Wide Bandgap Power Devices in Megawatt Applications

Although researched for many decades, it is only recently that wide bandgap power devices have started to achieve an acceptable market entry level in terms of overall performance competitiveness in special applications with relatively lower power ratings. Therefore we will discuss the status of SiC in particular in connection with Megawatt applications and we will compare the potential benefits and challenges of introducing SiC technology. We will also discuss the widely proposed Si IGBT and SiC unipolar diode hybrid solution at 1.7 kV including experimental results and some important challenges to the acceptance of this concept in MW applications. **Iulian Nistor and Andrei Mihaila, ABB Corporate Research; Munaf Rahimo , Liutauras Storasta and Chiara Corvasce, ABB Switzerland Ltd., Semiconductors**

Driven by energy-efficient industrial and renewable energy applications, the demand for power semiconductors has been increasing rapidly. Hence, the longer-term prospects of the global power semiconductor market are very positive with forecasts showing 50 % market growth to each about $24.0 billion by 2015 [1]. In particular, the power module market has seen a tremendous growth, driven primarily by industrial motor drives, renewable energy, hybrid and electric cars, and consumer electronics. Today, the vast majority of the sold semiconductors and power modules are based on Silicon technology. Figure 1 shows the Silicon based power semiconductors and their power and frequency range in MW PE applications. While further innovations in Silicon based power semiconductors are continuously pushing the boundaries of performance [2-3], certain application requirements e.g. very high temperature operation (>200°C), very high switching frequency (>10kHz), and/or high voltages (>10kV) might prove to be more suitable for emerging Wide Bandgap (WBG) power semiconductors, such as SiC and GaN.

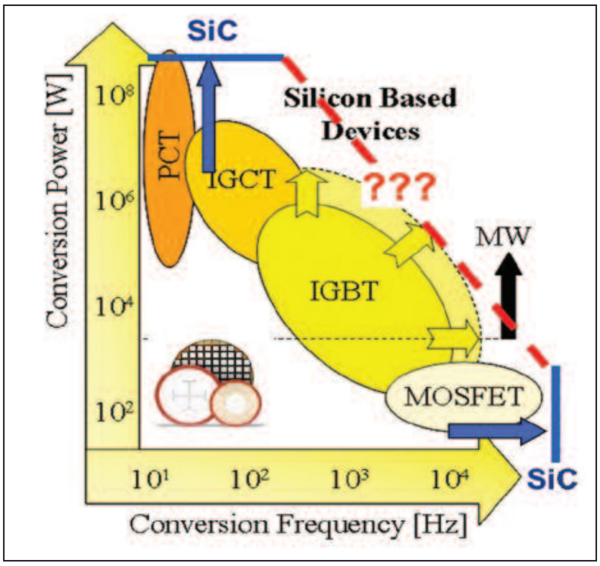

Figure 1: Power semiconductors and their power and frequency range in MW PE applications

SiC technology overview

SiC has been referred extensively as the future material for power semiconductors, with significant developments in demonstrating the capability of the technology. For example with reference to Figure 1, SiC provides benefits in conduction losses for low frequency applications at very high voltages (>15kV) by avoiding the need for series connections of lower voltage Si devices. Similarly SiC is extremely suitable in applications at very high frequencies and low power levels due to the extremely low switching losses. The area of interest for MW applications is however at medium frequencies and medium voltages where currents can be significantly large.

However, there have been few aspects which have contributed to the fact that SiC is yet to fulfill its promised potential over the whole power range. They are all related to the advancement made in Silicon devices and applications in terms of power, losses, cost and system topologies.

Power: Single device/chip area remains limited in SiC due to defects and resulting yield aspects, temperatures above 200°C limited by package and increased losses for unipolar devices such as diodes and MOSFETS (strong positive temperature coefficient for on-state). Large area Si device concepts and processes are advanced with high operating temperature designs up to 175°C.

Losses: SiC bipolar devices suffer from high V_o and unipolar from strong on-state temperature coefficient. System and package designs not developed for low inductance and thus higher frequency applications and related EMI issues. Si devices are continuously advancing in terms of loss reduction and Integration. For higher power, Silicon devices are soft and are also targeting relatively higher frequency operation with fast versions. In the lower power range, the Super Junction MOSFET concept provides good performance.

Cost: With SiC system development for high frequency applications is required to compensate the higher device costs. Silicon devices continuously reaching higher performance/cost ratios through lower losses and integration solutions.

System topologies: Higher frequency trends evolving only in emerging and niche applications. Topology trends in established applications targeting lower frequencies and hence, lower on-state losses with existing Si based solutions.

While keeping these points in mind and still taking SiC as the main player in the

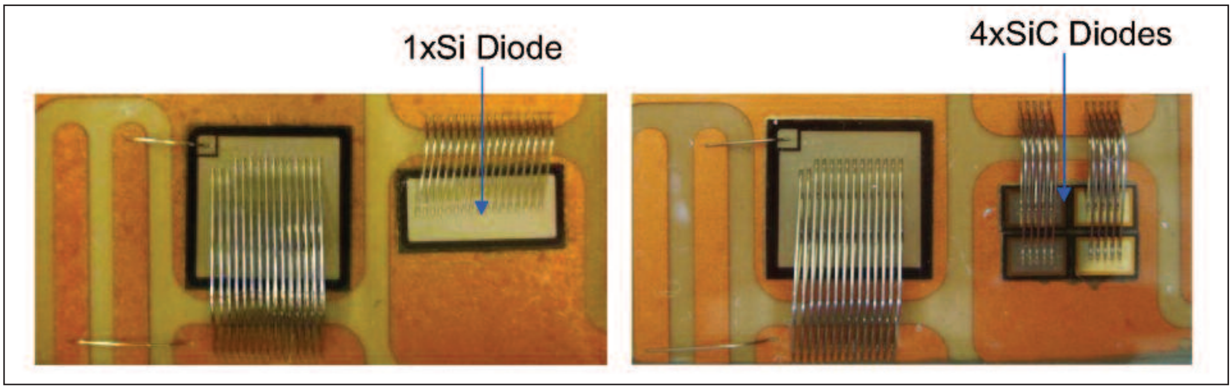

Figure 2: 1.7 kV/100 A Si IGBT chip paralleled with 1.7 kV Si Diode or 4 x 1.7 kV/25 A SiC Schottky diodes (right)

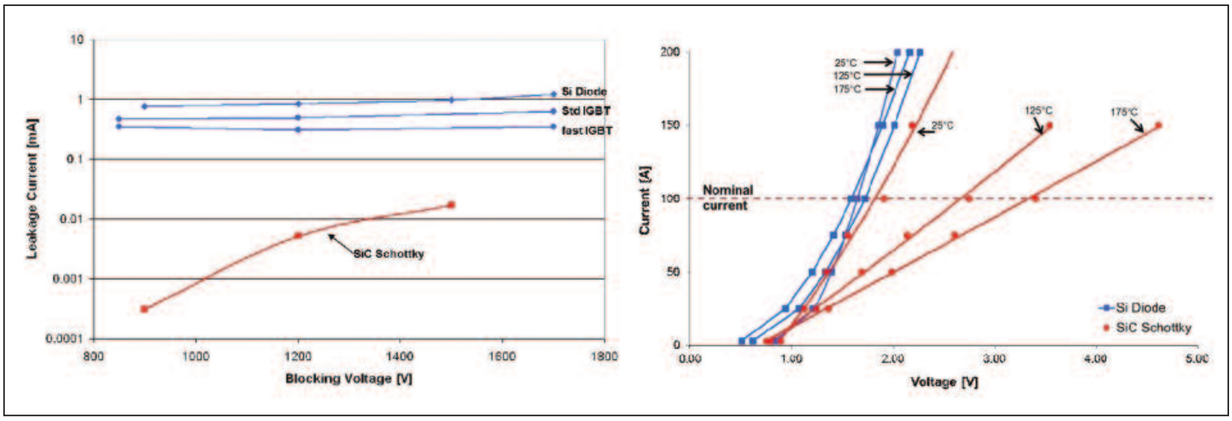

Figure 3: Static measurements on 1.7 kV Si/SiC Schottky diodes (leakage (left) and on-state (right))

high power WBG field, some new aspects are starting to "change the game" compared to the situation of the industry just a few years back. For example, most of the SiC technology developments were focused in the past either at voltages around 600V-1200 V or above 10 kV. Today we observe a development trend towards voltage levels of 1200V and 1700V, where many interesting applications for MW levels can be identified.

This trend also indicates that a certain performance/cost level is difficult to reach for SiC technology at voltages below 1200V, where the competition is fierce from Si SJ concepts and upcoming GaN on Si technologies. Furthermore from a manufacturing point of view, more material manufacturers have indicated that they are working on releasing 150 mm SiC wafers in the foreseeable future. It is therefore expected that such a step will definitely bring a much needed cost reduction of SiC technology. In addition, the first SiC 1200V MOSFETs have been released on the market, albeit at very high cost compared to Silicon semiconductors [4]. New market developments in renewable and automotive applications have brought forward the need for higher frequency/temperature devices.

In particular, the introduction of 1700 V SiC diodes with reasonably high current ratings (in excess of 20 A per chip) has provided an important step to exploit the hybrid solution with specially optimized fast Si IGBTs for MW applications. This approach shows strong potential for providing the best entry path for SiC in MW applications, since it combines a cost efficient solution using a Si switch with the benefits of the SiC diode technology. This concept has been reported before at different voltage levels [5,6], but these voltage levels were not very suitable for MW level applications. It is our target here to focus on the 1.7 kV voltage class and show that the optimization of the IGBT towards lower turn-off losses will provide a much improved solution in combination with SiC Schottky diodes for a total reduction of switching losses of nearly 40%

Evaluation of SIC potential

At substrate level one fast 1.7kV/100A IGBT chip has been paired either with one Si diode as a reference, and with four parallel SiC Schottky diodes to reach the same current ratings as shown in Figure 2. These substrates were fully characterized in static and dynamic electrical tests under nominal and SOA conditions and different temperatures.

The static measurements demonstrated the much improved high temperature performance of the SiC diode in terms of leakage currents as shown in Figure 3. The level of the leakage currents was very low and quite stable with the temperature when compared to the Si diode and different IGBT versions presented in the same graph.

In contrary to the exceptional reverse bias characteristics of SiC devices, the on-state tests show a strong increase with temperature for the unipolar SiC diode as shown in Figure 3 reaching relatively high on-state values when compared to Si diodes. This aspect raises concerns about the so called unipolar/bipolar voltage limit in SiC (about 200V in Si technology). In addition, such a device behavior will penalize the SiC diodes in rectifier applications below few kHz due to increased conduction losses.

On the expected positive side, SiC Schottky diodes show practically no reverse recovery losses compared to bipolar Si diodes as shown in Figure 4. In this case, the diode reverse recovery losses were reduced from 27.5 mJ for Si diodes to less than 1 mJ for SiC diodes. In addition, the recovery losses show little dependency on the test conditions including the commutating di/dt, the stray inductance and temperature. When the SiC diode is paired with a Si IGBT, this property

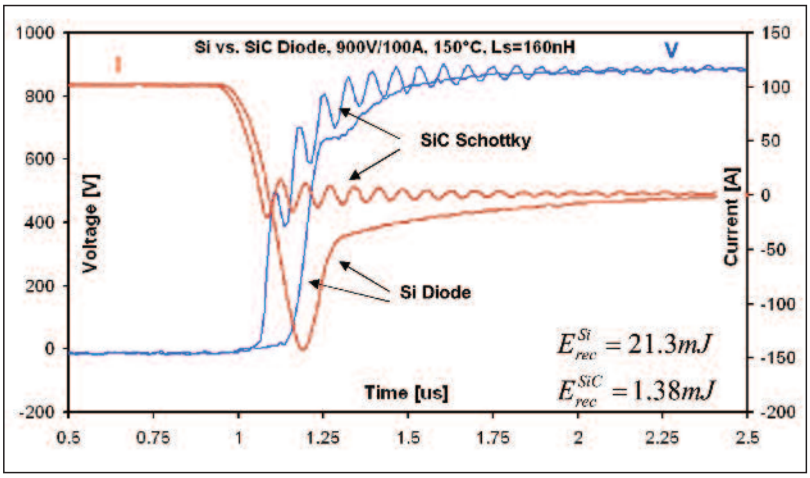

Figure 4: Reverse recovery waveforms of 1.7kV Si Diode compared to SiC Schottky diode

can prove to be advantageous in reducing the turn-on switching losses of the IGBT. However, the benefit obtained only from reducing the turn-on losses cannot justify the higher cost of using SiC device. Therefore the turn-off losses of the IGBT have to be reduced also to achieve further switching loss reductions in the combined solution.

An optimized 1.7kV fast IGBT chip has been developed on the SPT+ platform [7]. This optimized IGBT chip has approximately 25 % lower turn-off losses than a standard IGBT chip, and consequently its on-state is increased by about 10 %. With further reduction of the emitter efficiency, the turn-off losses could be reduced by 44 %. Such an extreme low injection efficiency design might bring undesirable performance in terms of short circuit ruggedness, therefore we estimate an optimum fast IGBT design to deliver 2.45 V on-state with 19 mJ turn-off losses at 100A. A comparison of turn-off waveforms between standard and fast IGBTs is shown in Figure 5.

It was shown in our measurements that by combining the fast IGBT with SiC Schottky diodes, a further reduction of up to 60 % of the turn-on switching losses could be achieved as shown in Figure 5 (right). Further reduction of turn-on losses would be possible by reducing the value of the gate resistor Rg , but with the risk of increasing oscillations in the system. At high Rg values, the turn-on losses are dominated by the IGBT chip itself. Reducing further the Rg increases the speed of the turn-on process, but also the dv/dt and di/dt resulting in oscillations that could impact the electro-magnetic noise of the system. Hence, special low inductance solutions are required at package and system levels to tackle this issue. Overall, we estimated that the pairing of the 1.7kV fast IGBT chip with SiC Schottky diodes has the potential to reduce the total switching losses ($E_{SW} = E_{on} + E_{off}$) by about 40 % compared to the full Si approach as shown in Figure 6. Because the switching losses have a direct impact on the switching frequency of the semiconductor and application, it can be inferred that the hybrid solution could operate at higher frequencies than its Si counterpart.

It also noticeable the penalty of SiC diodes at low switching frequencies due to the strong degradation of the unipolar behavior with temperature.

Although established for low voltage applications, the method of hard switching of semiconductors is still debated in MW applications. Some technical solutions such as Power Electronic Transformers and in general any DC/DC isolated converters rely on alternative approaches such as resonant type topologies, where the soft switching removes the constrains on the diode component [8]. Such resonant applications could still benefit from increased switching frequencies by minimizing the size of the high frequency Isolation transformer, but this would require a full SiC module including a MOSFET or JFET switch.

For other applications in MW range, such as MV drives and transmission of

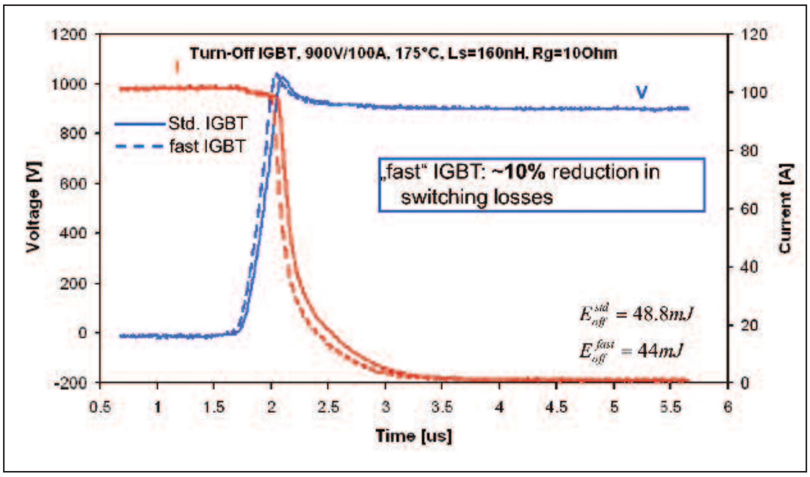

Figure 5: Turn-off waveforms of standard and fast 1.7kV IGBTs (left) and turn-on waveforms of fast 1.7kV IGBTs in parallel with Si and SiC Schottky diodes showing the significant reduction in turn-on losses due to the absence of the reverse recovery charge in the unipolar SiC diode

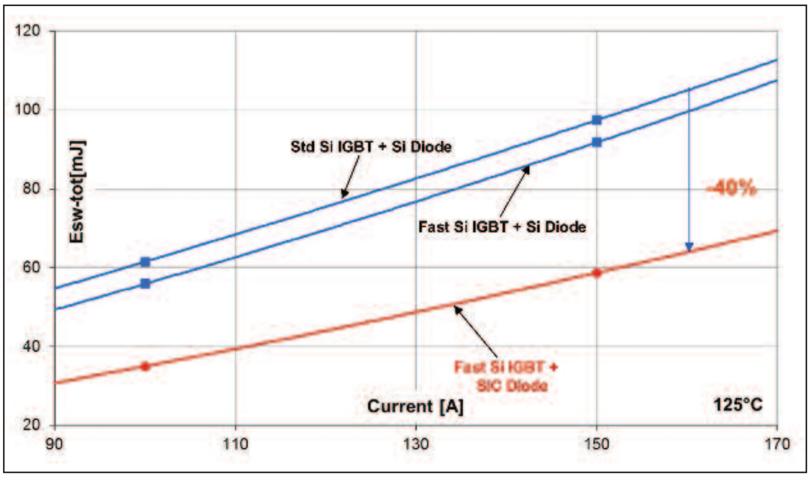

Figure 6: Total switching losses comparison for 1.7 kV fast SPT+ IGBT in parallel with Si or SiC diodes

high power over large distances (HVDC), the trend points towards multilevel topologies. Such topologies rely on an increased number of semiconductor stages, each stage being switched on and off at a relatively low frequency (sub 1 kHz). In our view, for such multi-level approaches, the hybrid Si + SiC approach does not prove to be a suitable solution. Instead, a full SiC solution using higher voltage switches might prove of more technical interest in this case [9].

Conclusions

Overall, a reduction of up to 40% of the total switching losses is demonstrated by using a hybrid approach combining specially designed fast IGBT chips and SiC Schottky diodes. This has very important consequences on the system design, allowing a 3 to 5 fold increase in the operating frequency without derating of output power capability. In order for this increase of efficiency to be fully utilized, further developments haue to take place in reducing the package parasitics and system layout, for example by developing 1.7 kV phase leg IGBT modules. Given that the challenges related to the packaging will be solved in the coming years, we see the hybrid technology approach as a first entry point for SiC technology in MW PE applications. Nonetheless, in the long run this solution limits the extension of SiC only to diodes and the operating temperatures will remain limited by the Si IGBT switch and current packaging concepts. This article is derived from a paper given at PEE's Special PCIM 2012 Session [10].

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