

thinQ!TM Silicon Carbide Schottky Diodes: An SMPS Circuit Designer's Dream Comes True!

Dr. Christian Miesner, Product Marketing Manager Silicon Carbide,

Dr. Roland Rupp, Project Manager Development Silicon Carbide,

Holger Kapels, Discrete Development Manager,

Michael Krach, Project Manager Silicon Carbide,

Dr. Ilia Zverev, Concept Engineering Manager

ABSTRACT

Infineon Technologies AG has introduced a brand-new family of nearly ideal semiconductor rectifiers: the Silicon Carbide (SiC) Schottky diodes. This paper describes the basic properties of the novel Silicon Carbide semiconductor material in relation to market requirements and application benefits. Now commercially available, the SiC Schottky diodes display unique behavior with a blocking voltage up to 600 Volts (V). The behavior is described here with special emphasis to the ideal switching characteristics. These characteristics are enabled by the absence of reverse recovery charge and current in these diodes. Finally, key applications of the SiC Schottky diodes are described and system optimization options such as miniaturization and part count reduction are indicated.

THE DRIVING MARKET FORCE FOR A UNIPOLAR DIODE WITH HIGH BLOCKING VOLTAGE

System miniaturization—the reduction of system size and weight—is a significant trend in electronics. Miniaturization is primarily, but not exclusively, being driven by the increasing number of portable applications. In most portable electronic devices, the dimensions and weight of the power supply make it the predominant part of the whole system. For example, in a typical portable computer, the power supply accounts for more than 10% of the total weight of the system. As a result, all manufacturers of Switch Mode Power Supplies (SMPS) have defined roadmaps to increase the power density in their products.

The two major approaches to implementing these roadmaps are:

- Reducing the size of passive components (by increasing the switching frequency and/or reducing the size of EMI filters through low noise generation)
- Reducing the power losses and the corresponding cooling effort (heat sink and/or fan)

To achieve these goals, the main semiconductor power components must achieve a significant reduction of switching power losses. For this reason, unipolar semiconductors such as MOSFETs and Schottky barrier diodes are

replacing bipolar devices. The beauty of unipolarity is the absence of stored charge carriers and, therefore, theoretically instantaneous switching transients limited only by small parasitic capacitances.

Power MOSFETs, such as CoolMOSTM & OptiMOSTM, can be found with a wide range of blocking voltage from 20 V to 1000 V. On the other hand, today's Schottky barrier diodes have a maximum blocking voltage of 250 V due to the characteristics of the Silicon (Si) or Gallium Arsenide (GaAs) base material. The main reasons for this limitation are:

- Very high leakage currents, especially at higher temperatures, because the reverse losses are comparable to the forward losses
- Strong increases in the area specific on-resistance $R_{on,A}$ with breakdown voltage $V_{br}^{2.5}$
- Increases of the chip also increases the reverse losses

The input stage of an off-line SMPS usually requires devices rated in the range of 500 – 600 V. Thus, a strong and unsatisfied need exists for Schottky barrier diodes beyond the blocking capabilities of established semiconductors such as Si and GaAs.



SILICON CARBIDE SCHOTTKY DIODES SATISFY MARKET REQUIREMENTS

Silicon Carbide devices belong to the so-called *wide bandgap semiconductors*, so the voltage range for Schottky diodes now can be extended to more than 1000 V. This is possible because of benefits specifically related to the SiC material:

- Low leakage currents are possible because the metal semiconductor barrier is two times higher than that of Si
- Very attractive, specific on-resistance compared to Si and GaAs Schottky diodes is possible because of tenfold breakdown field strength (see Figure 1)
- High current densities are possible and allow very small die sizes, because the thermal conductivity is more three times larger than that of Si (i. e. comparable to copper)

Figure 1 shows the minimum specific on-resistance of Schottky diodes based on different semiconductors versus the desired blocking voltage (only drift region, substrate contribution to the resistivity is neglected).

The ends of each line symbolize the usable voltage range for the specific semiconductor.

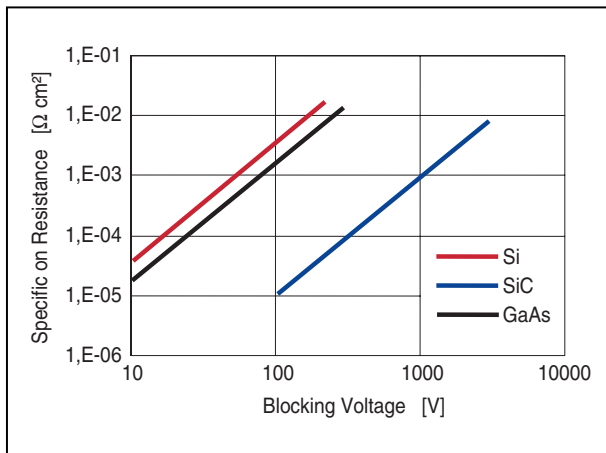


Fig. 1: Comparison of On-Resistances and Blocking Voltages

SiC ENHANCES SCHOTTKY DIODE BENEFITS TO A WIDELY EXPANDED VOLTAGE RANGE

SiC Schottky diodes offer a very low specific on-resistance with high rated voltages. Figure 2 illustrates the typical forward and blocking characteristics of 600 V SiC Schottky diodes up to 225 °C. Unlike Si and GaAs Schottky diodes, there is only a moderate increase in leakage current with increasing temperature. The area specific differential on-resistances of a 600 V SiC-Schottky diode

increases from about $0.9 \text{ m}\Omega\text{cm}^2$ at room temperature to $1.8 \text{ m}\Omega\text{cm}^2$ at 150°C . This positive temperature coefficient makes Schottky diodes well suited to implementations in parallel—without the risk of thermal runaway.

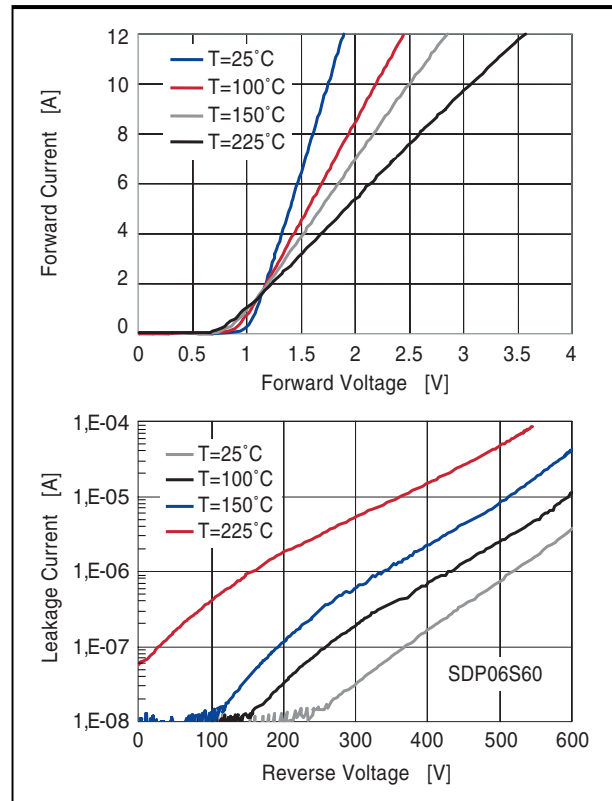


Fig. 2: 6A/600 V SiC Schottky Diode Temperature Dependence of Forward and Reverse Characteristics

DYNAMIC PERFORMANCE OF SiC SCHOTTKY DIODES CLOSER THAN EVER TO IDEAL DIODE

When switching off a Schottky diode, there is no need to remove excess carriers from the n-region as there is for pn diodes. Hence, there is no reverse recovery current. Instead, only a displacement current for charging the junction capacitance of the diode can be observed. This is shown in Figure 3. Up to very high frequencies, the current transient depends solely on the external switching speed. The charge transported by the displacement current is very low compared to the reverse recovery charge Q_{rr} for pin diodes. Due to the different origin of this charge, we have named it Capacitive Charge Q_c .

Figure 3 compares SiC Schottky Diodes to benchmark Si diodes: Si pin double diodes (2*300V serial in one package) give better reverse current than ultrafast Si pin benchmark diodes, but have much higher forward voltage drop. The Capacitive Charge Q_c and the switching power losses of SiC Schottky diodes are not merely ultra low compared to Silicon

ultra fast diodes. Losses in Si diodes depend strongly on di/dt , current level, and temperature; but, in SiC diodes, they are more or less independent on these boundary conditions. See Figure 4. A dependence of Q_c on these parameters cannot be seen at the same scale as with a benchmark Si diode. Again, this is due to the capacitance-like behavior of this device in reverse direction.

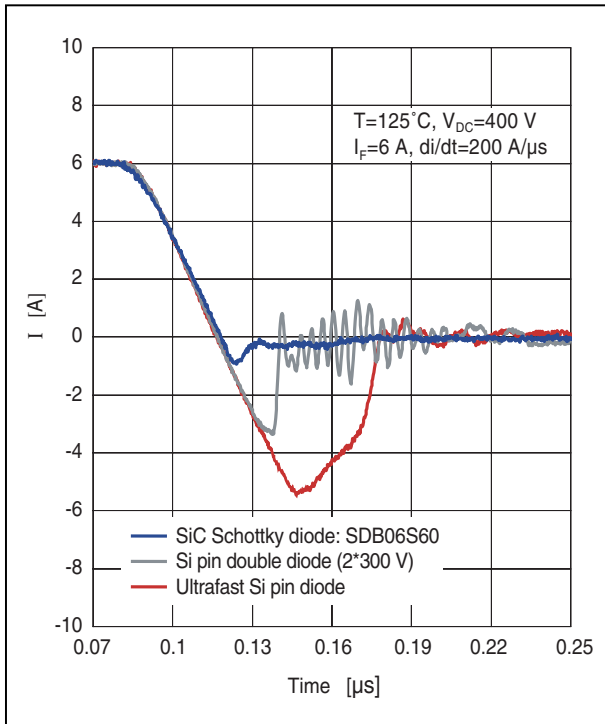


Fig. 3: Switching Comparison of SiC and Benchmark Si Diodes

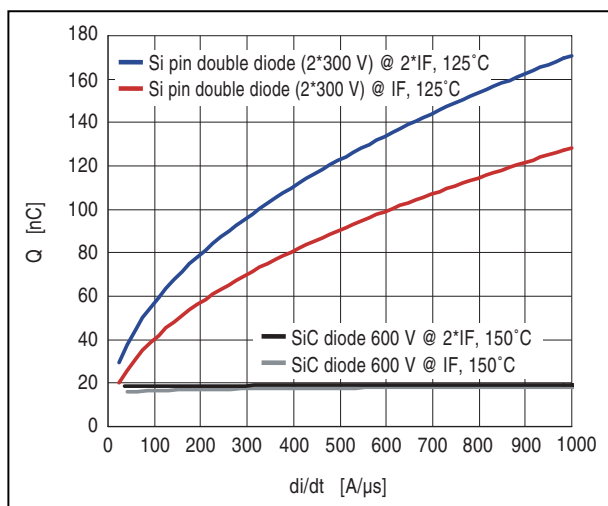


Fig. 4: Capacitive Reverse Charge Q_c of a 6A/600V SiC Schottky Diode

Figure 4 shows the capacitive reverse charge Q_c of a 6A/600V SiC Schottky diode under different switching conditions. It is compared with the Q_{rr} .

values of the benchmark Silicon solution (I_F : rated forward current of the respective device).

APPLICATIONS

Two application examples are discussed in this paper. The focus is on efficiency and system benefits derived from using a SiC diode instead of a conventional semiconductor diode. The two applications are:

- Power Factor Correction in SMPS (Boost Converter)
- Secondary Side Rectification (Rectification of the output voltage of an SMPS)

Power Factor Correction in SMPS (Boost Converter)

Worldwide, rapidly increasing requirements for power factor correction are driven by legal requirements. Boost converters are usually used to achieve active power factor correction. They can be driven in Discontinuous Current Mode (DCM) and Continuous Current Mode (CCM).

The DCM solution does not require an ultra fast diode, but has the following drawbacks:

- All circuit components must be oversized because of the high peak currents
- The system becomes unstable at light load
- A complex EMI filtering system is necessary

The CCM solution does not have these disadvantages. The circuit components do not need to be oversized, system operation is stable also under a light load, and the requirements on the EMI filter are less rigid than in the DCM case. However, the power losses in the MOSFET and in the diode due to reverse recovery dramatically limit the efficiency and switching frequency of a CCM boost converter when a conventional or ultra fast Si pn-diode is used. See Figure 5.

Because SiC Schottky diodes do not exhibit reverse recovery behavior, the stress on the MOSFET will be reduced due to very low current spike during the turn-on transient. A less expensive MOSFET can be chosen while simultaneously achieving higher reliability of the entire system. The efficiency shows a virtually independent behavior regarding frequency due to very low total switching power losses (Fig. 5), that are ideally suited to CCM. Boost converters can therefore be operated at much higher switching frequencies. The size reductions of the boost inductors extend the horizon in power density—with a correspondingly strong impact on the inductor cost.

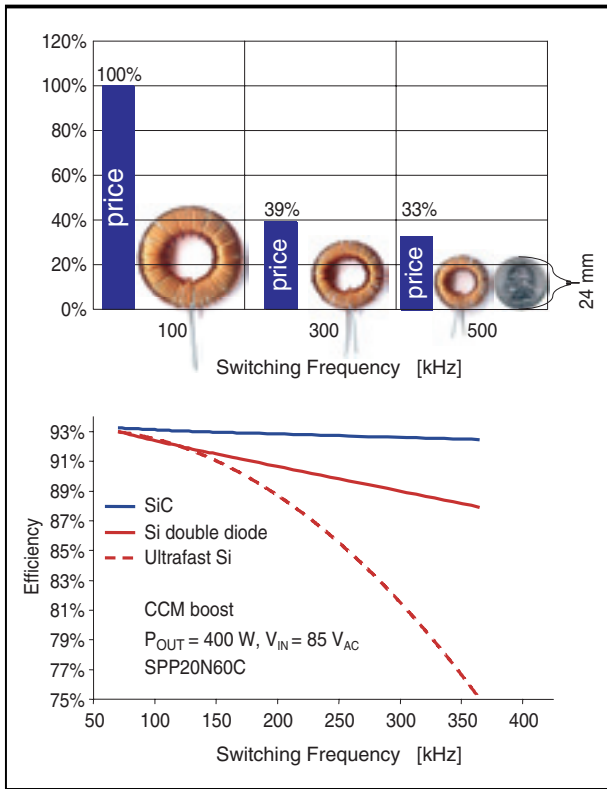


Fig. 5: Efficiency of a PFC boost converter and inductor size/price vs. switching frequency

Does higher switching frequency create EMI challenges? The EMI norm regulation begins at 150 kHz, so the main harmonic of the boost converter can be well inside this range. One will suspect complications achieving the EMI norm in case of higher switching frequency. Figure 6 shows the impedance of a typical current-compensated double choke inductor depending on the frequency.

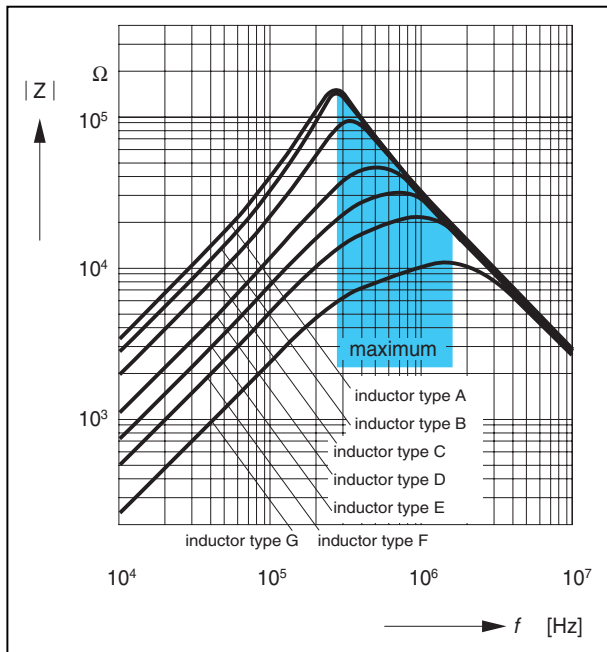


Fig. 6: Filter impedance vs. Frequency

As shown in Figure 6, the filter has its maximum impedance (i. e. highest damping efficiency) in the frequency range from 300 kHz to more than 1MHz.

The main and higher harmonics of a boost converter running at 300 – 500 kHz will be filtered with the maximum efficiency and, therefore, the increase of switching frequency to 300 – 500 kHz does not create a need for additional EMI filtering; whereas, the electrical noise can be even reduced. The properties described above now give circuit designers a new degree of freedom in optimizing PFC applications by:

- Increasing the switching frequency
- Reducing the size of passive components like inductors
- Shrinking the size of semiconductor switches
- Shrinking or avoiding heat sinks
- Increasing the reliability
- Increasing the power density

Products:

Chip/Package	TO220-2-3	TO263	D-PAK
600 V/6 A	✓	✓	
600 V/4 A	✓		✓

Secondary Side Rectification (Rectification of the output voltage of an SMPS)

An SMPS with an output voltage of 48 V (e.g. for Telecom applications) requires 250 – 300 V rated rectifiers on the secondary side. The trend to higher switching frequencies in the main converter is in strong contrast with the poor dynamic properties of the existing Si diodes on the secondary side. The GaAs Schottky diodes used today are commercially available up to a blocking voltage of 250 V. Replacing the GaAs with SiC Schottky diodes is now very attractive because:

- SiC Schottky diodes have low leakage currents and only a small temperature dependence for this leakage
- Their higher blocking capability (300 V instead of 250 V) improves the reliability
- SiC diodes are a very cost-effective alternative to GaAs diodes

Products:

Chip/Package	TO220-2-3	TO263
300 V/10 A	✓	✓
300 V/2x10 A	✓	✓