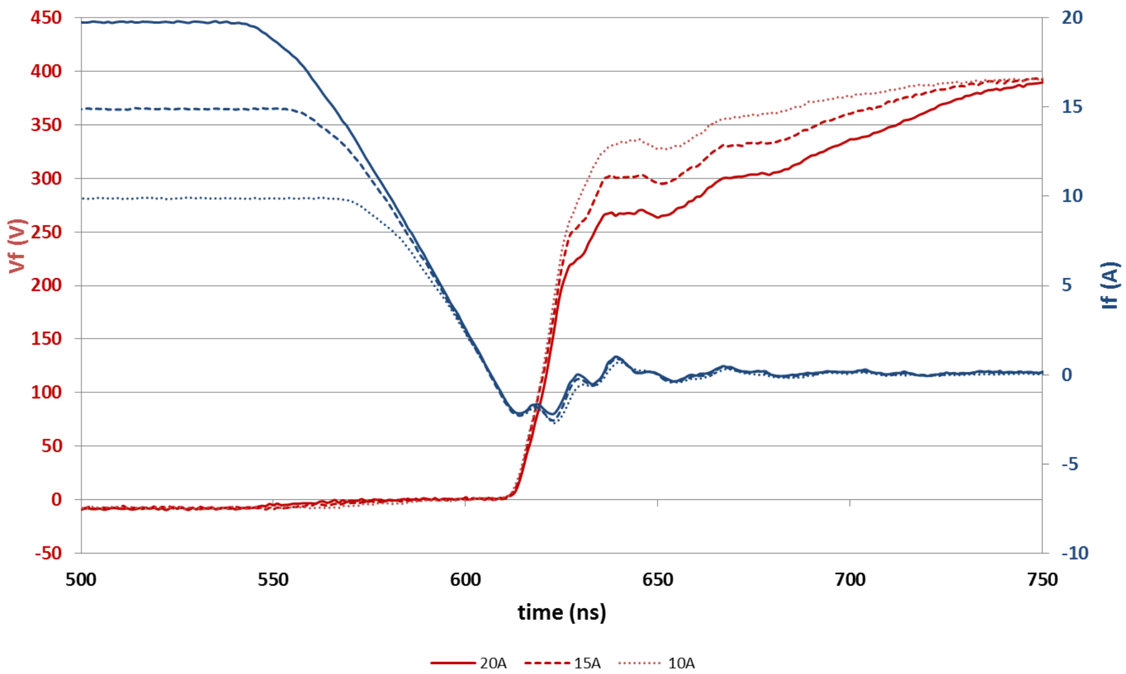

Figure 10: Switching waveforms at turn-off of SiC diodes showing independency of the switched current

It is obvious that switching an IGBT faster reduces its switching losses. In contrast, the reverse recovery losses in the complementary Si diode increase with faster switching (di/dt), as can be seen from Figure 11. This property of Si diodes makes it difficult to reap the complete benefits of fast switching an IGBT. SiC diodes, on the other hand, have only capacitive charge which is independent of the switching speed. Therefore, the recovery energy in the SiC diodes is independent of the di/dt of the active switch, as can be seen from Figure 12. Thus, for fully benefiting from the benefits of a fast switching IGBT in a hard-switched application, it is recommended to use a SiC diode.

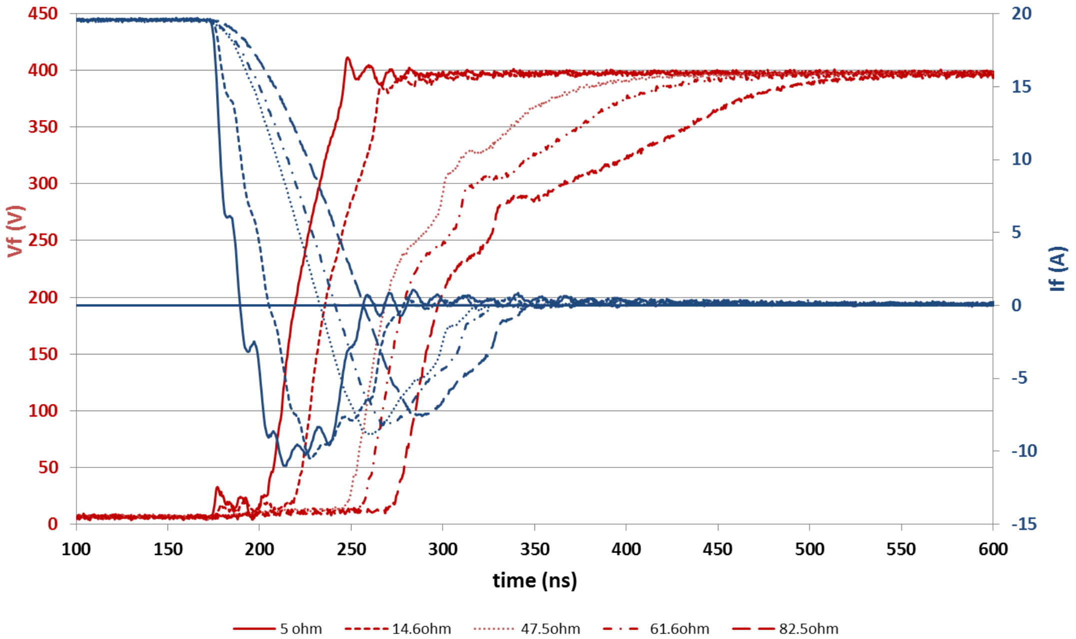

Figure 11: Switching waveforms at turn-off for a Si diode showing high dependency of the recovery peak on the di/dt

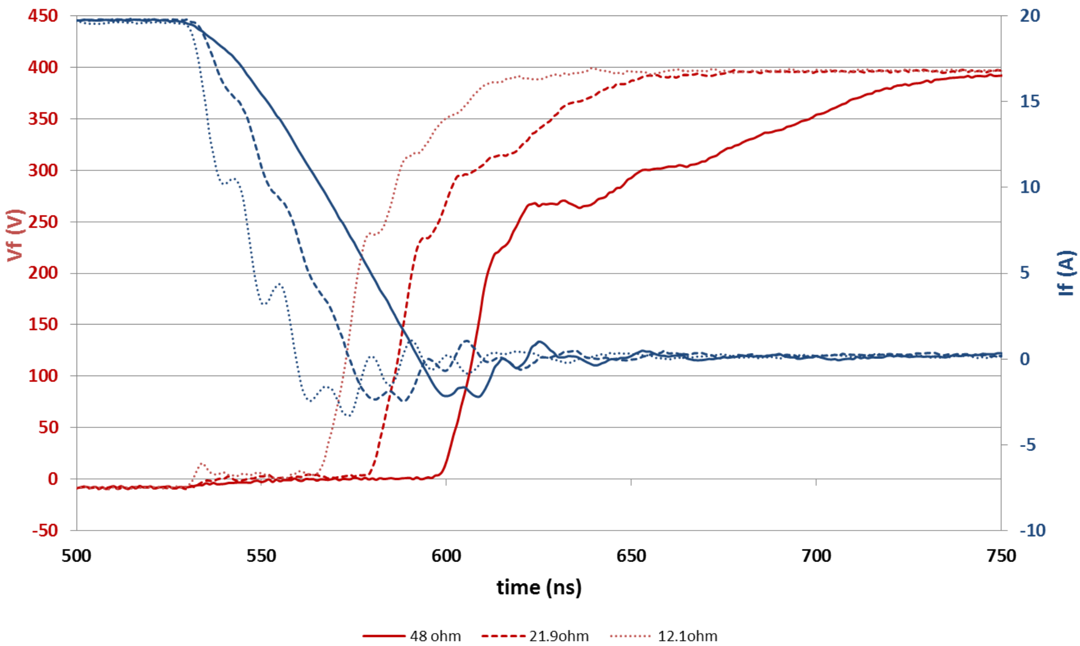

Figure 12: Switching waveforms at turn-off for a SiC diode showing independency of the recovery peak on the di/dt

4 Limitation of the SiC Schottky Diodes

4.1 Higher Voltage Drop

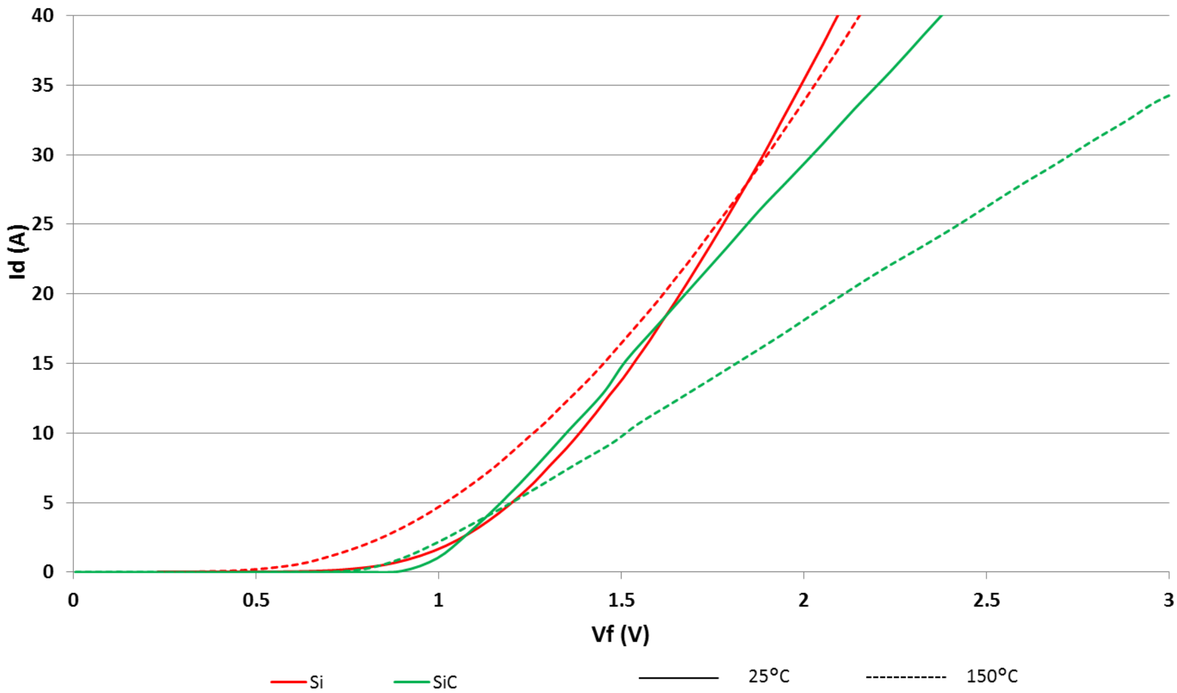

Figure 13: Forward characteristics of Si vs SiC diodes

Although SiC diodes fare excellent as far as the switching behavior is concerned, their conduction behavior is rather poor compared to Si diodes. The reason for this is the following: SiC diodes are unipolar diodes and lack conductivity modulation (conduction due to minority charge carriers), unlike Si PiN diodes which are bipolar devices. This can be confirmed from Figure 13, where the forward characteristics of the Si and SiC diodes are compared. At higher temperature, the threshold voltage decreases, but the contribution due to the drift region increases (as it is like a resistor). The forward voltage drop of the SiC diode is more dependent on the junction temperature, and the gap between the two diodes widens at higher temperatures. This is a limitation of the SiC diode.

5 Summary

Figure 14 compares the figures of merit of the SiC schottky diode compared to the Si diodes (Rapid-1 and Rapid-2). Clearly, the SiC diode has orders of magnitude lower FOM compared to the Si diodes, implying that the SiC diodes have a better electrical performance.

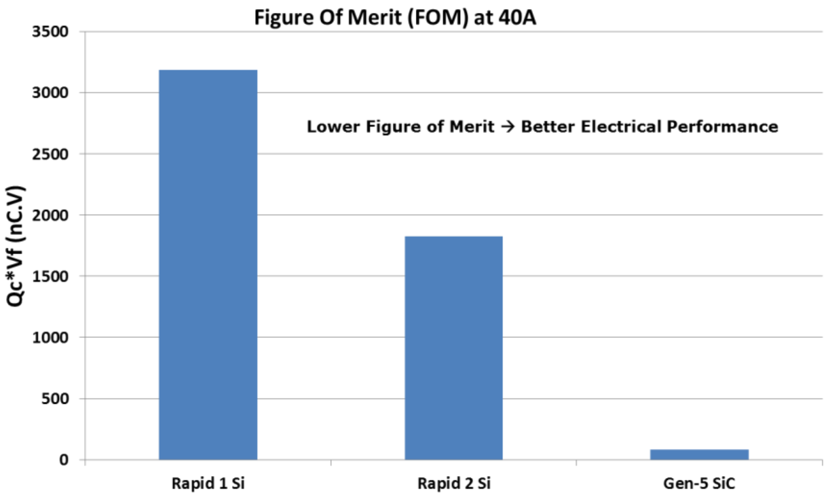

Figure 14: Comparison of the Figures of Merit (FOM) of SiC schottky diodes compared to Si diodes

The reverse recovery energy E_{rec} of the SiC diodes is compared to that of the Si diode in Figure 15:5. It can be seen that the E_{rec} for the Si diode increases drastically with current, whereas that for the Si diode is very flat as discussed earlier. SiC diode results in nearly 90% reduction in the recovery energy loss.

The SiC diode results in energy savings not just in the diode, but also in the complimentary IGBT, and it can be seen that the turn on energy in the IGBT, E_{on} is reduced by up to 40% with the SiC diode.

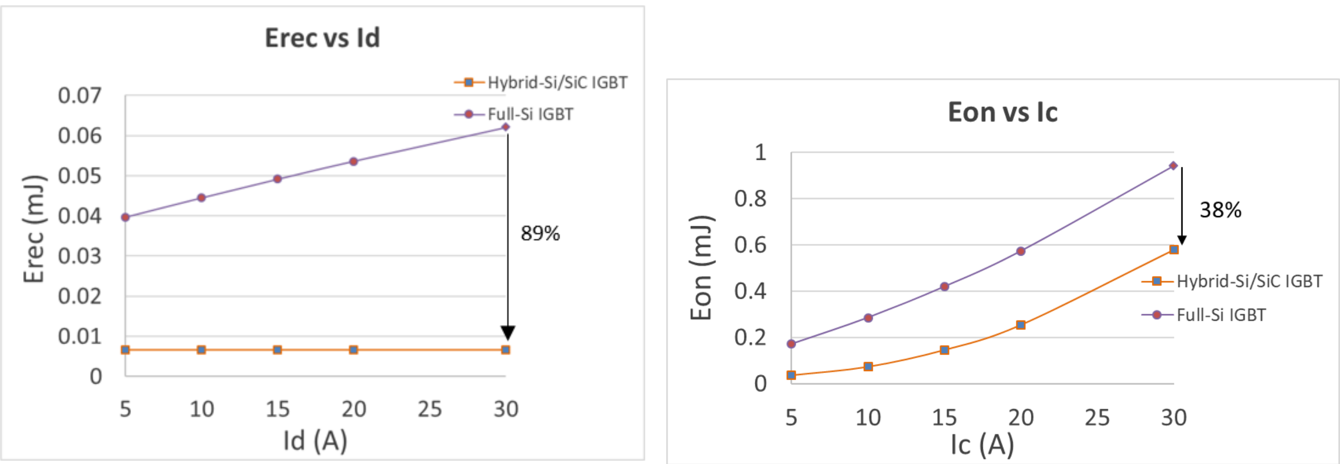

Figure 15: Comparison of turn-on and reverse recovery energy $E_{\text{on/rec}}$ at 400V, 20A, 25°C (2).

The above mentioned energy savings result in higher efficiency for on-board charger (OBC) and DC-DC converter applications. For a typical application example such as the classical boost PFC topology, the simulated efficiency is shown in Figure 16: Efficiency comparison for a typical application case. Classical Boost PFC
at $\boldsymbol{V_{ac}} = \mathbf{220V}, \boldsymbol{f_{sw}} = \mathbf{85kHz}, \boldsymbol{V_{dc}} = \mathbf{400V}, \boldsymbol{P_{out}} = \mathbf{3.3kW}$ as described in (2). It can be seen that the SiC diode results in up to 1.5 p.p improvement in efficiency at the PFC system level (including the losses passives). For OBC systems, the efficiency at nominal load is of more interest than the peak efficiency, where the benefit is about 0.7 p.p.

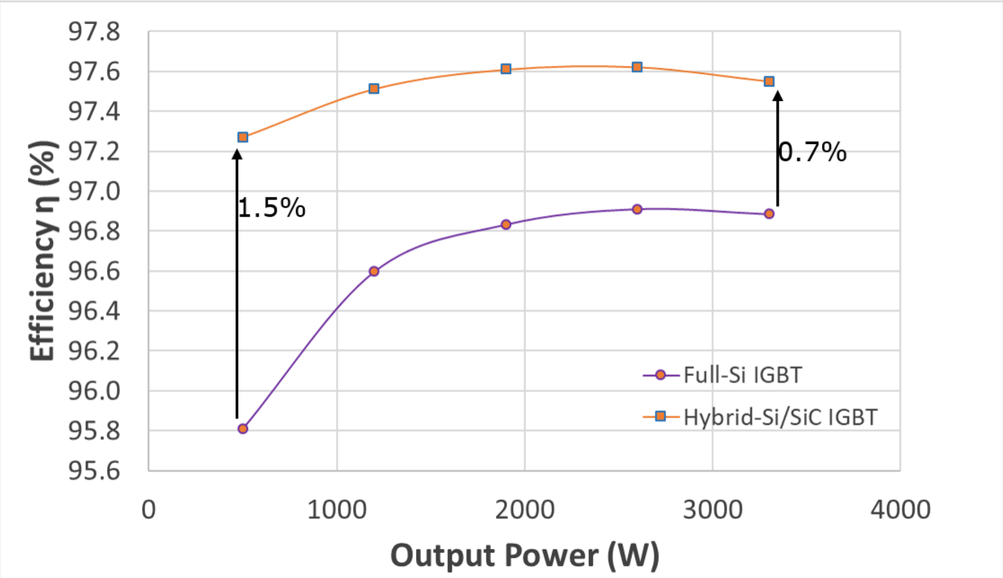

Figure 16: Efficiency comparison for a typical application case. Classical Boost PFC at $\boldsymbol{V_{ac}} = \mathbf{220V}, \boldsymbol{f_{sw}} = \mathbf{85kHz}, \boldsymbol{V_{dc}} = \mathbf{400V}, \boldsymbol{P_{out}} = \mathbf{3.3kW}$ (2)

Overall, CoolSiC™ Gen-5 SiC schottky diodes offer the following features compared to Si PiN diodes:

- No reverse recovery effects (Purely capacitive switching). Up to 90% reduction in the reverse recovery energy
- No forward recovery
- Upto 40% reduction in turn-on losses when switched in tandem with an IGBT
- Switching losses independent from load current, switching speed and temperature
- Possibility to switch the complimentary IGBT at its full speed, independent of the diode
- Upto 0.7 p.p. improvement in efficiency (application case of a typical boost PFC Topology)

6 Bibliography

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