

Silicon Carbide Schottky Diodes: Novel devices require novel design rules

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1 Abstract

The close-to-ideal properties of novel silicon carbide Schottky Diodes (CoolSiC™), that can reach higher blocking voltages than the actual Silicon Schottky limit of 250 V, are well suited for hard switching commutation. In order to maximize the benefit from these characteristics, a different design-in approach compared to conventional diodes is required.

2 Introduction

Silicon diodes have been used in power electronics for a while. Their properties and characteristics have been studied in very detail. Designing with such diodes has become a routine and as every routine it has established some paradigms. One of them is - for example – the selection of the appropriate current rating of a booster diode in continuous conduction mode PFC.

The introduction of silicon carbide high voltage Schottky Diodes will shift these paradigms. Due to their superior characteristics, the design guidelines must be rewritten.

3 Properties of silicon carbide

With silicon carbide, belonging to the so called wide bandgap semiconductors, the voltage range for Schottky Diodes now can be extended to more than 3000 V. This is possible by the material related benefits of SiC.

3.1 Dynamic characteristics of SiC Schottky Diodes

The quasi “reverse recovery” charge Q_c and the switching power losses of SiC Schottky Diodes are not only ultra low. Compared to silicon ultra fast diodes, where losses strongly depend on di/dt , current level and temperature, they are more or less independent on these boundary conditions (Fig. 1). A dependency of Q_c on these parameters can not be seen at the same scale as with a benchmark Si diode approach.

This is due to the capacitance like behavior of SiC device in reverse direction.

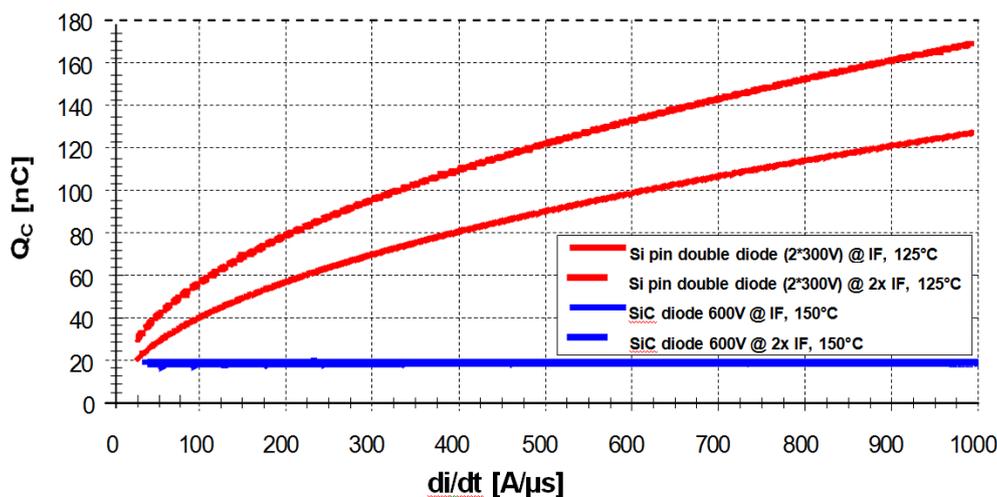


Figure 1: Comparison of stored charge in SiC (Q_c) and silicon diodes (Q_{rr})

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4 Active power factor correction (Boost Converter)

Worldwide requirements for power factor correction are growing strongly driven by legal requirements.

4.1 Basics of PFC Boost

Boost converters are usually used to realize active power factor correction (Fig. 2). They can be driven in Discontinuous Conduction Mode (DCM) and Continuous Conduction Mode (CCM).

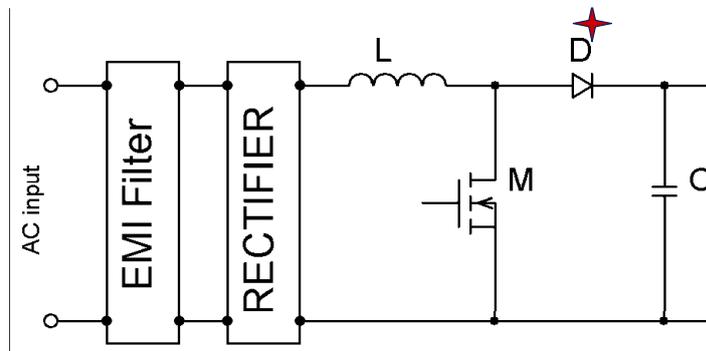


Figure 2: Schematic circuit of a power factor corrector (PFC) with a boost converter

4.2 How to select the right current rated device

Selecting the current rating for the PFC boost diode is an important design consideration. Differently rated currents mean different die sizes, power losses and cost. An optimal solution would be obviously the smallest die size, which can handle defined output power under given thermal considerations.

Inrush current during initial charge of the bulk capacitor ultra fast diodes have a limited inrush surge current capability. The initial charge of a relatively large bulk capacitor during the plugging in can exceed the maximum allowed peak current through the booster diode and even through the input rectifier bridge. This can be avoided using a conventional silicon diode initially charging the bulk capacitor from the rectified AC voltage, which avoids high surge currents in the booster diode (Fig. 3).

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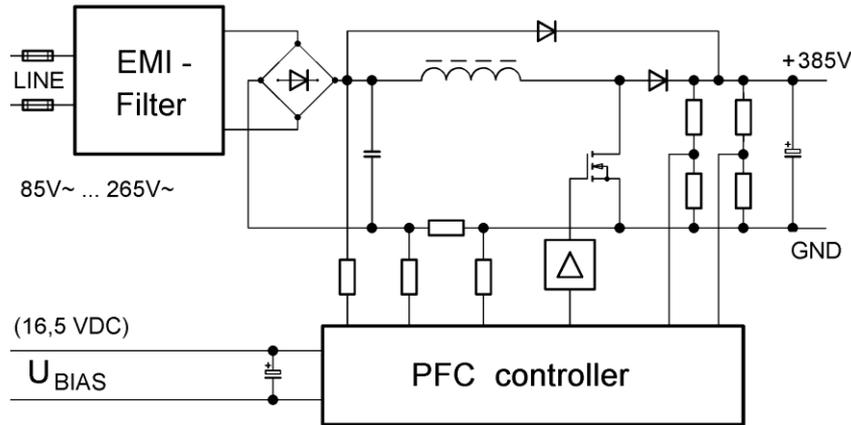


Figure 3: Bypass diode for inrush current

Another approach is to use a resistor in serial with the bulk capacitor for initial charge.

Pulse current during operation

During the sinus wave on the main line the peak current through the boost diode can reach relatively high values compared to it's average current (Table 1).

P_{OUT} , W	$I_{D\ average}$, A	$I_{D\ rms}$, A	$I_{D\ peak}$, A
75	0.202	0.247	1.509
100	0.271	0.329	2.013
200	0.542	0.659	4.025
300	0.813	0.988	6.038
400	1.084	1.317	8.051
600	1.626	1.976	12.076
800	2.168	2.635	16.101
1000	2.71	3.294	20.126

Table 1: Booster diode stress in CCM PFC ($V_{IN}=85V_{AC}$, $V_{OUT}=400V_{DC}$, efficiency=93%)

It is important not to exceed the maximum pulse current rating of the booster diode in order to maintain reliable operation. It is another selection criteria for the booster diode.

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Start up of PFC boost converter

After the bulk capacitor has been charged up through the bypass circuit up to the voltage corresponding to the amplitude of the main line the PFC controller starts up. The bulk capacitor will be charged as shown in Fig. 4.

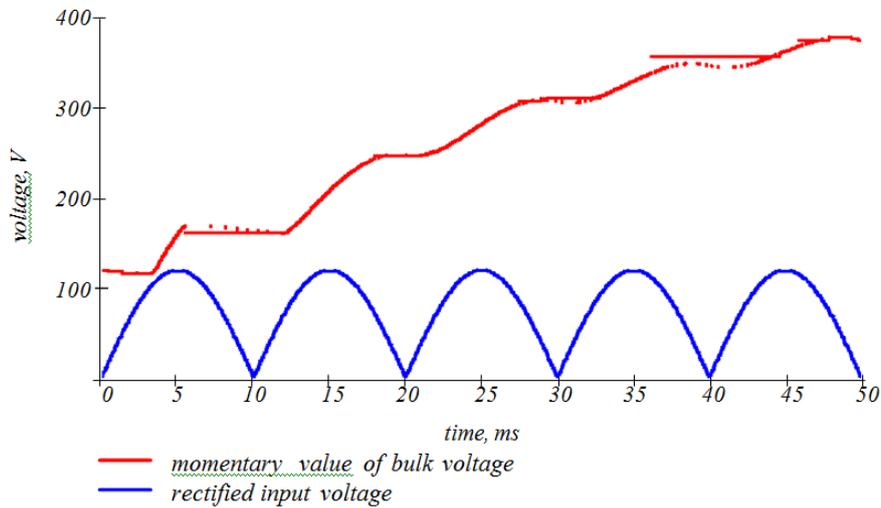


Figure 4: Bulk cap & main voltage

The control IC will try to charge the bulk cap with the maximum allowed duty cycle. Some Control IC's have a "soft start" for the duty cycle of the switch (Fig. 5).

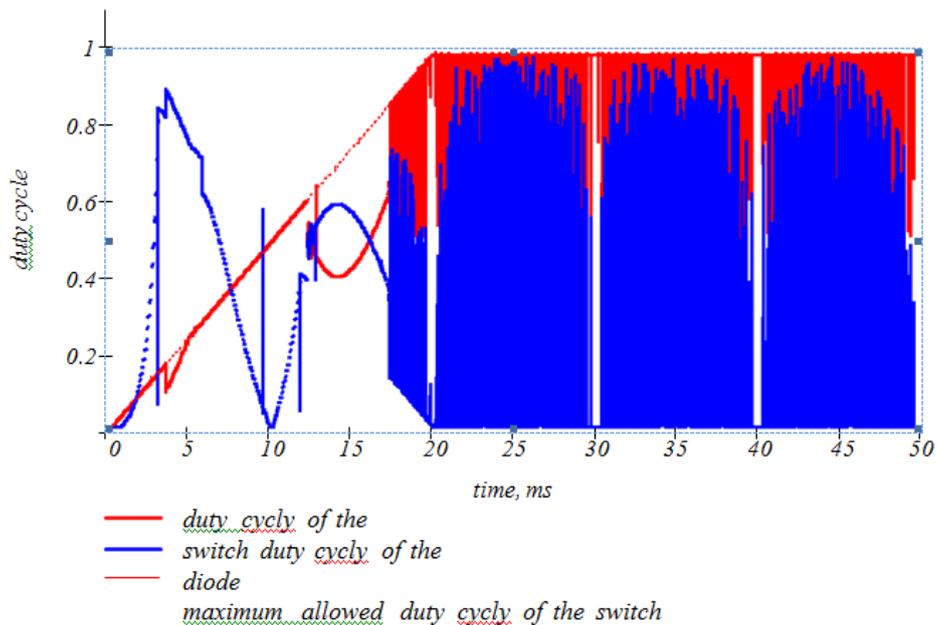


Figure 5: Duty cycle

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Nevertheless, the peak current limiting will be reached already at the first half period (Fig. 6)

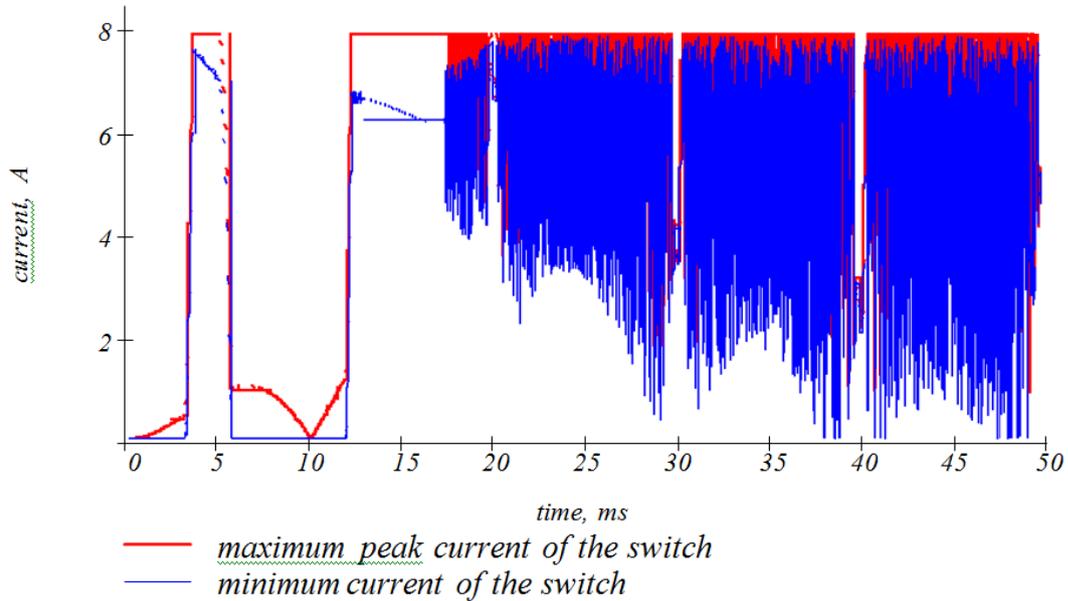


Figure 6: Maximum & minimum currents

The minimum and maximum current through the diode are equal to current limiting value, e.g. highest possible value (Fig. 6). On the other hand the “soft start” duty cycle limiting for the switch does not help for the diode. The diode conducts the rest of the switching period. This leads to very long duty cycles for the diode (Fig. 5). Combination of high peak current and long duty cycles causes large conduction power losses in the diode (Fig. 7).

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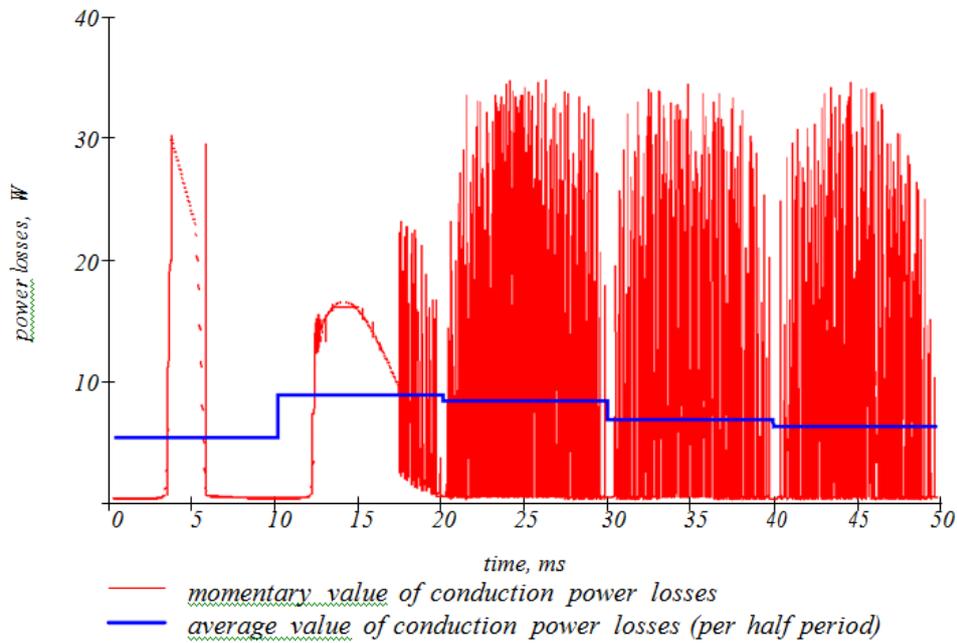


Figure 7: Conduction power losses in the diode

Increase in power losses leads correspondingly to a rapid junction temperature increase (Fig.8).

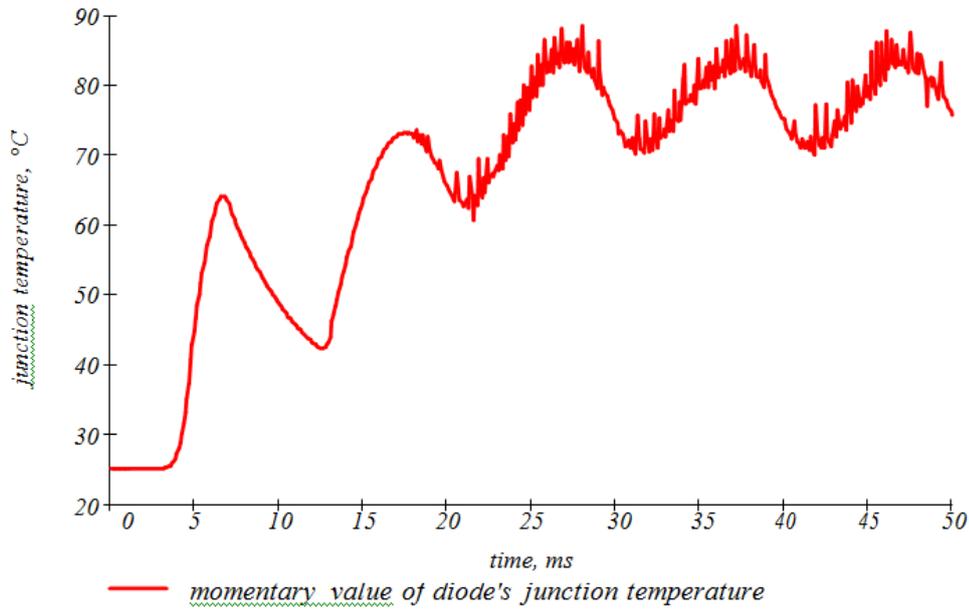


Figure 8: Junction temperature of the diode (start at 25°C)

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As long as junction temperature stays below the maximum specified value it is a safe design. It is important to consider that this first temperature increase can be higher than the junction temperature under full load. In case of “hot” restart (for example after mains drop out) the junction temperature may exceed the specified limit.

The duty cycle limiting for the switch does not protect the diode at all. Safe design should include junction temperature analysis during possible transients.

Current capability of Silicon Carbide diodes in CCM PFC Boost applications

SiC diodes have different features as ultra fast silicon diodes. The most important differences are the missing reverse recovery charge and the positive temperature coefficient of the forward voltage of the SiC diodes. Instead of reverse recovery charge there is only a small capacitive charge of the junction. Due this feature the SiC diode is best suited for continuous conduction mode (CCM) switching applications. The positive temperature coefficient of the forward voltage allows to operate SiC diodes in parallel, but on the other hand we have to design applications of SiC diodes carefully in respect to thermal household. With SiC diodes we have to avoid thermal runaway due to conduction losses, with silicon diodes we have to avoid thermal runaway due to switching losses.

3 Typ. forward characteristic

$$I_F = f(V_F)$$

parameter: T_j , $t_p = 350 \mu s$

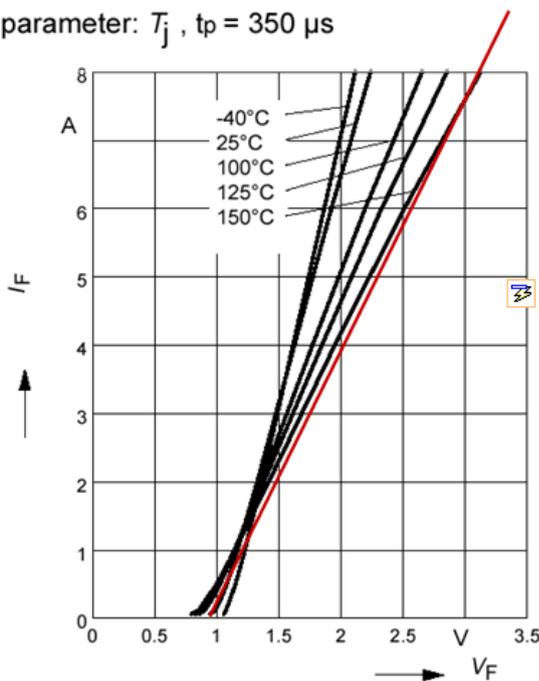


Figure 9: Forward characteristics of 4 A / 600 V SiC SBD

Fig. 9 shows the typical forward voltage versus forward current of a 4A-SiC diode with the temperature as parameter. We can approximate

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the forward voltage by a threshold voltage V_{T0} and a differential resistor R_{DIFF} . The worst case conditions according data sheet at a junction temperature of 150°C can be described as follows:

Approximation of forward voltage:

$$V_F = V_{T0} + R_{DIFF} I_F$$

Worst case conditions:

$$V_F = V_{T0} + R_{DIFFMAX} I_F$$

SiC diode Type	SDP02S60	SDP04S60	SDP06S60
Voltage/current rating	600V/2A	600V/4A	600V/6A
Package	P-TO220-3-1	P-TO220-3-1	P-TO220-3-1
Alternative package	P-TO-252-3-2	P-TO-252-3-2	P-TO-252-3-2
Thermal resistance J-C	10K/W	4,1K/W	2,6K/W
Power dissipation at $T_C = 25^{\circ}\text{C}$	15W	36,5W	57,6W
Maximum operating temperature T_J	175°C	175°C	175°C
Total capacitive charge	6nC	13nC	21nC
Typical threshold voltage at $T_J=150^{\circ}\text{C}$	0,9V	0,9V	0,9V
Differential resistance at $T_J=150^{\circ}\text{C}$	0,62	0,275	0,135
Max. differential resistance at $T_J=150^{\circ}\text{C}$	0,82	0,375	0,202
Max. forward voltage $V_{FMAX150}$	$0,9V+0,82 I_F$	$0,9V+0,375 I_F$	$0,9V+0,202 I_F$
Power dissipation at rated forward current	5,08W	9,6W	12,66W
Required heat sink including washer at $T_J = 150^{\circ}\text{C}$ and $T_A = 75^{\circ}\text{C}$	4,16K/W	3,1K/W	2,7K/W
Output power of CCM PFC boost converter at $V_{INMIN} = 90\text{V}$, $V_{OUT} = 400\text{V}$ with same P_D	383W	772W	1184W
Output power of CCM PFC boost converter at $V_{INMIN} = 180\text{V}$, $V_{OUT} = 400\text{V}$ with same	518W	1042W	1585W

Table 2: Power handling capability of SiC Schottky Diodes

In order to get a feeling about the current capability of SiC diodes we calculated the power dissipation PD based on:

- conduction losses at rated DC current, and
- the required heat sink at $T_J = 150^{\circ}\text{C}$ and $T_A = 75^{\circ}\text{C}$.

In a second step we calculated the output

power of CCM PFC boost converter with an estimated efficiency of 0,9 and a minimum input voltage of 90 V and 180 V that produces same power dissipation as calculated under DC conditions.

A SiC diode does not produce switching losses in the diode itself (only small capacitive losses in the MOSFET). So the total thermal house- hold can be used for current conduction. A 2 A- SiC is able to handle 380 W output power in an universal input CCM PFC boost converter in steady state condition.

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Secondary Side Rectification for 48 volts output

An output voltage of 48 V is used in a vast number of power supplies for telecommunication equipment and distributed power system servers. This output voltage theoretically allows to use silicon Schottky Diodes, but in practice gallium arsenide and silicon carbide Schottky Diodes are better suited for the secondary side rectification.

Basics

The basic circuit diagram of a typical Zero Voltage Transient (ZVT) phase shifted full-bridge converter is shown in Fig. 10. This type of converter is widely used in power supplies for telecommunication equipment.

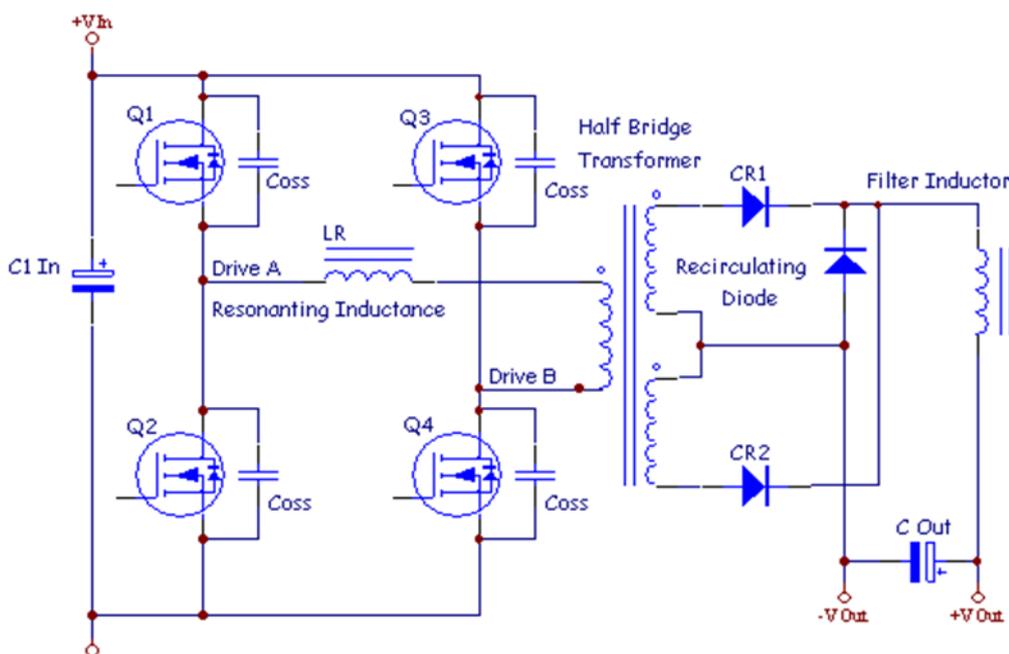


Figure 10: Circuit diagram of typical telecom AC/DC SMPS

The switching power losses in transistors are very low due to ZVT switching. This enables an increase of the switching frequency without serious efficiency drawback on the primary side. It also means that the diodes on the secondary side have only low switching losses. Here usually Schottky Diodes are in use. The voltage stress across the secondary side diode can be calculated using following equation:

$$V_{CR1}, V_{CR2} = 2 V_{IN} \frac{N_2}{N_1}$$

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Depending on the transformer design the voltage stress on the secondary diodes is typically in range from 150 V to 230 V. With some safety margin 180 V to 250 V rated diodes can be used. Selecting the 300 V rated diode will increase the derating and correspondingly the reliability of the system.

Comparison of electrothermal behavior of SiC and GaAs Schottky Diodes:

The total forward voltage drop of a Schottky Diode typically consists of 3 major parts:

Voltage drop due to ...	Variation with temperature increase
• Schottky barrier	Slightly decreasing
• substrate resistance	Nearly constant
• low doped drift layer	Strongly increasing proportional $T^{1.5 \dots 2.5}$

In Figure 11 the relevance and size of these parts is visualized for both a commercial available 250 V GaAs Schottky Diode and 300 V SiC Schottky Diode (SDP10S30)

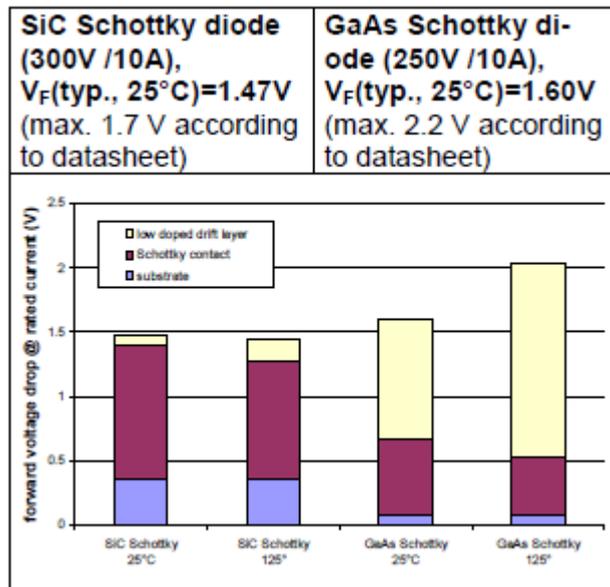


Figure 11: Split up of forward voltage contribution of the different device components for GaAs and SiC Schottky Diodes at 25°C and 125°C.

The large contribution of the drift layer in case of the GaAs diode makes fabrication control of the forward properties extremely difficult, because this layer is epitaxially grown and has a comparatively large scatter of key parameters like thickness and doping (typically ± 10 to 15 % on 4 inch GaAs).

Both SiC and GaAs Schottky Diodes are unipolar devices and therefore they are suffering from a similar mechanism in their temperature dependence of the n- drift layer resistance. This number is proportional to $1/\mu$ (μ : electron mobility (cm^2/Vs)) and μ is depending on temperature in a $\mu \sim T^{-k}$ manner with k being in the range of about 2.5 for low doping. On the other hand, highly doped semiconductors (substrate material) have nearly no temperature dependence of their resistivity, specifically for SiC substrates (doping $5 \cdot 10^{18} \text{ cm}^{-3}$) we measured a resistivity increase of less than 5 % between room temperature and 150 °C. Finally the voltage drop across the Schottky contact, i. e. the knee voltage of the rectifier, has a negative temperature coefficient.

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In case of 300 V SiC Schottky Diode these different temperature dependencies compensate each other up to temperatures of 175°C giving a nearly temperature independent VF in this T_{range} at rated current. Opposite to this the GaAs Schottky Diode shows a significant increase in VF with temperature due to the fact, that the resistivity component with the largest positive temperature coefficient is dominating.

The typical forward characteristic of both diodes at room temperature and 175°C is displayed in Fig. 12. The strong increase of the onresistance with temperature shown by the GaAs Schottky diode is crucial for overcurrent stress situations. The positive feedback by heating of the device by electrical power losses and resistivity increase can cause quick destruction of the device by thermal runaway.

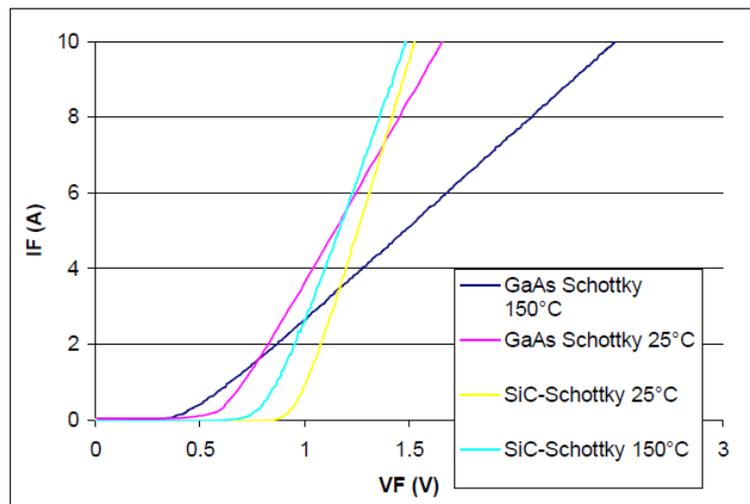


Figure 12: Forward characteristic at room temperature and 150 °C for a 250V/10A GaAs- and a 10A/300V SiC-Schottky diode in comparison. (Measurement conditions: isothermal, pulsed with 350µs)

Further it is an important fact that GaAs has a 9 times lower heat conductivity than SiC. Together with the above mentioned strong conductivity reduction this lead to a very limited peak current capability of the GaAs diodes ($IFSM < 2 \cdot IF$) in comparison to the SiC Schottky Diodes ($IFSM = 3.6 \cdot IF$). Even under high frequency pulse conditions (20 kHz) and small duty cycles (< 0.2) a damage of the GaAs Schottky Diodes may occur due to large mechanical stress caused by huge temperature differences and the very brittle behavior of GaAs. Based on these facts we can state a significant reliability advantage for the SiC Schottky diode in all applications where overcurrent stress is to be expected. Design with SiC vs. GaAs Schottky Diodes Power losses in a Schottky Diode can be distinguished into conduction, switching and leakage losses. Let us estimate the total power losses for 10 A/250 V GaAs and 10 A/300 V SiC Schottky Diodes under following conditions – continuous conduction mode rectifier operating at 300 kHz, peak current is 10 A, voltage stress is 200 V, duty cycle is 40%, $T_J = 125^\circ C$.

As it can be seen from Fig. 13 the total power losses are 13% lower in case of SiC diode due to lower voltage drop during the conducting stage. Please keep in mind that SiC diodes are rated to 300 V, not to 250 V like GaAs Schottky Diodes. Even with its higher breakdown voltage SiC Schottky has lower voltage drop. The 13% less total power losses seem to be a little advantage, but what does it mean for the thermal management? Fig. 14 shows the required total thermal resistance from junction to ambient for $T_{ambient} = 50^\circ C$. SiC Schottky diode will require a heat sink 30% smaller than necessary for GaAs diodes due to two reasons:

- SiC diode produce 13% lower power losses (or heat);
- SiC has better thermal conductivity as GaAs and in turn better thermal resistance from junction to case.

If a designer would replace a GaAs Schottky Diode with one in SiC technology the efficiency will increase and heat sink can be reduced by 1/3.

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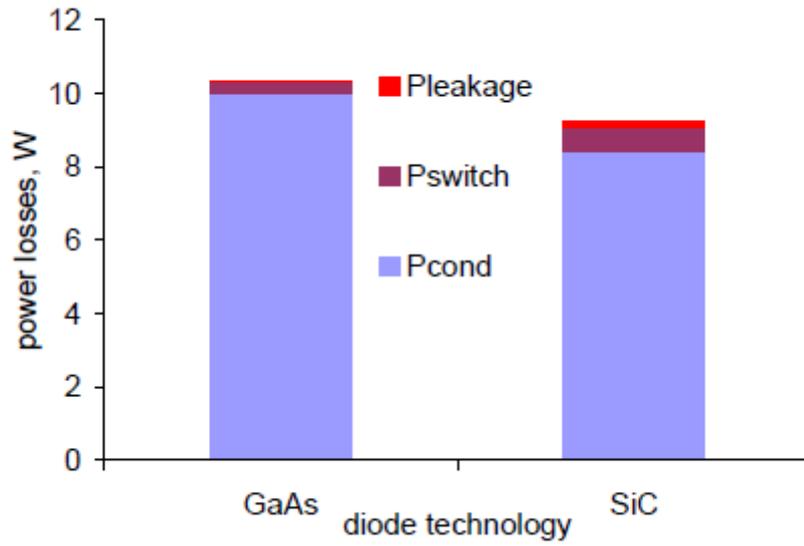


Figure 13: Total power losses in secondary side rectification diode

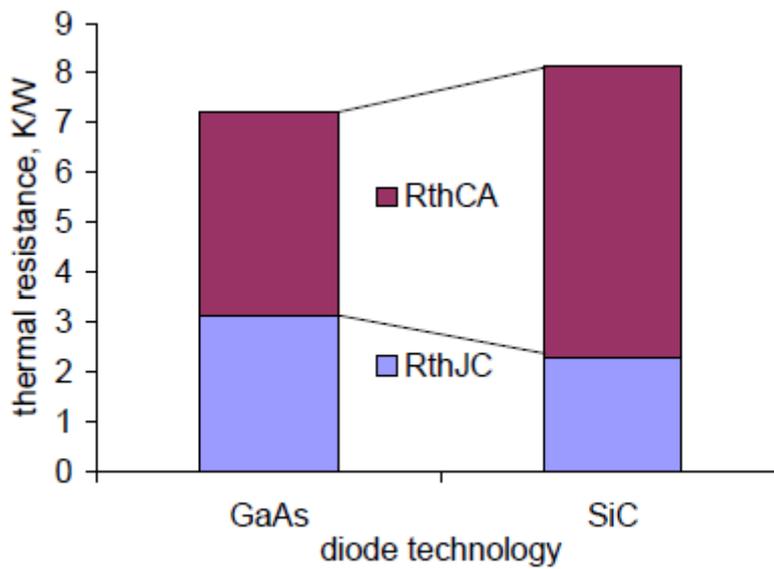


Figure 14: Total thermal resistance in this case

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5 Conclusion

With the properties of the CoolSiC™ Schottky Diodes described above, circuit designers now have a new degree of freedom in optimization of hard switching applications. Power handling capability per Ampere rated current sets a new reference in design rules. Design rule of 130°C junction temperature seems to be passed by with new semiconductor material – SiC. SiC as well as any new technology has great cost reduction & extension potential compared to existing ones. We expect powerful cost reductions over the next years. With SiC, a second source to GaAs Schottky exists now, and this second source can help to improve systems reliability and efficiency.