SiC power devices as key enabling components for the green energy transition – how the growth journey began and will go on

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Abstract

Especially for the modern power semiconductor technology SiC is meanwhile THE buzz word in the community. After the initial hype in the nineties and some kicks between 2000 and 2015 meanwhile the relevance of the technology is growing substantially from year to year. More and more applications – not just e-mobility – understand what kind of benefits these new components can deliver. The contribution will sketch why this innovative material is so interesting for power electronics, which benefits can be generated and how the next steps in development will look like.

INTRODUCTION

SiC as a base material for semiconductors, in particular high voltage power devices, is known for decades. However, material maturity and high cost for producing usable substrates were blocking points for a wider use. Some technical leap frogs before 2000 gave another push to the technology, leading to the introduction of first commercial devices in 2001. After the initial success, however, a period of uncertainty followed, for several reasons. Among them was a still unfavorable cost situation which limited an economical use of the powerful technology, and furthermore, transistors were not yet mature enough. In parallel the material base matured, characterized by larger wafer diameters with improved quality. New device concepts became possible and eventually with 150mm wafers being commercially available a cost performance level also for power switches based on MOSFET concepts was reached, enabling new perspectives. At the same time, the need for extremely efficient energy conversion systems and enabling components for carbon dioxide reduction during electricity flow between generation and consumption was growing and both elements drove the today's success of SiC based devices for high voltage/high power energy conversion systems. Today, SiC power semiconductors are fixed design elements for a wide range of applications. Mainly emerging applications like fast EV charging od stages to connect large scale storage systems to the grid or to renewable energy generation plants widely adopted the new MOSFETs already. The portfolio ranges today from 650V small power devices up to 3.3kV rated high power modules, being able to handle around 1000A. The device technology matured significantly proven by outstanding low field failure rates even compared to the established silicon power device technology. All over the world large production capacities are built up, connected to the transition towards 200mm SiC wafers. For the 2030 timeframe, market analysts predict a total market for SiC power devices in the range of 20 billion USD.

BENEFITS OF SIC POWER DEVICES

The wider band gap of SiC in comparison to the established silicon mono crystals results in a significantly higher internal breakdown field and thus, highly efficient device concepts which have been possible before for low voltage devices (e.g. <100V blocking voltage) are now extendable towards several thousand volt – the required values for components used in high power energy conversion systems. Namely Schottky barrier diodes (SBD's) and MOSFETs as alternatives to the typical silicon based pn diodes and IGBT's can significantly drop the losses during energy conversion. Since modern energy conversion circuits are based on switching processes the losses occurring in the switching elements constitute from conduction and dynamic (switching) losses. Dynamic losses in the mentioned silicon components are to a large extent related to the bipolar nature of the devices. Effects like stored charge in diodes (quantified by the Q_{rr} parameter in the datasheet) or tail currents which dominate the turn off losses in IGBT's are the most prominent examples. Regarding conduction losses, MOSFETs outperform IGBT's mainly under partial load operation since MOSFET have a linear I-V output characteristic compared to the IGBT with it's knee voltage named V_{CE_sat}. Having in mind that nearly all power conversion systems are running mostly under partial load this represents a huge benefit when the goal is a total loss reduction in the system. Since SiC SBDs and MOSFETs are mostly unipolar the offer significantly lower switching losses even at very high switching frequencies. This has a double effect – the system becomes more efficient and smaller since higher frequencies enable a shrink of size and weight dominating passive components. Figure 1 shows the impact on a very simple example of PFC stages from the early adoption period for SiC diodes in high power density power supplies [1].

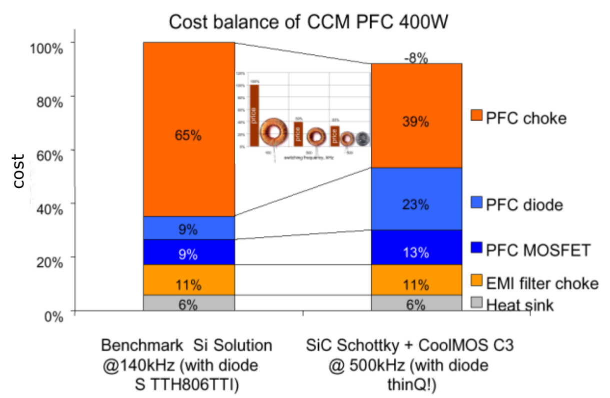

Fig. 1. Impact of SiC based power semiconductors on power conversion circuits – significant size reduction of passive components and overall cost benefit

Similar pictures can be drawn for other typical SiC applications like solar power conversion, basically always when a DC-DC stage with a choke is used today. The second effect beside the size shrink and the related material saving is an improved efficiency. In many modern systems SiC can cut losses by 50% or more. This leads directly to savings on the cooling side, heat sinks become smaller or can be eliminated completely, in case of forced cooling fans can be omitted, increasing the system up time substantially.

CURRENT USE CASES FOR SIC POWER DEVICES

The need for electrical energy will grow continuously, triggered by the evolution of the human mankind itself, but also by the move from fossil energy sources to renewables. Thus, the value of highly efficient conversion systems will grow and complete view application fields for power electronics are generated. Higher efficiency always leads to energy saving itself, but at the same time to a more effective material utilization e.g. when it comes to required battery capacities, the significantly smaller housings for SiC components or less material for heat sinks or passive components lead to a net positive contribution towards to global goals to reduce CO_2 footprints. Even at chip level it can be shown that due to the smaller size of SiC chips compared to silicon ones the power handling capability power wafer can be increased dramatically. Thus, also the production efficiency increases in case of SiC based semiconductors since a given FAB capacity can now serve a much larger number of end applications.

Figure 2 illustrates the system saving opportunity by a direct comparison of a Si based inverter module on its heatsink vs a SiC solution.

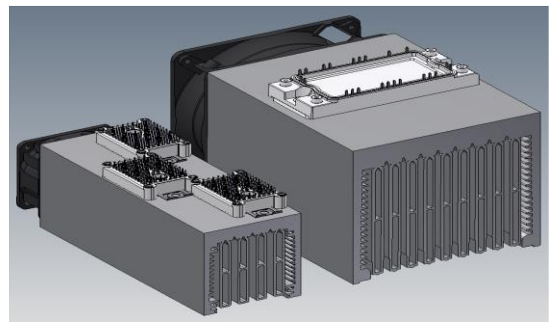

Fig. 2. Potential to reduce the heatsink size by using SiC power switches instead of Si based semiconductors.

Although on a first glance the success of SiC power transistors seems to be connected to the electrification of cars and other so far combustion engine powered vehicles it is evident, that several other applications in the industrial sector are relevant for SiC. Examples are charging infrastructure as the key enabler to move the electric fleet, but also energy storage systems on large scale as essential parts of the regenerative energy generation and distribution network. Three concrete examples will be discussed in more detail in the following subsections.

A) EV fast charging

EV fast charging systems are characterized today by a continues increase of power handling capability, driven by the need to charge e.g. a large BEV with 15.. 20min. The power ratings are between 200 and 300kW max for passenger cars. Due to the various types of cars being typically charged at a public charging station, the output voltage varies a lot, reaching well above 800V in many cases. Thus, high voltage conversion stages are required. In same scenarios even the vehicle-to-grid capability is an additional requirement, asking for bi-directional energy flow in the conversion system. Finally, large scale storage is often connected to larger fast charging stations to enable multiple high power charging processes in parallel without having the full power delivered by the grid permanently. SiC enables this technology, alongside with additional features like lower noise. The key technical parameters are first of all a simplification of the topology compared to silicon based setups. As a second KPI the efficiency increases dramatically, leading to smaller cooling systems and

eventually enabling the very high-power densities connected to the limited size for the very high-power ratings.
Figure 3 shows as an example how the circuit topology can be simplified.

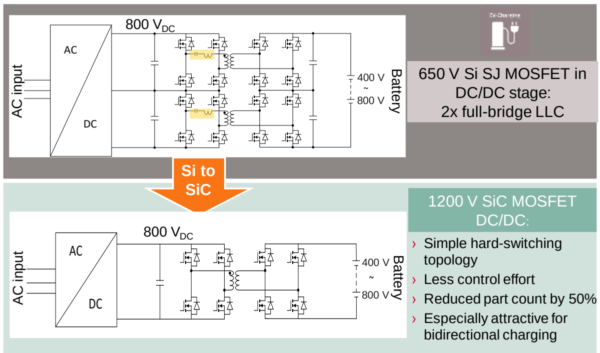

Fig. 3. Topology simplification for fast charging enabled by SiC power transistors.

A further trend supporting the use of SiC devices in fast charging is the expected increase in DC voltage ratings. For commercial vehicles like trucks and buses already today solutions based on 1100V DC bus voltage are in development.

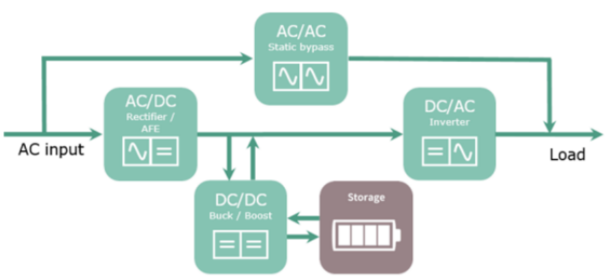

Fig. 4. Principle of an online UPS – energy is permanently transferred via two stages

B) Uninterruptable Power Supplies – UPS

UPS systems are widely used to ensure continuous power supply to a sensitive consumer in case of power dropouts. In such a case they step in and continue to supply from battery. The basic functional principle of an online UPS is shown in Figure 4. The energy is processed by two stages continuously; thus, the efficiency of both stages decides about the running cost of such a system since wasted energy basically adds to the cost of ownership. A conversion circuit based on fast and highly efficient SiC devices can drop the losses by 40% as shown in [2]. I has been shown than for a 1 MVA system – a typical one like used in hospitals or other critical infrastructure – the amount of wastes energy in a 5y period could be dropped from 840MWh down to 450MWh, what is of course a clear contribution to CO_2 saving, but also a measurable benefit for the operator due to energy bill savings in the range of several 10 thousands of USD, depending on the actual energy price.

C) Motor drive solutions – servo motor drives

Typically, the use of SiC in motor drives has been seen critical since the biggest strength of SiC devices – fast switching at low losses – is not relevant in this applications since due to the motor as the consumer after the inverter the switching speed and frequency are limited. However, mainly for servo motor drives today SiC is already an interesting new approach to significantly improve the system in general. And once more the potential to reduce losses is the major driving force. But how can that be is the switching performance is of secondary importance? Studies have shown that due to the mission profile for the power semiconductor in servo motor drive inverters SiC can drop losses by up to 80% in certain operating modes. Figure 5 shows a typical load profile of a servo motor.

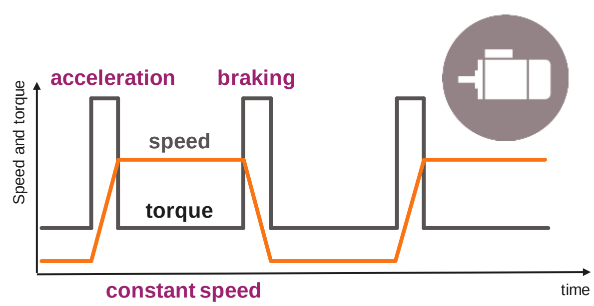

Fig. 5. Typical load profile for a servo motor drive

The current in the inverter is proportional to the torque. Thus, more than 80% of the total time the inverter is in partial load mode and under such conditions the linear I-V characteristic of MOSFETs compared to the IGBT reduces the conduction losses dramatically. But also in all switching modes still lower losses can be achieved with SiC MOSFETs compared to IGBT's due to the lack of Q_{rr} and tail currents which heavily impact the switching loss balance of IGBT's. The reduced losses can be transferred in various system advantages. On the one hand side on could simply drive a more powerful motor with the same inverter. The 2nd option is to use the loss reduction e.g. to eliminate forced cooling systems. In any case, SiC helps to reduce cost and material consumption, enabling greener solutions for our society.

A GLIMPSE INTO THE FUTURE

Technological progress with respect to material and devices will progress over the next years. Consequently, further applications will reach cost performance thresholds where a deep penetration of SiC based inverters is not just from an energy saving point of view reasonable, but also from a commercial point. Typical examples are here classical motor drives, white goods or HVDC systems. In addition, more new applications fields for power semiconductors and in particular for wide bandgap-based components will develop. Recently applications like electric aircrafts, heat pumps or solid-state circuit breakers become more and more in the focus of SiC, again driven by the substantially lower losses in operation compared to traditional solutions. An important additional impact will be generated by progress is areas around the actual chip technology. It is evident already today that with the further shrink of wide band gap chips new packaging solutions, being able to manage the higher power densities, will be required. Infineon introduced recently the so called .XT technology for discrete devices where the typical solder technology to attach a chip to the package is replaced by an intermetallic connection. Figure 6 shows which benefits can be generated by this simple innovation while chip and actual package frame remain unchanged.

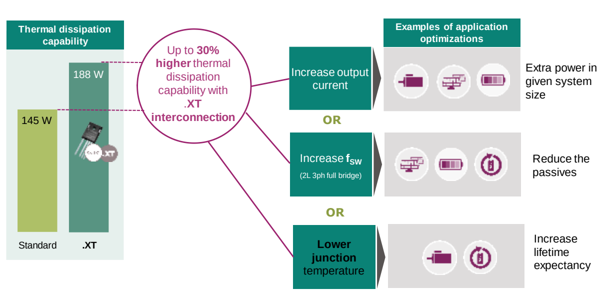

Fig. 6. System impact of .XT die attach technology of SiC MOSFETs

Similar new approached are expected in the future also for other package platforms or in the area of control devices like driver IC's. One example is for instance the intelligent management of short circuit or other overload conditions outside the chip by fast detection and shot down procedures.

CONCLUSIONS

Global megatrends like increased demand for electrical energy and decarbonization at the same time drive the need for highly efficient power semiconductor devices. Especially wide band gap-based components like SiC based transistors and diodes can act as enabling elements to achieve new levels of efficiency and power density. Both performance indicators have clear contributions to the social-economic success and the rescue of our planet. The technical and commercial success of SiC transistors will support the further development of both, innovative devices and high-quality material and processing technologies all around the world. Wide band gap technologies will continue to bring a net positive impact on the CO_2 balance of power electronic conversion circuits by its potential to reduce energy waste. But even more benefits are generated by the option to save scarce and expensive materials in the system.

ACKNOWLEDGEMENTS

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ACRONYMS

MOSFET: Metal-Oxide-Semiconductor-Field-Effect-Transistor
SiC: Silicon Carbide
IGBT : Insulated Gate Bipolar Transistor
SBD : Schottky Barrier Diode
CCM: constant current mode
PFC : Power Factor Correction
EMI : Electromagnetic Interference
HVDC : High Voltage Direct Current
EV : electric vehicle
BEV : Battery driven Electric Vehicle
Q_{rr} : stored charge, reverse recovery charge
KPI : Key performance indicator
UPS : Uninterruptable Power Supply