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The Future of Power Semiconductors: Rugged and High Performing Silicon Carbide Transistors

In the past, energy efficiency was the key design and marketing road to success with solar converters. SiC diodes, for example used as part of the booster circuit, were the best solution to achieve efficiency levels of 98 percent or better.

The use of SiC based power semiconductor solutions has shown a huge increase over the last years, it is a revolution to rely on. Driving forces behind this market development are the following trends: energy saving, size reduction, system integration and improved reliability.

SiC devices are well placed to meet all the above market challenges. The new wide band gap technology is more than an evolutionary step forward, as we have seen in previous years with each new generation of silicon power devices, but has the capability to be a real game changer. SiC based systems have the revolutionary capability which can be characterized by a steep change in performance which can make them attractive for designers targeting innovative and disruptive solutions. IGBTs or Super-Junction MOSFETs in combination with SiC Diodes have already become the norm in various applications, such as solar, chargers or power supplies. This combination – a fast silicon based switch matched with a SiC Diode – is often termed a “hybrid” solution. In recent years Infineon has manufactured several million hybrid modules and has seen them installed in various customer products. The first worldwide Hybrid module was developed more than ten years ago based on Infineon’s EconoPACK™ package platform.

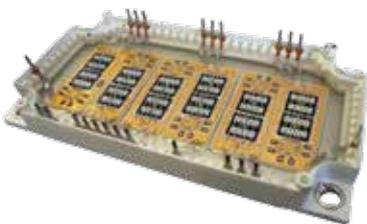


Figure 1: World’s first hybrid module solution in production since 2006.

Certain application segments will always be early adaptors of any new technology. Depending on the actual system value others will follow when cost/performance of the new technology is attractive enough to make a switch to a new higher technology solution. After the already well established designs using SiC diodes in high-end power supplies Infineon has identified solar inverters and boost circuits as the area’s most likely to benefit the most from this new technology. Behind this the associated market segments of Uninterruptible Power Supplies (UPS) and chargers are likely to follow. It is expected that more traditional segments like motor drives, traction and on a long time scale, automotive applications will in the future become very interested in a large scale change over to the new semiconductor technology.

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Today, the ongoing major trend in solar designs is the increase of power density based on a reduction of switching losses, enabling smaller heatsinks, and also allowing higher operating frequencies, enabling smaller magnetics. SiC diodes have increasingly become a staple component in modern solar string inverter solutions as well as in micro-inverter applications. Recently, Infineon’s SiC diode technology reached its 5th generation. SiC diodes made further progress by using options for die shrink in order to achieve a more attractive cost position. In addition, new

technology features were implemented which will give additional customer benefits compared to the previous generations for example lower forward voltage drop, resulting in lower conduction losses, increased surge current capability and an enhancement of the breakdown behavior. Hybrid solutions are a standard part of today’s solar inverters all around the world. Infineon has become a trusted partner of this technology after more than 15 years availability, a proven track record and dependable high volume production.

With its integrated manufacturing concept – manufacturing of SiC chips utilizing the same production lines as the high volume silicon power chips – Infineon is able to guarantee reliability and process stability at the same level as its silicon products. In addition, this integrated concept brings volume flexibility, a key factor in order to handle needed emerging technologies in fast moving market segments. Based on a deep system understanding and a clear focus on cost performance it has been possible to successfully define products by forming optimized combinations between silicon and silicon carbide based semiconductors. This move, away from a purely semiconductor technology driven definition of products, towards solutions tailor made for the targeted system is seen as a key element for the success of SiC in the future. Based on the experience with the diode technology, a similar roll out of SiC transistors will follow in the next few years. This is an important next step in order to move SiC much closer to the level of a mainstream technology. As listed above, key elements will be:

- proven ruggedness

- attractive cost/performance enabling a measurable system advantage
- volume production capability
- product definition driven by system understanding

During the last years, intensive studies have been carried out mainly in order to understand the system benefits of SiC. The increase of switching frequency for a converter using unipolar SiC transistors can result in dramatically reduced volume and weight of the magnetic components. From an analysis carried out by Infineon, a converter built on SiC devices is a third of the size and 25 percent of the weight compared to a current Si based reference solution.

Thanks to the significant reduction in volume and weight, the system costs can also be reduced by more than 20 percent.

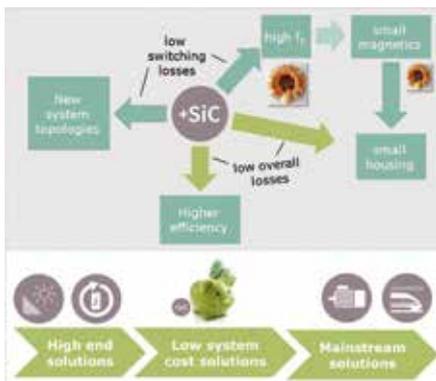


Figure 2: Benefits of SiC depending on use in arenas and applications.

Over the next few years, SiC solutions will expand into other application fields such as industrial or traction drives. The reasons for this are the market forces pushing for loss reduction, not only for the sake of improved efficiency but also for smaller packages – resulting from reduced heat sink requirements. As shown in figure 2, SiC is already being used for high end and niche solutions. Today's designs use these benefits to reduce system cost in specific application areas.

In the future, more and more applications will benefit from the overall loss reduction made possible by implementing SiC solutions. In this regards, the next major step forward will be the introduction of SiC switches.

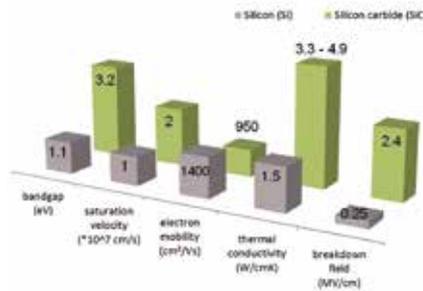


Figure 3: Material property comparison of silicon vs. silicon carbide.

To understand the differences between Si and SiC solutions, it has to be made clear that silicon carbide devices belong to the so-called wide band gap semiconductors. A comparison of Si vs. SiC material properties is shown in figure 3. The voltage range for fast and unipolar Schottky diodes as well as field effect based SiC switches (MOSFET, JFET) can be extended to over 1000V. This is possible because of inherent properties of the SiC material:

The low leakage current in high voltage Schottky-diodes is possible because of the metal-semiconductor barrier which is two times higher than in Si Schottky diodes.

The very attractive, specific on-resistance of unipolar transistors compared to Si is achieved because of the breakdown field strength which is approximately ten times higher.

Figure 4 shows the minimum specific on-resistance of different semiconductors versus the desired blocking voltage (only the drift region is used here, any substrate contribution to the resistivity is neglected). The end points of each line symbolize the usable voltage range of the specific semiconductor in a unipolar configuration excluding Super-Junction MOSFETS.

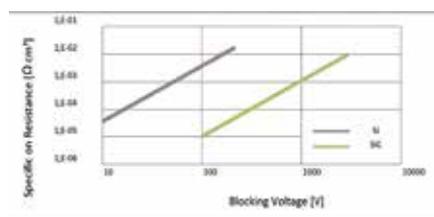


Figure 4: Comparison of on-resistance and blocking voltage of SiC and Si.

SiC transistors are about to become an attractive alternative to today's established IGBT technologies in industrial power electronics. The dedicated material properties of SiC enable the design of minority carrier free unipolar devices instead of the charge modulated IGBT devices at high blocking voltages. This is based mainly on the high critical field which is provided by the wide bandgap. The loss restrictions of IGBTs are caused by the dynamics of minority carriers. In MOSFETs those minority carriers are eliminated. As an example, extremely high dv/dt slopes in the range above 100kV/μs have been measured for SiC MOSFETs. In the beginning, the superior dynamic performance of SiC based transistors compared to IGBTs in the area of 1200V and higher was seen as the most important advantage. However, recent results indicate a significant future potential in the IGBT technologies, as shown by Infineon's TRENCHSTOP™5 technologies.

Taking the long term view, however, the fundamental differences between the IGBT and the unipolar SiC switch will increasingly attract attention. With the two major differences being: first, the linear, threshold free I-V curve of the output characteristic, second, the ability to integrate a body diode with the option of synchronous rectification. Based on these properties, the device offers threshold-free conduction behavior in synchronous rectification mode. In addition, the number of necessary components is reduced by half. This leads to a significant reduction of the required power module footprint.

On system level, the feature of threshold-free conduction behavior offers a significant potential for loss reduction. Many systems are operated for a large portion of their lives under partial load conditions and conduction losses are considerably lower compared to the competing standard IGBT technologies. Even at very low frequencies of less than 5 kHz and unchanged dv/dt slopes it can be seen that a threshold-free switch with integrated body diode, in synchronous rectification mode, offers a potential of 50 percent total loss reduction compared to a commercial IGBT solution available today. The comparison in losses can be seen in figure 5.

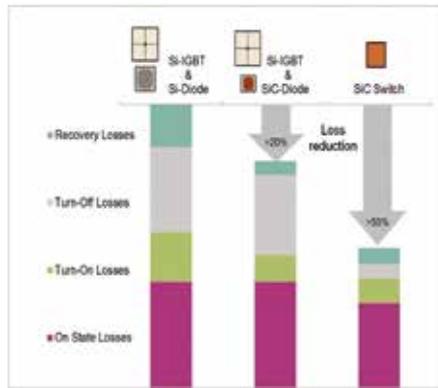


Figure 5: Loss reduction of 50 percent is feasible even with IGBT like dv/dt's operating at 5kHz.

Obviously, the loss reduction will be even higher in applications where there is no dv/dt limitation and at much higher switching frequencies. This is common in DC-DC boost or buck/boost topologies providing the benefit of smaller, lighter and lower cost magnetic components. Various studies have already proven that – even with more expensive power switches – the bill of material can be reduced over a wide spectrum of applications. This number of applications will increase over the mid-term time frame based on the anticipated cost reduction over time for SiC based components.

The objective for a SiC transistor design is for the most parts to achieve the lowest area specific on-resistance. This is quite logical, since this parameter defines cost and also indirectly the remaining dynamic losses which are caused by chip capacitance values. The smaller the die for a given resistance, the lower the capacitance values.

The high defect density is reflected in various idiosyncrasies or traits of SiC MOS based devices. One example is a weak transconductance in comparison to silicon based power MOSFETs, combined with a low threshold voltage.

Another effect is a non-physical temperature behavior of the on-resistance. Physics indicates that the Ron will typically increase at higher temperatures. Components available today sometimes show zero or even negative temperature dependence. This is due to the fact that the defect related resistance contribution has a negative temperature coefficient and thus, a different temperature

behavior is observed. The less the Ron increases with temperature, the higher the impact of channel defects on the device performance. A drop of the defect related resistance contribution can be effectively achieved only by increasing the applied field across the oxide in on-state above values being usually used in silicon based MOS power devices. Since high fields across the oxide in the on-state can potentially accelerate the blocking capability wear out it can be deemed a long term reliability risk.

The overall goal is to combine the low Ron-potential offered by SiC with an operational mode where the part remains inside the well-researched safe oxide field conditions. In the on-state this can be achieved by moving away from the planar surface, with its high defect density, towards other, more favorable surface orientations. MOS channels on the so called a-face of SiC offer a factor of at least ten times lower defect densities. For this reason, one possible approach is to use a TRENCH based structure, similar to many modern silicon power devices. Beside the low channel resistance the cell density in such structures can be naturally higher than in planar structures, ending up in a more effective material utilization. Additionally, this would lead to a lower area specific on-resistance. However, in Trench-based components the field stress on the oxide at Trench corners is a critical issue and, especially in SiC, this can be a show stopping argument. This semiconductor chip is proposed to use an about ten times higher electric field compared to Si solutions. There are various possibilities in place to realize an effective shielding of the critical areas, e.g. by deep pn elements. In contrast to the on-state dilemma in the DMOS, the off-state challenge can be addressed by an ingenious design.

A powerful SiC switch offering a proven and established ruggedness similar to silicon based components will have a bright future in power electronics applications – even if new challenges are attached to the new technology. In the beginning, there will have to be additional efforts to utilize the technology in the best and most effective way. Challenges include EMI topics arising from faster

switching or cooling challenges caused by much higher power densities. The latter are inevitable and combined with the chip shrink which will not be offset by the expected loss reduction.

To enable a faster penetration of the SiC transistor technology it is beneficial to address these valid concerns. In this regard, it is essential to partner with customers to minimize any design and implementation processes made necessary by the new technology.

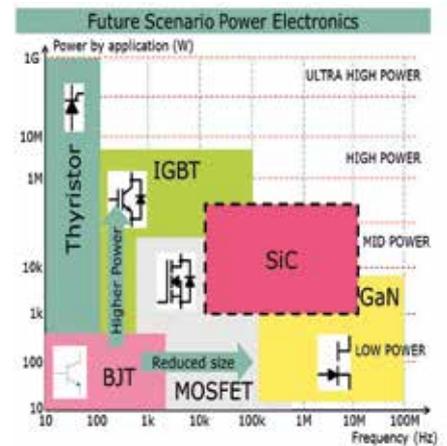


Figure 6: SiC switch market 1kW- 500kW @ 10kHz-MHz.

It is axiomatic that new semiconductor technologies will be the key enabler to meet the increasing demands for improved power density and efficiency of applications based on power semiconductors. However, the replacement of silicon based components will not be a matter of the next coming years. Instead, wide band gap technologies are able to complement silicon based solutions, especially where they can open up new application niches which cannot be addressed by current technologies. SiC is seen here as the major innovation for industrial power applications targeted at components with blocking voltages above 100V and power ratings up to several hundreds of kilowatt as shown in figure 6. After the successful market introduction of SiC diode technologies, SiC based transistors will be the next major step. By now much higher levels of performance are expected from the wide bandgap material. For a fast market acceptance, ruggedness and system oriented product features are key elements ◀