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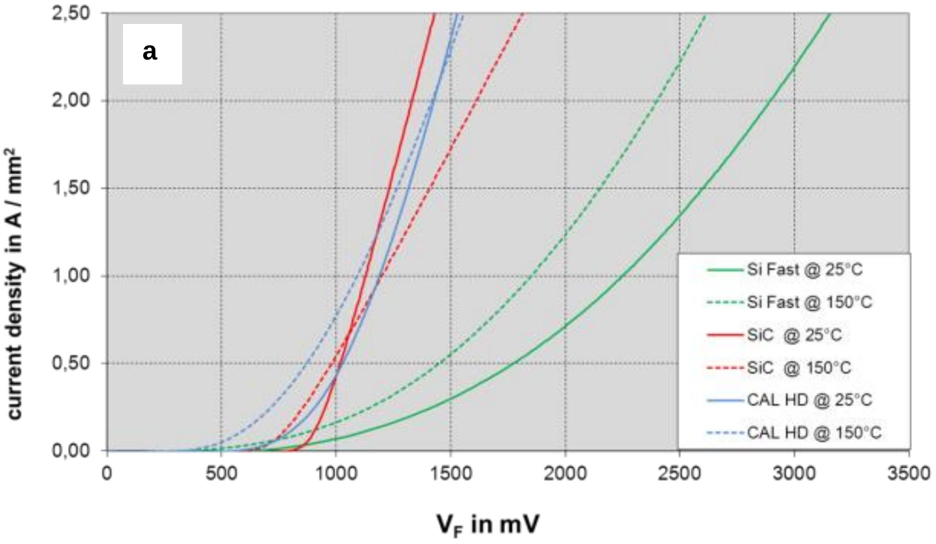
SiC in Power Electronics

The future for silicon carbide (SiC) in power electronics looks promising. According to forecasts, the power modules with SiC will move into applications like renewable energies, UPS, drives and automotive. Applications like wind and traction might follow. The total market of SiC power devices is predicted to rise to more than US$ 1 billion by the year 2021 [1]. In some markets, such as solar, SiC devices are already in operation despite the fact that the prices for those modules are still higher by factors as compared to conventional Si devices.

What makes this material attractive enough that higher cost are willingly being accepted? First of all, being a wide band gap material, SiC offers new approaches for the design of power semiconductors. In conventional power Si technology, IGBT switches are used as switches for voltages higher than 600V, and Silicon PIN-freewheeling diodes are state of the art. The design and soft switching behaviour of Silicon power devices cause considerable power losses. With the larger band gap of SiC, high voltage MOSFETs can be designed, blocking voltages up to 15 kV, while providing extremely low dynamic losses. With SiC, the conventional soft-turn off Silicon diodes can be replaced by diodes in Schottky design, also offering extremely low switching losses. As an additional benefit, SiC has a 3 times higher thermal conductivity as compared to silicon. Together with small power losses, SiC is an ideal material to boost power density in power modules. Current designs are available in SiC hybrid modules (IGBT + SiC Schottky diodes) and Full-SiC modules.

SiC hybrid modules

In SiC-hybrid modules, a conventional IGBT is switched together with a SiC-Schottky diode. Although the main benefits of SiC devices are clearly related low dynamic losses, the static losses of SiC-Schottky diodes are discussed first. Often, the static losses of SiC devices seem to be higher compared to conventional Silicon devices. Figure 1.a shows the forward voltage drop V_f of a conventional soft switching 600V SEMIKRON CAL HD freewheeling diode, a Fast Silicon diode optimised for low switching losses and a SiC Schottky diode, all rated at 10A.



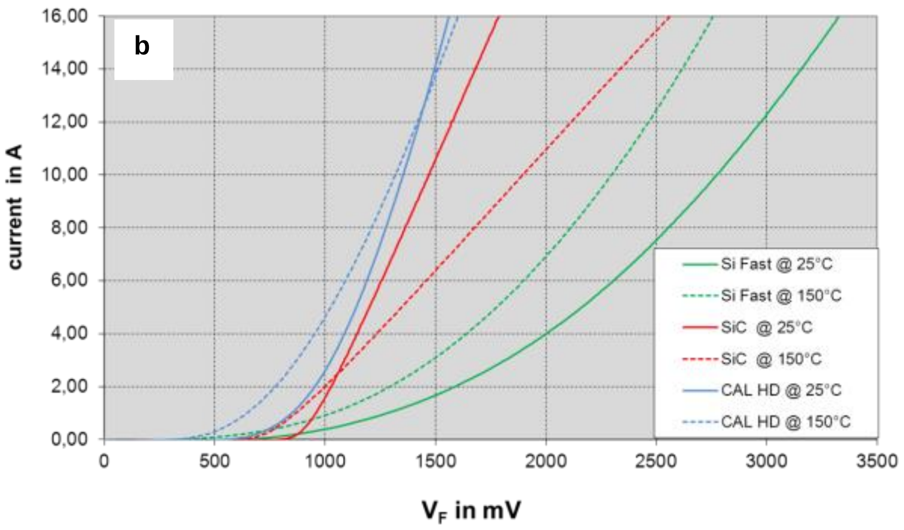


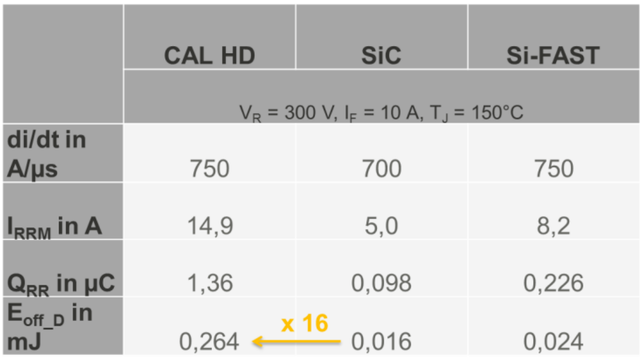
Figure 1.a: forward current and forward voltage drop of different freewheeling diodes at 25°C and 150°C. A 10A SiC Schottky diode, a conventional soft switching Silicon diode (CAL HD) and a fast Silicon diode (Si-Fast) are compared. 1.b: the forward voltage drop and current density (forward current divided by chip area) of the same diodes.

At the rated current of 10A, the Silicon freewheeling diode reveals the lowest forward voltage drop, the V_f of the SiC Schottky diode is higher, whereas the Fast Si diode shows the highest forward voltage drop. The temperature dependence of the forward voltage is quite different: the Fast Silicon diode has a negative temperature coefficient, as V_f is lower at 150°C than it is at 25°C. The temperature coefficient of the CAL is positive for currents above 12A and the SiC-Schottky diode, as characterised by positive temperature coefficient even for currents as low as 4A.

Since diodes are often paralleled to achieve high power devices, a positive temperature coefficient is required to avoid unbalanced current sharing and inhomogeneous operation temperature of the paralleled diodes. Here the SiC-Schottky diode shows the best behaviour. But compared to the conventional Silicon diode, the static losses are higher for the SiC Schottky. As the diodes were compared based on the nominal current of 10A, it is important to take into account that the definition of nominal currents is sometimes unequal between devices by different suppliers. To gain better insight to device performance, it is useful to the plot the current density (forward current divided by chip area) as a function of the forward voltage drop, which takes into account the chip area.

Figure 1.b shows that for equivalent current densities, the conventional Silicon and SiC Schottky diode have quite similar forward voltage drops, whereas the V_f of the Fast Si diode is still highest. In other words: Silicon and SiC diodes have comparable static losses, as identical chip areas are used. Usually SiC chips exploit smaller chip sizes, as the nominal current rating is done considering static and dynamic losses, causing low total losses, and therefore allow a chip size shrink.

Looking at the dynamic losses of SiC Schottky diodes, the main benefit of SiC devices becomes clear.



	CAL HD	SiC	Si-FAST
	V_R = 300 V, I_F = 10 A, T_J = 150°C		
di/dt in A/µs	750	700	750
I_{RRM} in A	14,9	5,0	8,2
Q_{RR} in µC	1,36	0,098	0,226
E_{off_D} in mJ	0,264	0,016	0,024

x 16

Table 1: dynamic parameters of a conventional Silicon freewheeling diode (CAL HD), a SiC Schottky diode and a Fast Silicon diode. All diodes have a 1200V, 10A current rating.

Compared to the conventional Silicon diode, the reverse recovery current I_{RRM} is more than 50% lower for the SiC Schottky diode, the reverse recovery charge Q_{RR} drops by a factor of 14 and the turn-off energy E_{off} is lower by a factor of 16. The Si-Fast diode shows better characteristics than the conventional Silicon diode, yet it does not reach the superior dynamic characteristics of the SiC Schottky diode. Due to the low dynamic losses of SiC-Schottky diodes, the inverter losses can be reduced significantly, saving expenses for cooling and increasing the power density of the inverter. In addition, the low dynamic losses make the SiC Schottky diodes ideal for high switching frequencies.

On the other hand, fast-switching freewheeling diodes may come with a drawback, as the very steep decrease of the reverse current may lead to a current cut-off and oscillations. In the case of Silicon diodes, the current cut-off is controlled by soft turn-off characteristics. Figure 2 compares the turn-off characteristics of the CAL HD and the SiC Schottky freewheeling diodes.

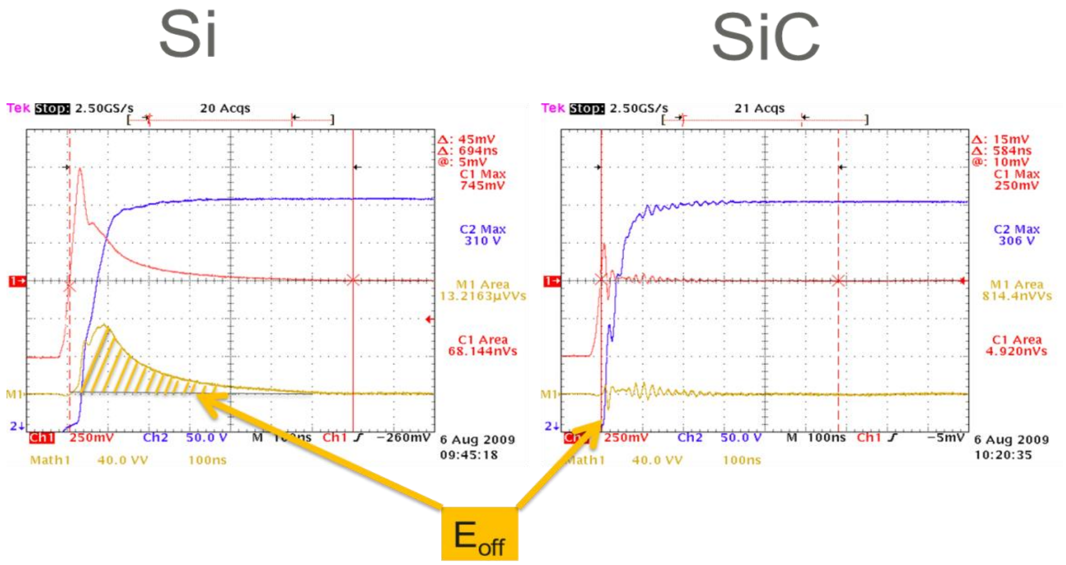


Figure 2: turn-off characteristics of Silicon and SiC freewheeling diodes. The turn-off energy of the SiC diode is barely visible. As the turn-off energy of the SiC diode is small, the reverse current drops rapidly, leading to small oscillations in reverse current and voltage.

With the Silicon-based CAL HD diode, the well-known soft turn-off behaviour of CAL Silicon freewheeling diodes is observed. As the reverse current is reduced smoothly, no overvoltage peaks nor oscillations are visible. On the other hand, the soft turn-off behaviour causes a significant turn-off energy, because a considerable reverse current is flowing as the voltage at the diode rises. The SiC Schottky diode basically does not show any reverse recovery charge, and consequently an extreme low turn-off energy. Due to the rapid decrease of the reverse current, small oscillations are induced, visible as ripples in the reverse current and in the voltage drop. In our case, the fast turn-off behaviour of the SiC Schottky diode was addressed by an optimised chip layout on the DCB and a low stray inductance of the module. Consequently, the voltage oscillations are small and do not lead to significant overvoltage peaks. It is therefore possible to manage the disadvantages of fast-switching diodes and fully exploit the benefits of SiC Schottky diodes by optimised module designs. In Figure 3, the advantage of the SiC diodes is shown by comparison of a conventional silicon module and a SiC hybrid module equipped with fast Silicon IGBTs and SiC Schottky diodes.

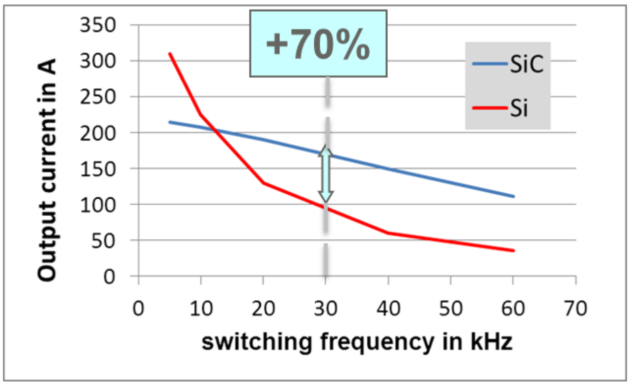


Figure 3: output current of a conventional Silicon 6-pack module (1200V, 450A trench IGBT + CAL freewheeling diode) and a SiC hybrid 6-pack module (1200V, 300A Fast IGBT + SiC Schottky). Thermal loss calculation of SKiM93 modules on water cooler.

As expected, the superior dynamic behaviour of the SiC Schottky diodes significantly increases the output power of the module significantly. With the given chip setup, which was chosen for optimum performance at higher switching frequencies, the usable output current can be increased by more than 70% at 30kHz. As the switching frequency rises further, the benefit of the hybrid-SiC module is even larger. The lower losses and the resulting higher power output on module level can be exploited on several ways. Weight and volume of inverters can be reduced significantly, important for example for automotive and aerospace applications. Exploiting high switching frequencies smaller LC-filters are possible, reducing size and inverter cost. Last but not least, the lower losses supply also an significant advantage in energy efficiency, important for solar, UPS, and automotive applications.

Full-SiC modules

Using SiC switches like SiC MOSFETS the overall losses of power modules can be decreased even further. In Table 2, static and dynamic losses of a 1200V, 25A 6-pack IGBT module are compared to a 20A Full-SiC module.

		25A IGBT 6-pack Mini-SKiiP 13AC12T4	**20A Full-SiC** 6-pack Mini-SKiiP 13ACM12V15
V_{CE}	20A, 150°C	1,8V	2,1 V
E_{ON}	150°C, 20A, 600V	2,7mJ	0,9mJ
E_{OFF}		1,9mJ	0,3mJ

Table 2: static and dynamic losses of a 1200V, 25A IGBT module (trench IGBT + CAL diode) in comparison to a 20A Full-SiC module (SiC MOSFET + SiC Schottky)

The static losses of the Full-SiC module are higher by 17%, while the dynamic losses are significantly lower: turn-on losses are lower by a factor of 3, the turn-off losses by a factor of more than 6. Consequently, the usable output power of a Full-SiC module much higher compared to conventional Silicon technology, especially at higher switching frequencies, Figure 4.a

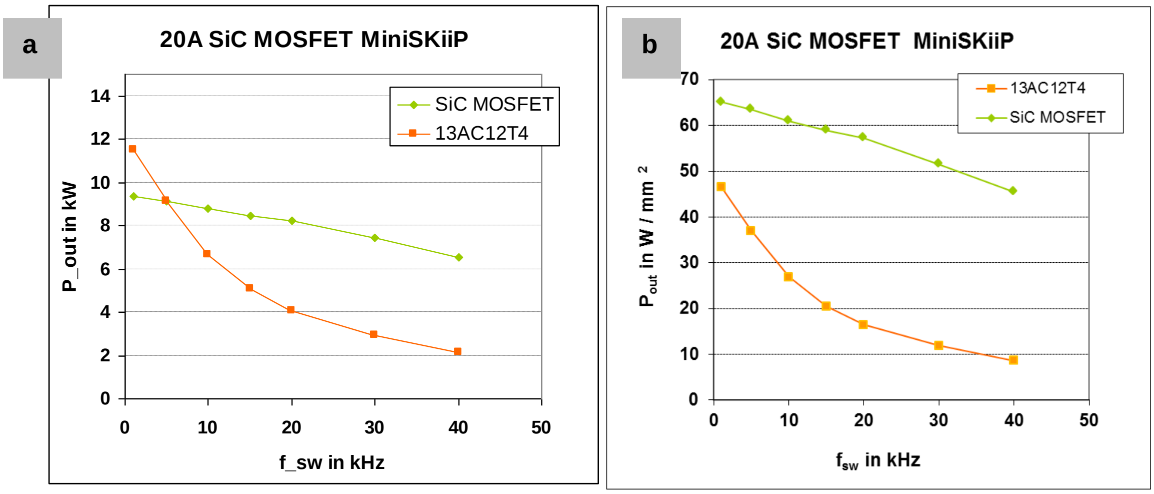


Figure 4.a: output power P_{out} of a 1200V, 20A 6-pack Full-SiC module and a conventional 1200V, 25A 6-pack IGBT module. 4.b: output power divided by chip area showing the power density of the used power semiconductors. Thermal loss calculations on air-cooled heat sink, 40°C ambient temperature.

At switching frequencies higher than 20A, the output power of the Full-SiC module is more than 100% higher as compared to the IGBT module. In addition, there is little dependency of the output power on the switching frequency. In turn, the Full-SiC power module can be used up to very high switching frequencies, as the output power is only 28% lower at 40kHz compared to the output power at 10 kHz. At switching frequencies lower than 5kHz, the IGBT modules shows higher output power. This is a result of the SiC chipset used in the Full-SiC module, which was optimised for very high switching frequencies. An optimisation for lower switching frequencies is also possible. Again, it is useful to address the power density of both modules by considering the chip areas used for the Silicon and SiC chips. In Figure 4.b, the output power is divided by the chip area, showing the power density. The power density of the Full-SiC module is much higher as compared to the IGBT module, even at switching frequencies lower than 5kHz. An optimisation of Full-SiC modules for low switching frequencies is therefore possible by using larger chip sizes. SiC devices can provide higher output currents and output power over a broad range of switching frequencies, as the SiC chip sizes are adapted.

High power SiC devices

High power requires extensive paralleling of power chips and modules. At present, Silicon IGBTs and conventional freewheeling diodes are available up to a nominal current of 200A, the maximum nominal currents of SiC MOSFETS and Schottky diodes are below 100A so far. Consequently, a large number of SiC chips have to paralleled in order to achieve high power ratings.

Taking into account the fast switching behaviour and oscillation tendency of SiC devices, a low inductive module design and optimised chip layout on the DCB's is required. In the following, a 1200V, 900A Full-SiC module is compared to a 1300A conventional Si module. The IGBT module exploits two DCBs in parallel, each equipped with 9x75A trench IGBTs in parallel, together with 5x100A CAL freewheeling diodes. In order to obtain the equivalent power output with SiC, and due to the lower current rating SiC devices available, the full SiC modules exploits two DCBs, each equipped with 23x20A SiC-MOSFETs and 34x13,5 SiC-Schottky freewheeling diodes. A total of 46 SiC-MOSFETs and 68 SiC Schottky diodes are paralleled in the Full-SiC module.

Table 1 shows the basic data for the Si and the Full-SiC module in comparison.

		1300A IGBT~~Single~~	**900A Full-SiC**~~Single~~
R_{th}	IGBT / SiC-MOSFET	0.040 K/W	0.022 K/W
R_{th}	Diode/SiC-Schottky	0.056 K/W	0.033 K/W
V_{CE}	900A, 150°C	1.7 V	3.4 V
E_{switch}	150°C	220mJ	62mJ
$E_{rr\ diode}$		58mJ @920A	3,7mJ @700A

Table 3: electrical and thermal data of a 1200V, 900A Full-SiC module and its 1300A IGBT equivalent.

Comparing the thermal data, the full SiC module reveals a lower thermal resistance than the conventional Silicon module. This is due to the higher thermal conductivity of SiC compared to Si and the better heat spread: in this layout, 4 SiC diode chips replace 1 Silicon diode on the same amount of space. The lower thermal resistance of the SiC devices is particular important, as in this case as a total area of 21 cm^2 Silicon chips was used compared to only 10 cm^2 in the case of the full SiC module. The on-state losses of the Full-SiC module are higher compared to those of the Silicon module. The same is true for the forward voltage drop of the SiC Schottky diode. The dynamic losses of the Full-SiC module are extremely low: the SiC MOSFETS have 4 times lower switching losses than the Silicon IGBT, the SiC Schottky diode has 8-9 times smaller losses.

Lower dynamic losses and better thermal dissipation lead to a considerably higher power output, Figure 5.

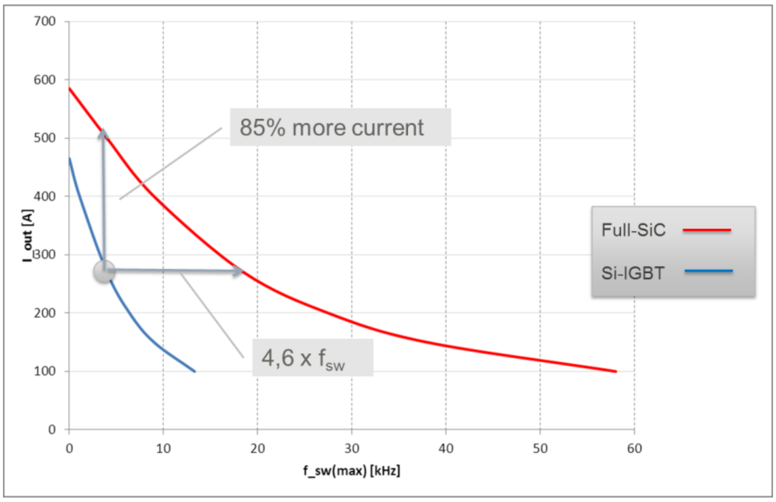


Figure 5: output current of a 1200V, 900A Full-SiC module compared to a 1300A IGBT module. Thermal loss calculation on air-cooled heat sink, ambient temperature of 60°C.

Even at low switching frequencies of 4kHz, the advantage of the Full-SiC module is obvious: the usable output current can be increased by 85%. Again, it is important to recognise that SiC is not restricted to very high switching frequencies. In other words, the module section of the inverter can be nearly 2 times smaller as compared to the conventional Silicon IGBT technology, an advantage especially in high power applications like wind energy. The power of wind turbines has increased over the years, with the standard power being about 2-4 MW, wind installations up to 7.5 MW are already available. The available room for the power inverters is nevertheless restricted, and a reduction of inverter size not only addresses the space issue, but also reduces the cost for transportation and installation.

Summary

At module level, SiC has two main benefits: smaller chip sizes and lower dynamic losses. At system level, these advantages can be exploited in several ways. Lower dynamic losses lead to a significant increase of the output power, offering the chance to save weight and volume. Worth mentioning is the fact that this power increase can be achieved without additional cooling power. Since SiC leads to an actual loss reduction compared to Silicon devices, higher output power is possible with the same cooling efforts. Small power losses improve the energy efficiency, enabling the design of high efficient inverters, e.g. for solar and UPS applications. In addition, low dynamic losses make SiC devices ideal for higher switching frequencies above 20kHz. Exploiting high switching frequencies allows for reducing the cost and size of LC filtering.

Depending on the chip area used, SiC shows advantages also at switching frequencies as low as 4kHz. Other advantages of SiC are related to the enhanced thermal heat dissipation and the positive temperature coefficient, important for paralleling SiC chips. All of that makes SiC a very attractive material for a wide range of possible applications. However, the price of SiC power devices is still higher by factors, causing the prices of Hybrid and Full-SiC modules to be much higher compared to conventional Silicon solutions. These higher costs constrain the market entry, and SiC solutions have found their way into niche applications mainly. Cost evaluations show that in many applications, the price of SiC modules needs to be 2-3 times higher in order to achieve positive business cases. In some applications, higher prices may be affordable, as benefits like small size, low weight, high efficiency, etc. can outweigh the higher cost. Much more than with conventional Silicon solutions, the total cost of ownership needs to be carefully considerated with SiC.

Some benefits are not related directly to higher power output or higher efficiency. For example, reduced size and weight of wind inverters not only saves space inside the wind installation, but also reduces transportation and installation efforts. SiC offers lots of benefits and forces designers of power systems to think differently, to review conventional designs and to find new ways to take full advantage of the SiC technology. At module level, low inductive designs, optimised DCB layouts for extensive chip paralleling and of course new assembly technologies like SEMIKRON sinter technology for high reliability and high operating temperatures are needed. SEMIKRON supports the SiC solutions by intensive research, SiC devices can be assembled in all standard packages; optimized solutions and topologies are evaluated in close relationship with the customers, which is indeed necessary. Tailored solutions are the way to be cost competitive.

However, the price issue persists and needs to be resolved for a broad breakthrough of SiC devices in the power electronics market. And the outlook is positive: according to market studies, the prices of SiC Schottky diodes are expected to drop by ~30%, the prices for SiC MOSFETs are expected to drop by about 40% within the next years, significantly increasing the competitiveness of SiC. It can be expected that the prices of Hybrid-SiC and Full-SiC modules will be suitable not only for niche applications, but also for standard solutions within the next 3 years. Indeed, it's been a long way for SiC into power electronics, and the quest for a broad market entry is not yet finished. But the signs are positive for SiC to become a mature technology for power electronic applications within the next years.

References

[1] IMS Research, 'The World Market for Silicon Carbide & Gallium Nitride Power Semiconductors – 2012 Edition", February 2012.