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SiC Power devices – Recent progress and upcoming challenges

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Abstract

The interest of the power electronics community in modern SiC based power semiconductors is nearly 20 years after the first promising news about this technology stronger than ever. New applications like solar power conversion and the price reduction rate which was possible mainly by larger wafer diameters represent the most important factors in this development. The driving force for the use of SiC in power electronics is the potential benefit to realize low loss and very fast unipolar diodes and switches with blocking voltages from 600 V up to several kV. Efficient solutions and high power densities are the most important benefits in applications.

While diodes are meanwhile established and well accepted for the blocking voltage range from 600V up to 1700V the still open question is the future of silicon carbide based transistors. Especially above 100V, compared to the today predominantly used bipolar silicon structures like IGBT's, unipolar devices feature a linear increase in voltage drop with the forward current and a positive temperature coefficient of the resulting differential on-resistance. It enables paralleling as well as attractive part load performance mainly compared to IGBT's with its threshold voltage in the output characteristic. In addition, the absence of a minority carrier flow in the main operation regimes enables a switching performance which can be compared to the possibilities of modern 30V...100V unipolar silicon devices today at much higher blocking voltages. The reason for the ultra low loss performance of high voltage unipolar devices is the wide bandgap of SiC which leads to a 10 times higher critical electrical field (compared to Si) and therefore to 10 times "thinner" devices with a corresponding low on-resistance.

Among other wide band gap semiconductors which theoretically offer comparable features like SiC, silicon carbide has gained an outstanding status regarding base material quality and technological maturity. Nevertheless, one of the main hurdles for a fast market penetration was the SiC crystal size, quality and cost. In 1993 the SiC wafer size was just 1inch in diameter with more than 1000 so called micropipes per cm² (simply holes through the entire wafer). Thus, only very small chips with tiny current ratings could be fabricated by special technology equipment. Now, in 2010, the situation has clearly improved: 100mm wafers with a micropipe density well below 5/cm² are commercially available at substantially reduced area specific wafer costs, and next standard diameters closing the gap to silicon are visible in short term. In 2007, 100mm material has already reached the quality status of the formerly best available 3" material and offered a next step in cost reduction for SiC components. Next steps towards 150mm are anticipated on mid term scale. Furthermore, an essential condition for an increased power density will be fulfilled by the availability of power electronic components allowing higher switching frequencies at high blocking voltages, combined with an enlarged range of operating temperature. But more important, mainly with respect to the ongoing discussion about greenhouse effects the aspect of energy saving by power electronics becomes a focus point for power electronics and here SiC is an ideal tool to offer efficient solutions by its ability to offer low loss systems.

Regarding commercial products, fast SiC Schottky diodes in the voltage range between 300 V and 600 V were introduced on the market 2001 by Infineon (1200V in 2006) for the first time and later by Cree and STM (in 2009) [1]. Recently, 1700V devices where released as bare die from Cree [2] while they are in use in commercial inverters already since 2006 by Siemens [3]. Because of the virtually zero reverse charge storage of Schottky diodes these diodes are the nearly ideal partner for e.g. the Silicon CoolMOS™ switch in order to fully exploit the high frequency capability of this "pair" in the large growing market of power factor correction in high end power supplies. The higher costs of the new technology are (well) compensated by the reduced size and consequently costs of passive components [4]. This application was a first and important step in order to establish SiC devices power electronics community. Today, the achievable power ratings are shifted towards higher values and modules for motor drives e.g. are used in power electronics [3]. Also for these applications, the first use will be in combination with powerful silicon IGBT's. Moreover, even among the single switch scenarios today a smart combination between the assets silicon technology can offer and the robustness of SiC components is considered to be an ideal solution for fast high voltage switching.

Important key features for a successful use of SiC power semiconductors in industry are cost and reliability considerations. Thus, power devices made from Silicon

Carbide should not only be considered on the pure electrical performance data, but on more aspects in order to capture all commercialization issues. How such considerations can be taken into account already while designing the device will be sketched on the example of recently released generations of modern Schottky Barrier diodes. For transistor devices a discussion of pro and con's of competing concepts will be given. As an additional aspect peripheral topics, mainly packaging and cooling, will be intensively discussed in order to show difficulties in utilizing the full SiC performance. Finally the status of high voltage (>3kV) components made by SiC will be given, again connected to a critical view in the existing mission profiles and application opportunities.

Application considerations will be made regarding the short and mid term use of SiC power devices. It will be shown how efficiency driven solutions in solar power e.g. are preferred entry markets and first drivers for this technology. Even the mainstream industrial motor drive inverter business can act as a killer application for those devices – provided that life cycle approaches are taken into account from the system side. For automotive applications, however, a benefit will be worked out much later on the time scale because of cost constraints, especially if hybrid cars are considered only. For purely electrical cars the efficiency has a much higher value and thus, here the application people can much easier derive a system advantage.

In summary, the door is open for SiC based wide band gap devices to become important players in the field of power electronics, especially for future applications requiring a high power density and system efficiency. An essential condition for an increased power density will be fulfilled by the availability of power electronic components allowing higher switching frequencies, higher blocking voltages as well as higher operating temperatures in a next step. Mainly with respect to the ongoing discussion about greenhouse effects the aspect of energy saving by power electronics becomes more and more important and here WGB components are an ideal tool to offer efficient solutions by its ability to offer low loss systems. Anyway, for the foreseeable next couple of years it can be anticipated that smart combinations of SiC and silicon power devices will have the highest potential of success in commercial applications due to their outstanding cost-performance ratio. This holds for already commercialized examples like the Si-CoolMOS duo in high end PFC circuits and hybrid 1200V and 1700V Si IGBT-SiC diode modules in motor drives as well as for upcoming switching solutions like the cascode or the a newly presented cascode light solution with even more advantages for the user [5]. On a mid term scale it can be expected that from 300V up to 1700V nearly all power ratings can be addressed by the hybrid SiC-Si IGBT modules. Taking into account the energy saving potential given buy such a setup in form of a lifecycle energy saving potential also an economically benefit can be obtained even with up to a factor of two higher costs for such a module.

Full SiC solution (transistors) in modules probably will cover the range interesting for solar industry with several tens of kW. A further trend to very large chips could be a point of discussion due to reliability concern in power cycling and thus, all these solutions will base on paralleling of die with die sizes of about 4x4mm maximum. For discrete devices 1200V diodes and transistors with a couple of Amps up to some tens of amperes will be available, higher blocking voltages could be of interest as well, however, a cheap and powerful high voltage package is mandatory for a commercial success of such components. An interesting competition is expected at the 600V level between charge compensated silicon based solutions and the SiC transistors. Entering this huge market would have a dramatic impact on the overall success of WBG power devices; however, the precondition will be to meet the today's severe cost targets for a given R_{on} of silicon devices. Additional performance advantages like internal body diode, lower capacitances and higher ruggedness are soft facts which help to promote this technology, however, they probably are not as important as the cost in this market.

Finally for the higher blocking voltages, diodes as first commercial components are expected, delivering power ratings like today used in medium voltage inverters by paralleling in modules as already pointed out for the lower blocking voltages. In a first steps diodes for the 3.3kV up to 6.5kV will be realized as partners for today's silicon IGBT's, especially in order to reduce static losses and turn on losses of the switches. Very fast devices with an U_{BR} >3kV up to 10kV (both, diodes and switches) will be possible providing dynamic properties like given by today's silicon technology for a few hundred volts. Whether this potential can be utilized will be a challenge for the creative people working on the corresponding system architecture.

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