Power devices based on silicon carbide – how to manage them at system level and how they contribute to a greener world for all of us

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Keywords: SiC, MOSFET, E-mobility, renewable energy

ABSTRACT

A wider bandgap usually results in a significantly higher internal breakdown field. Compared to silicon, silicon carbide (SiC) has a higher breakdown-field value of about ten times. Thus, active layers of high-voltage devices can be made much thinner, and doped higher, when compared to silicon power switch designs. This effect eventually shifts the transition between fast and unipolar devices like metal oxide semiconductor field effect transistors (MOSFETs), Schottky barrier diodes (SBD) or junction field effect transistors (JFETs) and bipolar components like insulated gate bipolar transistors (IGBTs) to much higher voltages. While with silicon, the transition takes place at around 600 V, SiC components can be implemented in unipolar configurations at several kV. Unipolar devices enable low loss power conversion at higher switching frequencies, all in all being the ideal candidate for small systems at highest efficiency levels.

APPLICATION CONSIDERATIONS FOR SIC MOSFETS

Taking into account the technical benefits of SiC MOSFETs compared to IGBTs in high-voltage applications, one would indisputably select wide-bandgap components for all new designs. A few disadvantages still exist, however, including the following:

- The thermal performance, due to the very small die size, which results in much higher R_{th} values compared to silicon-based solutions handling the same power. In fact, even though total power losses are significantly smaller than in silicon chips, the loss power density is often much higher. Thus, smart thermal stacks are required.
- The power cycling performance of SiC chips, which is smaller for the same die attach technology, compared to silicon, reaching only about one-third of the silicon capability in power modules. The main reason is the higher Youngs modulus of SiC which causes higher mechanical stress to back-side joints.
- limitations in short-circuit withstand times.

Some further, but less critical, aspects might be added to the list, e.g. the need of a stabilized power supply for SiC MOSFET drivers in order to fix the targeted $V_{GS(on)}$, which is mandatory due to the weaker transconductance of SiC.

At any rate, the biggest obstacle for a broader rollout is still the cost of SiC compared to silicon, and some concerns about the maturity of the new technology. The latter issue has been successfully addressed in the last few years by an open discussion concerning the challenges and potential solutions to enable a field reliability similar to that of silicon technologies. In order to deal with the cost challenges, the key aspect is to identify system advantages which accompany the implementation of SiC that can justify the higher cost.

To assess this topic in detail a tipping point model (see figure 1) is proposed which takes into account application specific saving potentials, the cost delta between the state-of-the-art technology and the new solution based on SiC as well as certain dynamics like speed of implementation of new technologies.

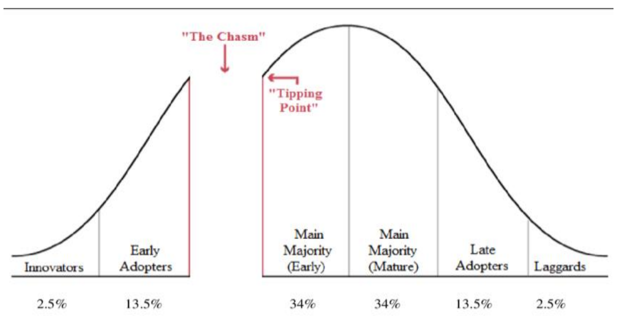

Fig. 1. Tipping point description based on market modelling

Our analysis showed that the wide range adoption of SiC started in applications like solar power conversion, high power EV charging, uninterruptable power supplies as well as industrial power supplies already in the recent years while the next hot topics are the electric vehicles, train propulsion and industrial motor drives, especially servo motor drives.

System advantages are mostly found by leveraging power density aspects (e.g. smaller inductive components enabled by higher switching frequencies, or smaller heat sinks due to lower losses to be dissipated).

Efficiency advantages include direct benefits like energy-bill savings in UPS systems which are from a cost point of view largely by operational aspects like shown in figure 2.

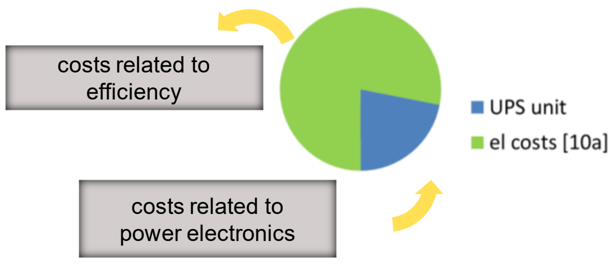

Fig. 2. Sketch of the total cost for UPS Systems, divided into invest (UPS unit) and cost of ownership (CoO, el cost = energy cost over 10 years as major part of CoO)

Other examples where efficiency is a major driving force are train propulsion, and battery size reduction in electrical vehicles. For this reason, e-mobility is expected to be one of the major volume applications for SiC power transistors in the next 10 years. Also, the required fast charging infrastructure is enabled in its future shape by SiC based inverter solutions. Eventually also the growing market of large-scale energy storage, often in combination with renewable energy generation, will be a playground for SiC based solutions, once more driven by efficiency in energy conversion and the consequently lower invest in battery capacity. Beside the efficiency advantage SiC enables a significantly less complex circuit topology as indicated in figure 3. It is enabled by the possibility to get fast switching high voltage MOSFETs.

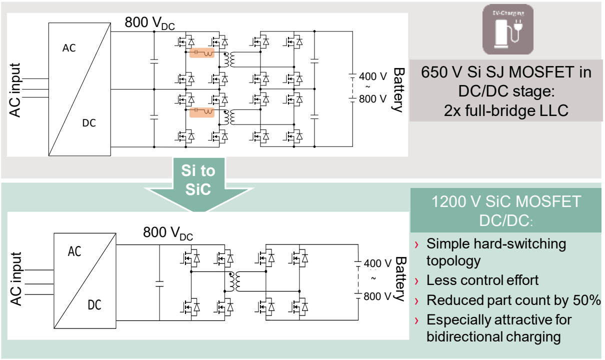

Fig. 3. Topology simplification for EV charging enabled by SiC MOSFETs

An indirect impact of increase efficiency comes in the form of smaller heat sinks or disruptive options to reduce cooling efforts by eliminating the need for forced cooling for example. Initially, cases, for which fast switching was not of interest, seemed to be outside the scope of application for SiC. Meanwhile it has become clear that even for low switching frequencies and comparable, commonly used switching slopes below 10 kV/µs such as those in motor drives, a loss reduction can be seen, mostly due to savings in on-state mode under partial load, or to the lack of tail currents and Q_{rr} related turn-on losses. In figure 4 a summary is shown about the opportunities enabled by SiC e.g. for servo motor drive solutions. Most striking seem to be the fact that forced cooling can be avoided and integrated motor inverter solutions might become reality.

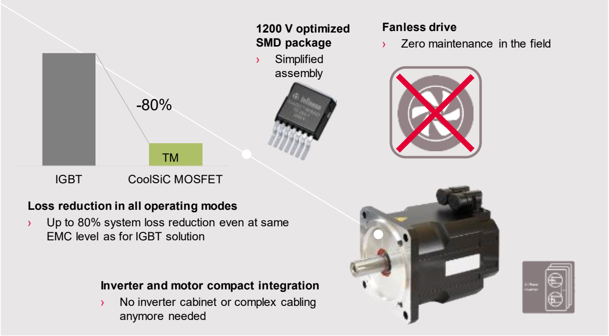

Fig. 4. Benefit of SiC MOSFETs in Servo motor drive inverters

Furthermore, taking the example of motor drives, innovative ideas like the use of sinus output filters between the inverter and the motor might be re-assessed. The technical advantages are clear – no dv/dt related stress at the motor, no expensive shielded cables, and no discussions about the short-circuit capability of the used switches. In the silicon world, those approaches have not been successful, since the filters were prohibitively expensive and bulky assuming the limited switching frequencies with IGBTs. However, new opportunities will be possible with SiC MOSFETS.

A special application for SiC MOSFETs are auxiliary power supplies for power systems which are operated on DC links. In those solutions, the power supply is often powered directly out of the high-voltage DC link and thus, a high-voltage capability and fast switching are common requirements. Silicon-based solutions for such circuits are either expensive and have high losses (like high-voltage Si MOSFETs) or very complex if implemented in a multistage setup. Since the required ohmic ratings are also quite high (500 mOhm up to 1 Ohm), the required SiC chip sizes are small. The small die size in a discrete packge has pros and cons. On the one hand side yields are not too much affected by the current defect density levels of SiC substrates and thus, a cost attractive component is possible, but thermal management becomes a substantial challenge. For that reason Infineon introduced under the brand .XT a special die attach methods based on a discussion soldering process which drops down R_{th} and Z_{th} by 25..35% as shown in Figure 5.

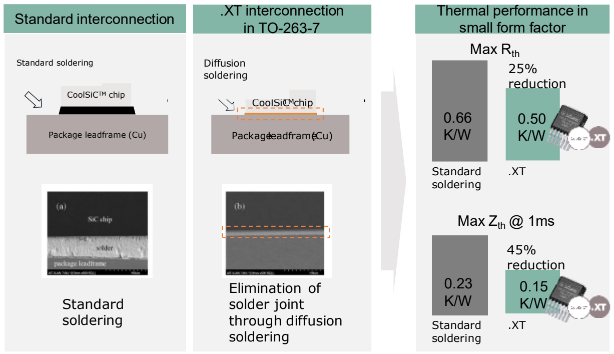

Fig. 5. Solderless .XT interconnection technology for small SiC chips in discrete packages helps to reduce the thermal impedance and improves the thermal management

The auxiliary power supply application is one of the very few examples where SiC can outperform silicon power devices in terms of cost at the component level.

SiC MOSFETs enable an easy fly-back based solution. Due to the low losses, the component can now also be implemented in an SMD package and thus, the assembly can be automated, and bulky heat sinks are no longer needed. Finally, with some adopted gate drive conditions, the system can be operated directly out of the controller, and a driver IC is no longer needed.

A further application where WBG switches are seen as an enabler are modern AC-DC stages (PFC – Power Factor Correction) in power supplies based on the totem pole topology [2], see figure 6. The full-bridge totem pole topology is bridgeless, hence, the biggest loss contributor of traditional circuits – diode losses – are no longer relevant. The simple topology offers a bi-directional power flow and can deliver outstanding efficiency levels. However, the topology can be implemented only if the semiconductor switches exhibit certain features. Generally, these have to be switched with 45 kHz ... 100 kHz, while one transistor acts as a boost switch and the second one as a synchronous rectifier. The transistors need to have extremely low Q_{rr} values and a low output charge Q_{OSS}. Finally, a smooth dependence of the output capacitance on the drain voltage is preferred. None of the three requirements can be delivered by silicon super-junction MOSFETs and thus, 650 V SiC MOSFETs or GaN HEMTs are the devices of choice to enable this new path towards low losses and high-power density PFC stages.

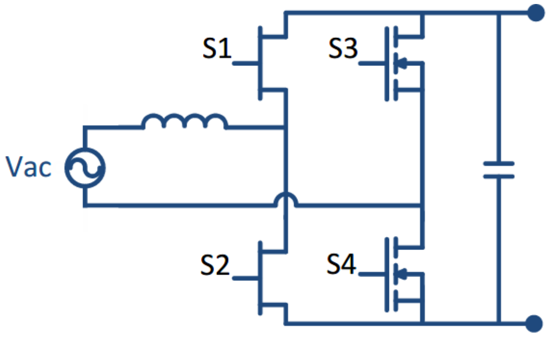

Fig. 6. Highly efficient CCM Totem Pole topology for PFC systems, enabled by the availability of Wide Band Gap switches like SiC MOSFETs or GaN HEMTs at the positions S1 and S2 (S3 and S4 being silicon transistors)

The list for use cases for SiC is growing continuously and both, established applications and emerging fields contribute to it. Examples are for instance the connection of large-scale storage systems to renewable energy generation plants or wind power as well as e-aviation. We expect a strong growth, outperforming the silicon numbers for power semiconductors. However, also for Si based technologies the end of the roadmap is not yet visible, innovative structures are shown regularly at scientific events and thus, the coexistence between silicon and wide band gap is expected to remain for the foreseeable period of time, although in certain segments SiC might take over the lead.

CONCLUSION

In conclusion, there are many motivations for implementing SiC MOSFETs in power circuits, as illustrated in the examples above. New operating conditions like higher frequencies and steeper voltage transients are mandatory - in combination with revolutionary system architecture such as power PCBs instead of bus bars, or passive cooling instead of complex cooling setups. Those moves enable leveraging the full potential of the new technology, it must be accepted that the changeover to SiC MOSFETs will require additional one-time efforts. Far fewer hurdles can be expected if the emerging applications do not rely on traditional system architecture, one of the most prominent examples being aircraft electric propulsion. Additional enabling elements for the success of SiC are the availability of well matching driver IC's and adopted assembly and packaging concepts. Interesting to observe will be the future with respect to additional attributes often connected to SiC. Namely high temperature operation (above 200°C) and extremely high voltages so far did not leave the academic sector. Maybe a technology push in the next few years is able to change this situation, at least the capabilities to offer such exotic components was proven by numerous groups in the past.

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ACRONYMS

SiC: Silicon Carbide
MOSFET: Metal Oxide Semiconductor Field Effect Transistor
SBD : Schottky Barrier diode
IGBT : like insulated gate bipolar transistors
JFET: junction field effect transistors
UPS : uninterruptable power supply
DC : direct current
SMD : surface mount device
AC : alternating current
WBG : wide band gap
PCB : printed circuit board
HEMT : High electron mobility transistor
GaN : Gallium Nitride