Whitepaper

From SiC to Thin SiC: Pushing Power Diodes to the Next Level

By Dr. Sebastian Fahlbusch, Manager Power Product Application Competence Center

Nowadays, Silicon Carbide (SiC) and Gallium Nitride (GaN) are regular headline grabbers in the technical press. This is because devices constructed using these wide bandgap technologies are superior to their silicon counterparts across many critical metrics and open up new, previously unfeasible applications. This white paper describes the structure and applications of SiC diodes and explains their advantages over silicon devices. It then introduces a new range of SiC diodes developed by Nexperia to have a thinner device structure and discusses the additional benefits these provide over standard SiC diodes in power applications.

Advantages of Silicon Carbide over Silicon

The differences between the characteristics of silicon and 4H-SiC, which is the polytype predominantly used in commercial power electronics, are illustrated in **Figure 1.**

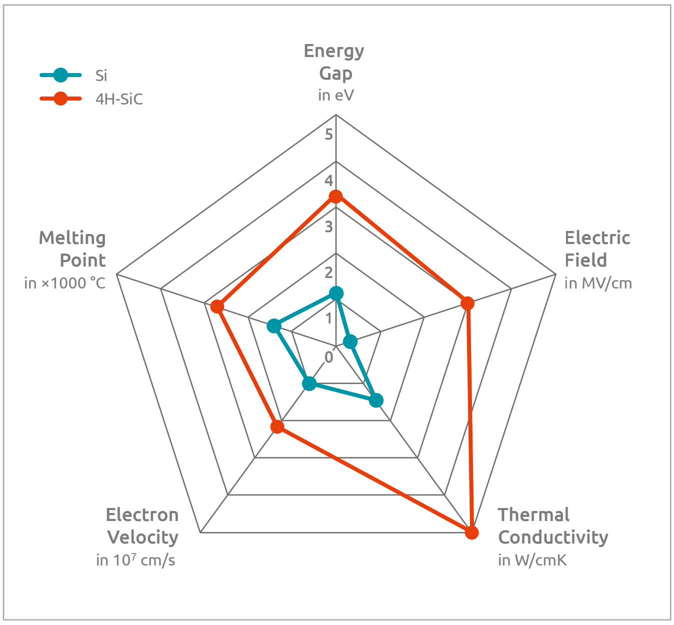


Figure 1: Silicon and 4H-silicon carbide characteristics compared.

Wide bandgap semiconductors materials have a larger energy gap than conventional semiconductors like silicon. As a result, SiC has -10x better dielectric breakdown field strength with a thinner drift layer for the same voltage rating. This leads to lower resistivity and better conduction performance with a smaller die size than other products with a similar voltage rating. In addition, the approximately 3.5x better thermal conductivity of SiC allows more power dissipation for a given chip area. The maximum operating temperature of SiC is also almost twice that of Si. While packaging is typically a limiting factor in continuous operation, the extra margin with SiC gives confidence during transient thermal events.

Additionally, because of the small die size, device self-capacitance and the associated charge are lower for a given current and voltage rating. This, combined with the higher electron saturation velocity of SiC, enables faster switching speeds with lower losses.

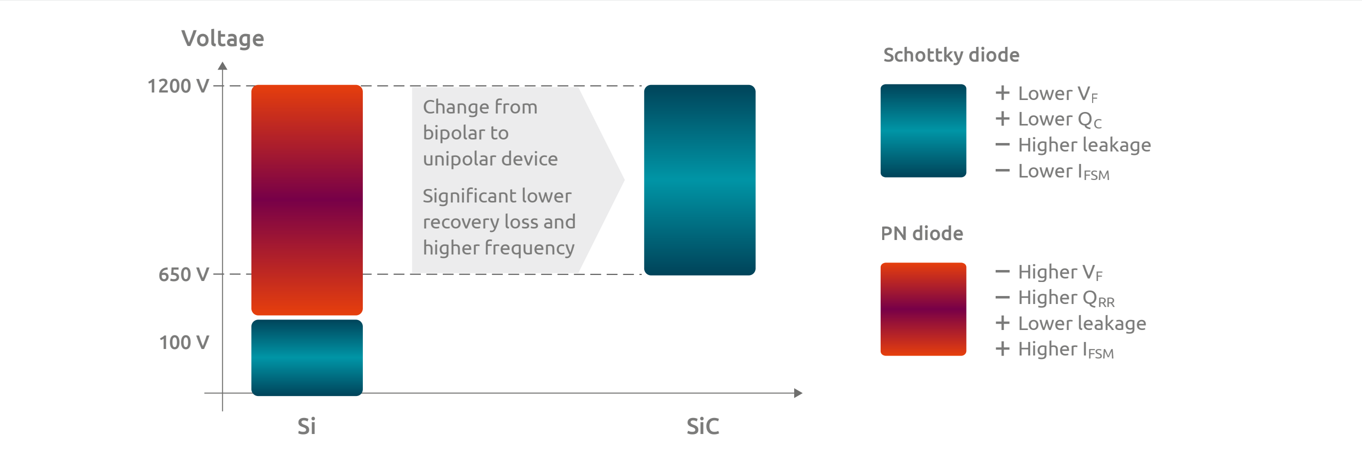


Figure 2: Comparison of Si and SiC power diodes vs blocking voltage.

SiC Diodes Operating Characteristics

SiC diodes are unipolar Schottky metal-semiconductor devices where conduction is only through majority carriers, i.e. electrons, resulting in negligible charge stored in the junction depletion layer during forward bias. In contrast, P-N junction diodes are bipolar and store charges that must be removed during the transition to reverse bias. **Figure 2** illustrates these differences.

This causes a spike in reverse current and leads to higher power losses in the diode, switching transistors and snubbers, which worsens as the switching frequency increases. The SiC diode also exhibits a reverse current spike due to the discharge of its self-capacitance under reverse bias, but this can be an order of magnitude less than in a P-N junction diode, meaning less power dissipation not only in the diode itself but also in the corresponding switching transistor. The maximum forward voltage drop of SiC diodes is comparable with the best ultra-fast silicon types and is still being improved, with minor differences for higher blocking voltage ratings. Despite being a Schottky type, the reverse leakage current and resulting power dissipation in a high-voltage SiC diode under reverse bias are relatively low and similar to an ultra-fast Si diode of the same voltage and current class. Any slight difference in dissipation caused by variations in forward voltage drop and reverse leakage current between SiC diodes and ultra-fast Si diodes is more than offset by the improvement in dynamic losses with SiC due to the absence of reverse charge recovery effects. This is further elaborated in the section on MPS diode reverse recovery characteristics.

A silicon diode’s recovery current and time vary widely with temperature changes, making circuit optimization difficult, but significantly, with SiC, there is no such variation. In some circuits, such as ‘hard-switched’ power factor correction stages, a silicon diode acting as the boost rectifier can dominate losses, going from forward bias at high current to reverse bias at typically 400 V for a typical single-phase AC input. The characteristics of SiC diodes can bring significant efficiency gains to this application.

An additional advantage of SiC diodes over Si is that they can be connected in parallel because their forward voltage drop has a positive temperature coefficient (in the application-relevant area of the I- V curve), which helps correct any current imbalances. This compares with the negative temperature coefficient of Si P-N diodes which can produce thermal runaway when devices are connected in parallel, requiring heavy derating or additional active circuitry to force current sharing.

A further benefit of SiC diodes’ comparable soft switching behaviour is a significant reduction in EMI. When Si-diodes are used as switching rectifiers, the potentially snappy spike in reverse recovery current, with its broad frequency spectrum, can cause conducted and radiated emissions. These create system disturbances (via various coupling paths) that may result in system EMI limits being exceeded. At these frequencies, filtering can be complex due to this stray coupling. In addition, EMI filters designed to attenuate switching fundamental and low harmonic frequencies (often below 1 MHz) typically have high self-capacitance, making them less effective at higher frequencies. A snubber can be used across a silicon fast recovery diode to limit edge rates and damp oscillations, reducing stress on other components and EMI. However, the snubber has to dissipate significant energy, adversely impacting system efficiency. Another often-overlooked source of loss is forward recovery. During transition from off- to on-state temporarily the diode voltage drop increases in silicon diodes which produces overshoot, ringing and additional loss. This effect relates to the initial lower conductivity of the junction of Si-based P-N diodes and is absent in SiC diodes.

The absence of minority carriers in SiC diodes enables their superior efficiency. Consequently, they require less cooling, meaning they can be used to provide higher power density in smaller and lighter products. Due to the significant reduction in switching losses (in both the device itself and the corresponding transistor), SiC diodes enable higher switching frequencies. The dissipated heat is therefore reduced, meaning additional cost savings can be made through less complex EMI filtering and smaller magnetic components. Additionally, device junctions can withstand higher temperatures for more rugged performance and better reliability without risking thermal runaway.

Nexperia's Merged PiN SiC Schottky: A closer look into high-end silicon carbide power diodes

Compared to silicon fast recovery diodes, some characteristics of the basic SiC Schottky diode can be further improved, including leakage current (caused by imperfections at the metal-semiconductor interface) and surge current rating (which relates to the device's unipolar nature and relatively high drift layer resistance). Leakage current can be improved with a thicker drift layer, which increases its ohmic and thermal resistance, but this is a disadvantage in power applications. Nexperia's 'Merged PiN Schottky' (MPS is a hybrid of a SiC Schottky and P-N junction diode) overcomes this constraint while providing maximum robustness in the presence of surge currents. The MPS structure shown in **Figure 3** effectively parallels the two diode types, a Schottky diode and a P-N diode.

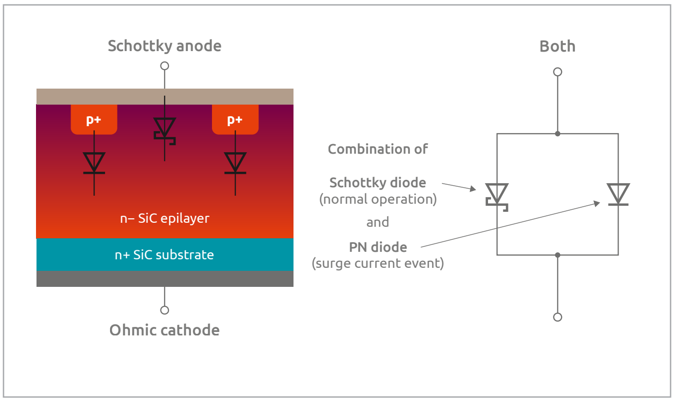


Figure 3: The Nexperia hybrid 'Merged PiN Schottky' diode.

P-doped areas are implanted in the drift zone of a conventional Schottky arrangement forming a P-ohmic contact with the metal at the Schottky anode and a P-N junction with the lightly-doped SiC drift or epi-layer. Under reverse bias, the P-wells 'push' the general area of maximum field strength downwards into the almost defect-free drift layer, away from the metal barrier with its imperfections, reducing the overall leakage current. The effect is shown diagrammatically in **Figure 4.**

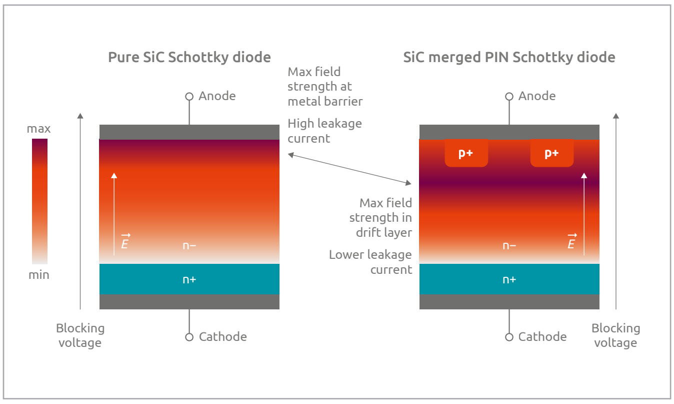


Figure 4: Adding P-wells to a SiC Schottky diode displaces the area of maximum field strength under reverse bias, away from the anode metal.

The P-wells' physical placement and area, compared with the size of the Schottky diode, and doping concentration all affect the end characteristics, with forward voltage drop traded against leakage and surge currents. Consequently, an MPS device can operate at a higher breakdown voltage with the same leakage current and drift layer thickness. The improvement in surge current rating comes from the fact that the differential resistance of a bipolar device is lower than that of a unipolar type. Although the Schottky area has a lower voltage drop (at low current) and can conduct the whole current (even high surges), this voltage increases beyond the P-N diode cut-in voltage, which starts to conduct with lower differential resistance. This diverts current, limiting dissipated power and relieving the MPS diode from thermal stress **(Figure 5)**.

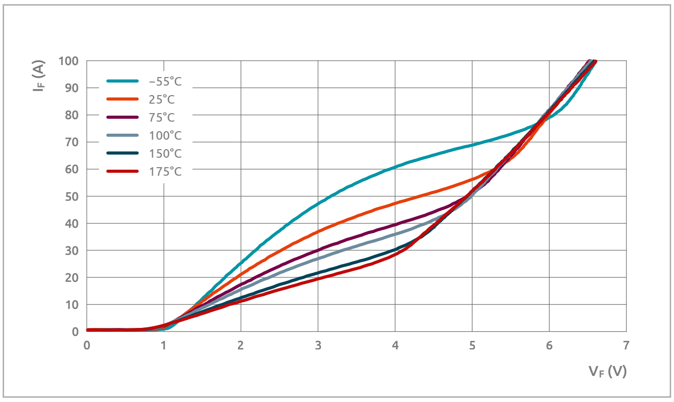


Figure 5: Static I-V behaviour of SiC MPS diodes, including overcurrent.

Under normal conditions, the P-N junction does not conduct, the overall effect is that of a unipolar diode, and there are almost no reverse recovery losses. Without the P-N diode, the Schottky diode alone would have to be significantly over-dimensioned if transient over-current events could occur in the target application. Parts can be paralleled (or extra circuitry added) to limit over current, but this increases cost. Again, the dimensions and doping of the P-wells create a trade-off between forward voltage drop (in regular operation) and surge withstand capability. The best choice is application-specific, and Nexperia offers diodes to suit a wide range of hard- and soft-switching applications.

MPS diode reverse recovery characteristics

Besides the static advantages, SiC MPS diodes offer benefits during dynamic operation in switching mode. One significant advantage over silicon-based P-N diodes relates to the reverse recovery behaviour. As previously described, SiC MPS diodes behave like Schottky diodes under nominal conditions. Unlike conventional Si fast recovery diodes, only the majority carriers contribute to the overall current for SiC diodes. As a result, these show a purely capacitive switching behaviour, resulting in a lower reverse recovery charge than a Si fast recovery diode with the same electrical rating. The reverse recovery charge is one of the main loss contributors and thus adversely affects converter efficiency.

Figure 6 depicts the effects of different parameters affecting the reverse recovery behaviour, such as diode turn-off currents and junction temperatures. SiC exhibits almost constant behaviour in the presence of these variations and little of the non-linear behaviour of Si fast recovery diodes. Hence, its behaviour is easier to predict for power designers because they do not need to consider a variety of ambient temperatures and load conditions. A similar property of both diode technologies is that the blocking voltage affects the capacitive portion of the overall recovery charge. For Si-based P-N diodes, this is comparatively small because the stored minority carriers dominate the recovery charge during turn-off. Hence, the voltage dependence of the capacitive charge is often negligible. In contrast, due to the absence of minority carriers in a SiC diode, the capacitive charge is the only contributor to the reverse recovery charge and causes losses during switching.

‘Thin SiC’ diode structure provides additional benefits

Nexperia’s ‘Merged PiN Schottky’ exhibits improved leakage and surge current ratings but also provides other advantages derived from reduced die thickness during manufacture. The unprocessed SiC substrate is N-doped, and SiC epitaxial layers are grown to form the drift region. The substrate starts with a thickness of up to 500 µm, but after epitaxy, this adds unnecessary electrical and thermal resistance in the current and heat-flow path to the back-side metal. This increases forward voltage drop and junction temperature for a given current. A solution is to ‘thin’ the underside of the substrate by grinding. During this process step, material quality is vital, along with the precision of the grind, to avoid non-uniformities and consequent performance degradation of the diode and potential field failures. In addition, an advanced manufacturing capability is required for this process, not least because of the hardness of SiC (9.2 to 9.3 on the Mohs scale, compared with silicon at around 6.5).

Figure 7 illustrates the effect of the process, with Nexperia’s ‘thin SiC’ technology achieving a reduction to about one-third of the original substrate thickness. As a result, the thermal resistance from the junction to the back-side metal is dramatically reduced, resulting in lower operating temperature, higher reliability and lifetime, higher surge current capability and lower forward voltage drop.

The inherent advantages of SiC and Nexperia’s advanced manufacturing processes result in a component whose behaviour is closer to that of an ideal diode.

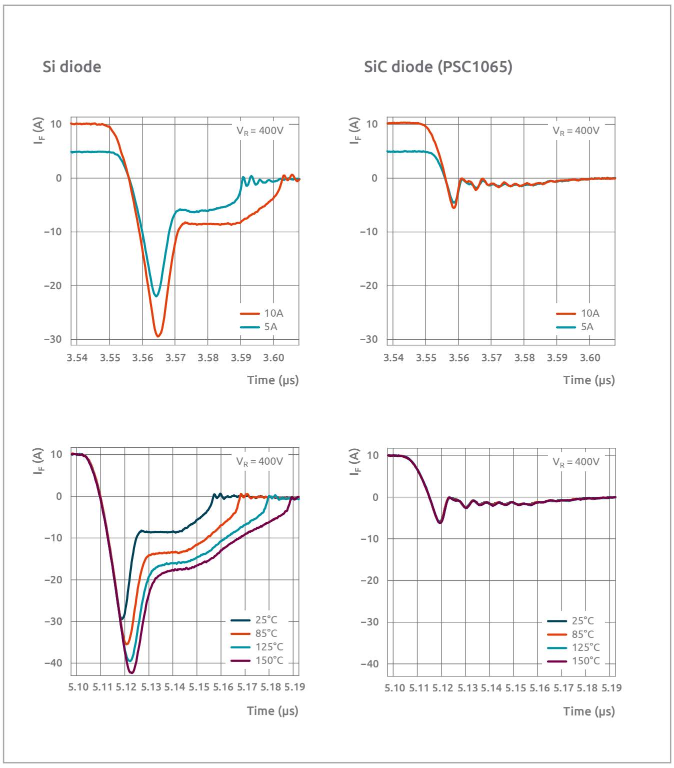


Figure 6: Comparison of reverse recovery behaviour of Si and SiC under various operational conditions.

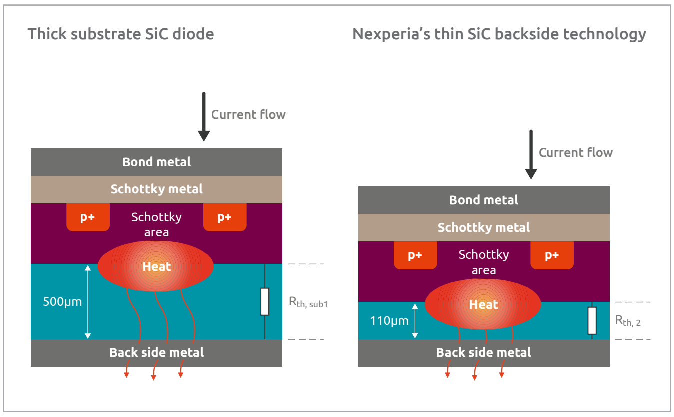
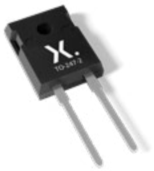


Figure 7: Nexperia’s ‘thin SiC’ process (right) improves diode electrical and thermal performance compared to standard SiC diode construction (left).

Product range

Qualification	V_{RRM} (V)	I_F (A)	TO-252-2 (DPAK R2P)	TO-263-2 (D2PAK R2P)	TO-220-2	TO-247-2
Automotive and industrial	1200	6				
		8				
		10				
		16				
		20				
	650	6				
		8				
		10				
		16				
		20				

Conclusion

Compared to silicon, SiC diodes provide superior technical advantages like significantly better switching performance and allow system engineers to improve their power applications. SiC diodes enable higher efficiency and power density, lower EMI, better reliability, and lower system complexity. In addition, higher switching frequencies can be achieved without sacrificing output power or overall system efficiency. Consequently, smaller magnetics and other passive components can be used, reducing converter size, and lowering the total cost of ownership.

Nexperia introduced its SiC Schottky diode technology that combines both advanced Merged PIN Schottky structures as well as 'thin SiC' technology benefits to maximize performance. Currently available products have a voltage rating of 650 V, but future devices will operate up to 1200 V and 20 A current in DPAK, D2PAK, TO-220 and TO-247 packages.

References

1 www.nexperia.com
2 Diode Application Handbook. Design Engineer's Guide

About Nexperia

Nexperia is a leading expert in the high-volume production of essential semiconductors, components that are required by every electronic design in the world. The company's extensive portfolio includes diodes, bipolar transistors, ESD protection devices, MOSFETs, GaN FETs and analog & logic ICs that meet the stringent standards set by the Automotive industry. Headquartered in Nijmegen, Netherlands, Nexperia annually ships more than 100 billion products. These products are recognized as benchmarks in efficiency - in process, size, power and performance - with industry-leading small packages that save valuable energy and space. With decades of experience, supplying to the world's biggest companies, Nexperia has over 14,000 employees across Asia, Europe and the U.S., offering global support.

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