



CoolSiC™

CoolSiC™ MOSFET: a revolution for power conversion systems

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Abstract

Silicon carbide (SiC) transistors are increasingly used in power converters, placing high demands on the size, weight and/or efficiency. The outstanding material properties of SiC enable the design of fast-switching unipolar devices as opposed to bipolar IGBT devices. Thus, solutions which have been up to now possible in the low-voltage world only (< 600 V) are now possible at higher voltages as well. The results are highest efficiency, higher switching frequencies, less heat dissipation, and space savings – benefits that can, in turn, also lead to overall lower cost.

MOSFETs have been meanwhile commonly accepted to be the concept of choice. Initially, JFET structures seemed to be the ultimate choice for merging performance and reliability in a SiC transistor. However, with the now established 150 mm wafer technology, trench-based SiC MOSFETs have also become feasible, and thus, the DMOS dilemma of having either performance or high reliability could now be solved.

Introduction to SiC

Wide band gap-based power devices such as SiC diodes and transistors, or GaN HEMTs, (high electron mobility transistor) are established elements nowadays in the library of power electronics designers. But what is so fascinating about SiC compared to silicon, and what features make SiC components so attractive that they are so frequently used despite higher costs compared to silicon high-voltage devices?

In power conversion systems, one continuously strives to reduce energy losses during power conversion. Modern systems are based on technologies in which solid-state transistors are switched on and off in combination with passive elements. For the losses related to the transistors used, several aspects are relevant. On the one hand, one has to consider losses in the conducting phase. In MOSFETs, they are defined by a classical resistance; in IGBTs, there is a fixed conduction loss determinant in the form of a knee voltage (V_{ce_sat}) plus a differential resistance of the output characteristic. Losses in the blocking phase can usually be neglected.

However, there is always a transition phase between the on and off state during switching. The related losses are defined mostly by the device capacitances; in the case of IGBTs, further contributions are in place due to the minority carrier dynamics (turn-on peak, tail current). Based on these considerations one would expect that the device of choice is always a MOSFET, however, especially for high voltages, the resistance of silicon MOSFETs becomes so high that the total loss balance is inferior to that of the IGBTs, which can use charge modulation by minority carriers in order to drop the resistance on conduction mode. Figure 1 summarizes the situation graphically.

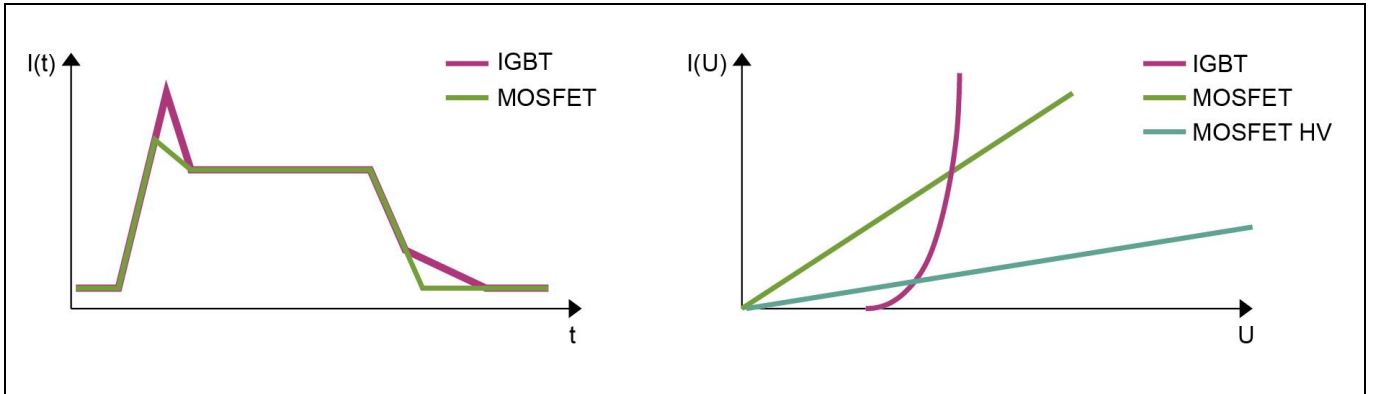


Figure 1 Comparison of the switching process (left, assuming same dv/dt) and the static I-V behavior (right) between MOSFETs (HV indicates a similar blocking voltage as an IGBT – 1200 V and higher) and IGBTs

The situation changes when wide band-gap semiconductors are considered. Figure 2 summarizes the most important physical properties of SiC and GaN vs. silicon. Important is the fact that there is a direct correlation between the band gap and the critical electric field of a semiconductor. In the case of SiC, it is about 10x higher compared to silicon.

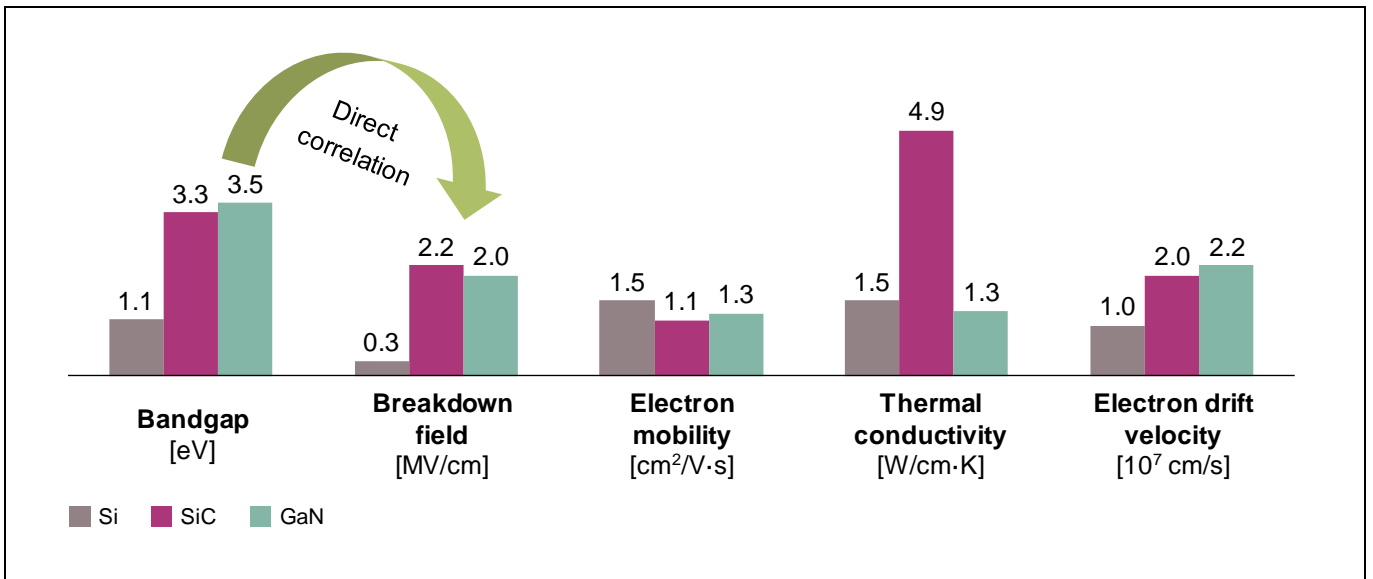


Figure 2 Comparison of important physical properties of power semiconductor materials

With this feature, the design of high-voltage devices is different. Figure 3 shows the impact using the example of a 5 kV semiconductor device. In the case of silicon, one is forced to use a relatively thick active zone due to the moderate internal breakdown field. In addition, only a few dopants can be incorporated in the active area thus resulting in a high series resistance (as indicated in figure 1).

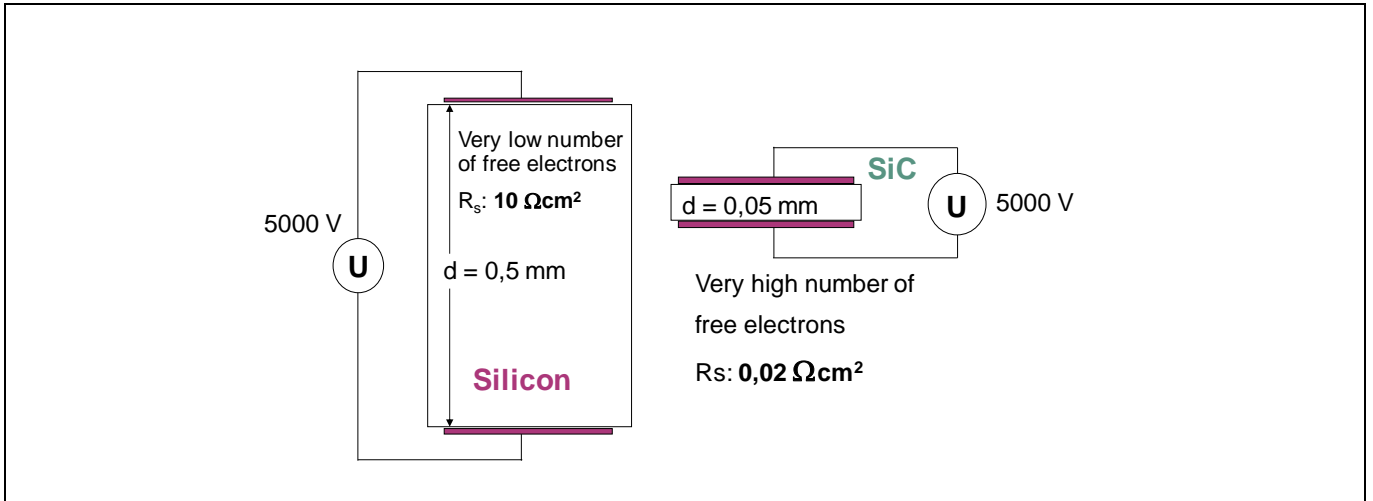


Figure 3 Dimensioning of 5 kV power devices – difference between silicon and SiC

With its 10x higher breakdown field in SiC, the active zone can be made much thinner, at the same time, many more free carriers can be incorporated, and thus, there is a substantially higher conductivity. One can say that in the case of SiC, the transition between fast switching unipolar devices like MOSFETs or Schottky diodes and the slower bipolar structures like IGBTs and p-n diodes has now shifted to much higher blocking voltages (see figure 4). Or, in turn, what was possible with silicon in the low-voltage area around 50 V is now possible with SiC for 1200 V devices as well.

Infineon identified this potential over 25 years ago, and formed an expert team to exploit the technology. Milestones on that path were the first introduction worldwide of SiC-based Schottky diodes in 2001, the first power modules containing SiC in 2006, and just recently in 2017, the full switch to 150 mm wafer technology in the Villach Innovation Factory in connection with the premiere of the world's most innovative Trench CoolSiC™ MOSFET.

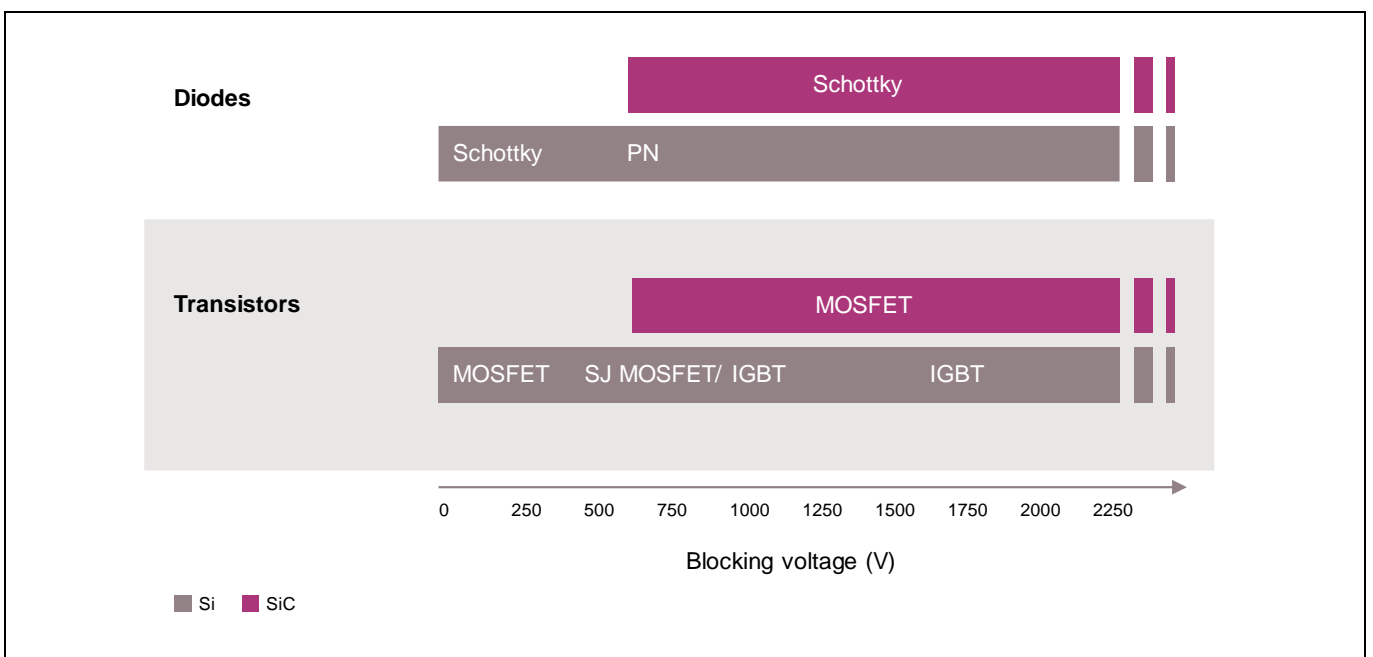


Figure 4 Device concepts for high voltages, comparison between silicon and SiC

SiC MOSFETs in the landscape of modern power devices

As sketched in the previous paragraph, SiC MOSFETs are used for the most part today in areas where IGBTs are the dominating component of choice. Figure 5 summarizes the major advantages of SiC MOSFETs vs. IGBTs. Especially at partial loads, significantly lower conduction losses are possible due to the linear output characteristic as opposed to the IGBT situation with a knee voltage. Furthermore, one could theoretically decrease conduction losses to infinitely small numbers by using larger device areas. This is ruled out in the case of IGBTs.

Regarding switching losses, the lack of minority carriers in conduction mode eliminates tail currents, and thus, very small turn-off losses are possible. Turn-on losses are also reduced compared to IGBTs, predominantly due to the smaller turn-on current peaks. Both loss types do not show an increase in temperature. However, in contrast to IGBTs, turn-on losses dominate while turn-off losses are small, which is often the opposite situation with IGBTs. Finally, there is no need for an additional freewheeling diode, since the vertical MOSFET structure itself contains a powerful body diode. This body diode is based on a p-n diode, which has in the case of SiC a knee voltage of about 3 V.

One could argue that in this case the conduction losses in diode mode are very high, however, it is recommended (and state of the art for low-voltage silicon MOSFETs) to work in diode mode for just a short dead-time diode conduction, between 200 ns and 500 ns for hard switching, and < 50 ns for resonant topologies like ZVS. The channel can then be turned on by applying a positive gate bias, which has the same advantage as in transistor mode on-state due to the lack of knee voltage. Since the diode is a bipolar component, a small reverse recovery effect is also in place; however, the total impact on switching losses is negligible.

Infineon has also recently introduced a 650 V CoolSiC™ MOSFET derivate, to be deployed in a complete 650 V product portfolio. This technology is intended to complement not only IGBTs in this blocking voltage class, but also the successful CoolMOS™ technology. Both devices have fast switching and linear I-V characteristics in common; however, SiC MOSFETs enable body diode operation in hard switching, and at switching frequencies above 10 kHz. Compared to superjunction devices, they show a much lower charge in the output capacitance (Q_{oss}) in combination with a smoother capacitance vs. drain voltage characteristic. These features enable the use of SiC MOSFETs in high-efficiency bridge topologies like half bridge and CCM totem pole, while CoolMOS™ devices have their strength in applications where a hard commutation on a conducting body diode is not present, or can be prevented.

This sets the grounds for a successful coexistence of SiC and superjunction MOSFETs in the voltage class between 600 V and 900 V. The application requirements will dictate the most suitable technology choice for designers.

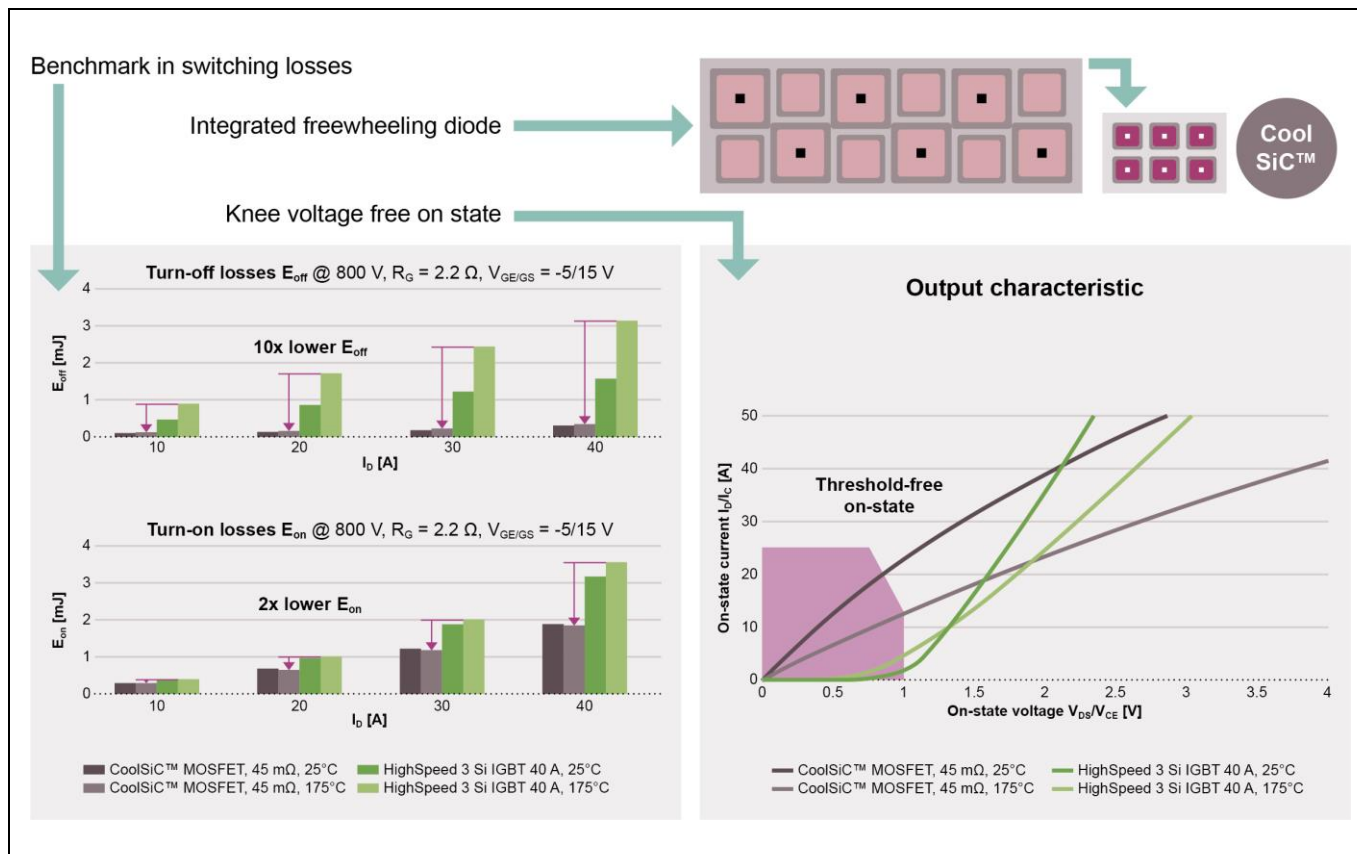


Figure 5 Summary of the advantages of SiC MOSFETs vs. IGBTs: left dynamic losses, right conduction behavior, upper left integrated body diode

Conclusion

A device design by Infineon has always been carefully oriented towards a beneficial cost-performance evaluation with a strong emphasis on exceptional reliability, which is what customers are used to getting from Infineon. The concept of Infineon's SiC-trench MOSFET follows the same philosophy. It combines a low on-resistance with an optimized design preventing too much gate-oxide field stress, and providing gate-oxide reliability similar to that of the IGBT.

For more information in the second part, click here: [HYPERLINK](#)

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