Efficiency Improvement with Silicon Carbide Based Power Modules

Whereas SiC switches have the overall lowest dynamic losses, they show higher static losses due to the lack of conductivity modulation and the necessary chip size limitations due to the still high SiC base material price. The frequency dependence of the total losses of the various 1200V configurations (Si-IGBT + Si free-wheeling diode, Si IGBT + SiC Schottky diode, SiC-JFET cascode plus internal body diode of the cascode) shows that a module solution containing a state of the art SiC switch will outperform all other options for switching frequencies >20kHz. **Xi Zhang, Daniel Domes, Roland Rupp, Infineon Technologies, Warstein/Neubiberg, Germany**

The demand for low switching loss, low conduction loss and high temperature devices is a major driving force of technology development in power semiconductors. In recent years, SiC (silicon carbide) based Schottky diodes have been introduced as discrete devices in standard TO-packages [1]. These new diodes have superior performance compared to Si-based devices, mainly with respect to switching losses and thermal performance and are well-established in up to 600V hard switching applications in high end power supplies [2].

Beyond this market entry, this emerging technology is also considered by many groups [3] as an ideal candidate for high power module applications.

The main target of this article is to get a better insight regarding the trade-off between static and dynamic losses when moving from highly cost effective Si-based to high performance, but costly, SiC-based solutions. For that purpose, the following switch configurations are compared:

- Si IGBT (Infineon IGBT4) with Si free-wheeling diode (Emitter Control4)
- Fast Si IGBT (Infineon IGBT2) with SiC free-wheeling diodes (Infineon 1200V SiC Schottky diodes)
- SiC JFET cascode switches (1200V normally on SiC JFET with 40V OptiMOS 2 Si MOSFET)

The SiC JFET is used due to the superior maturity and reliability of this switch in comparison with the SiC MOSFET [4].

IGBT power modules with SiC free-wheeling diodes

SiC Schottky diodes in discrete packages have been introduced into the market since 2001. The main advantages of these diodes are well described in [5]. The first commercially available high power module containing SiC Schottky diodes as free-wheeling diodes is a 600A, 1200V PrimePACK 2 IGBT power module, as shown in Figure 1.

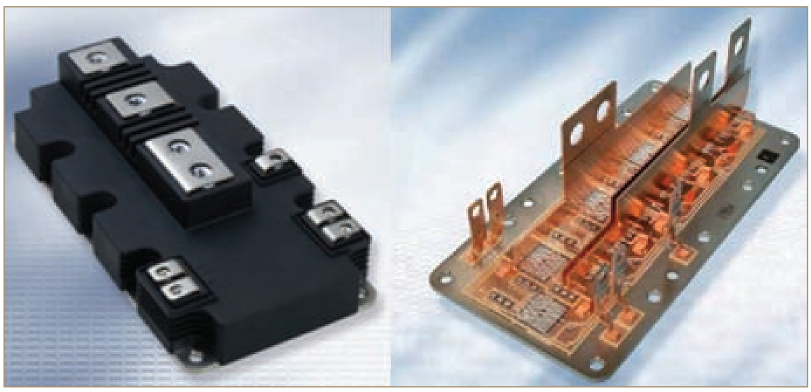


Figure 1: High power module FF600R12IS4F with integrated SiC schottky diodes as free-wheeling diodes in PrimePACK 2 package

The 1200V SiC diodes used are bare Schottky

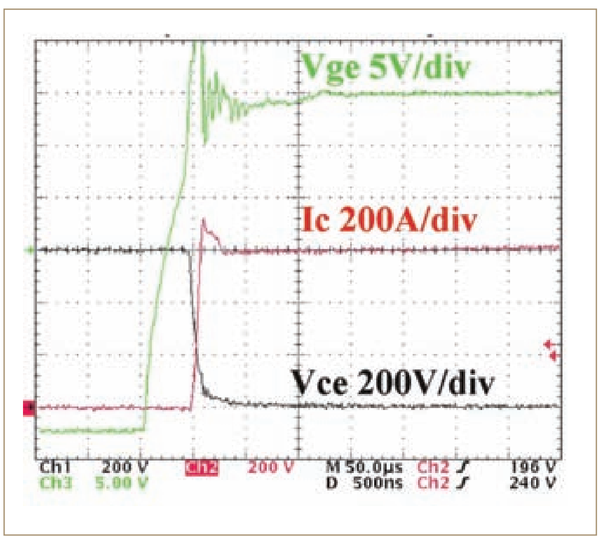


Figure 2: Typical turn-on behaviour of 1200V/600A IGBT S4 Chip with 360A SiC Schottky diodes (T_j = 25°C, R_{g_on} = 0.5Ω)

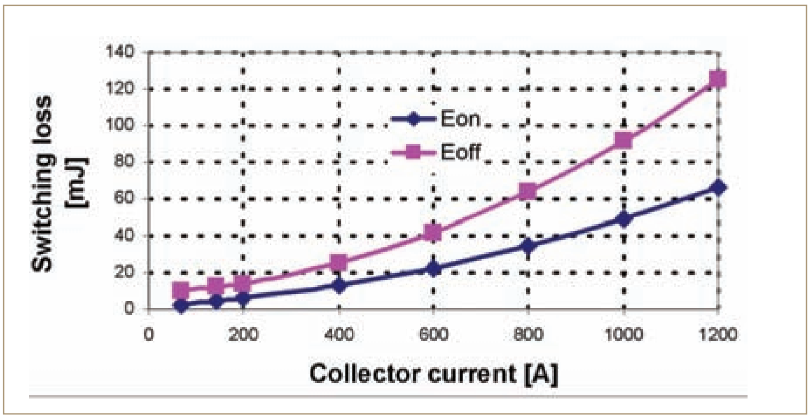


Figure 3: **Typical switching loss of PrimePACK 2 module FF600R12IS4F at 125°C with SiC Schottky diodes**

diodes with a p^+/p^- JTE edge termination structure and a Ti-Schottky barrier providing a barrier height of 1.27eV and allowing nearly the same threshold voltage as Si based PIN diodes. Each individual chip has a current rating of up to 15A. The required current rating of the free-wheeling diode is achieved by paralleling of multiple chips, which is easily possible due to positive temperature coefficient of these devices. The total amount of current rating of the diodes used per IGBT chip is 60% of the nominal IGBT current rating, thanks to the superior switching and thermal performance of these diodes.

Figure 2 shows the typical switching behaviour of SiC Schottky diodes in combination with Infineon's fastest S4 chip based on IGBT2 technology.

Due to the absence of reverse recovery charge of SiC Schottky diodes, the turn-on gate resistor of the IGBT can be reduced drastically to reduce turn-on losses (in the example 0.5Ω is used). The reverse recovery current, as can be seen in Figure 2, is also reduced in comparison to Si-based free-wheeling diodes. Figure 3 shows the typical switching loss of the module.

With the reduction of turn-on losses, the efficiency or the output power of the converter can increase. This is very attractive for applications which have efficiency as first priority (e.g solar application). But efficiency is not the only benefit when using SiC free-wheeling diodes. With decreased turn-on losses, the switching frequency can also increase. This leads to the possibility of choosing a much smaller output filter and thus, lower system volume and cost.

SiC JFET power modules

The conduction performance of Si-based MOSFETs is drops sharply when the blocking voltage of the switch gets higher than 1000V. IGBTs are a good choice for switches with blocking voltage >1000V. But due to the tail current during switching off, switching losses have certain physical limits. The desire for a faster switch with low conduction loss has driven the development of a new switch based on SiC material: SiC based junction field-effect transistor (JFET, see e.g. [8]).

The first prototype of a power module containing SiC JFET switches is an EasyPACK 2B module with H-bridge configuration. Figure 4 shows the package and DBC layout of the module.

The SiC JFET is a normally-on component with a pinch off voltage of ~ -15V, for compatibility with standard applications it is optional to provide normally-off switches (cascode configuration) formed by a 40V low-voltage Si-MOSFET (OptiMOS) in series with the 1200V SiC JFET. Each switch in the module contains six SiC JFETs in parallel achieving a R_{dson} in total of approximately 70m? .

Dynamic tests have been done with different gate resistor values (39 to 82?). The results are shown in Figures 5 and 6. The test conditions were T_j= 125°C, I_d= 40A, V_{dc}= 600V, inductive load.

A comparison of dynamic losses to IGBT module is shown in Figure 7. It can be seen

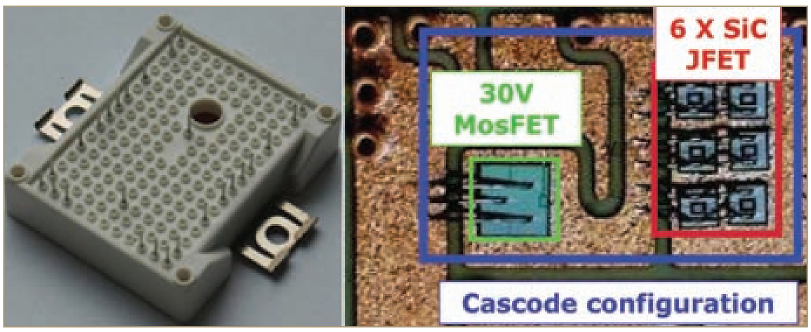


Figure 4: **Package and DBC layout of EasyPACK 2B JFET cascode module**

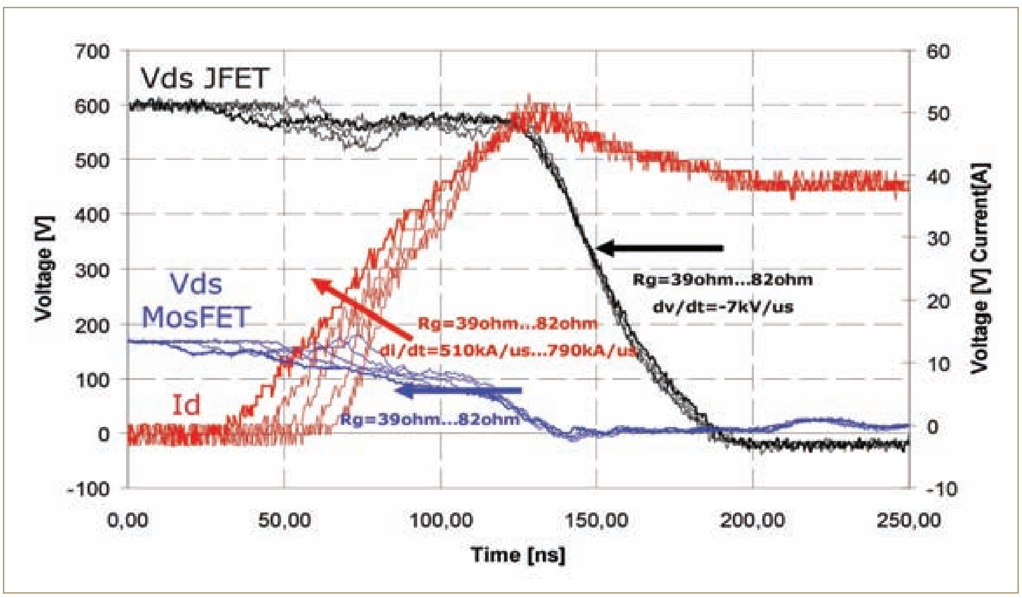


Figure 5: **Dynamic test waveforms of SiC JFET module at turn-on**

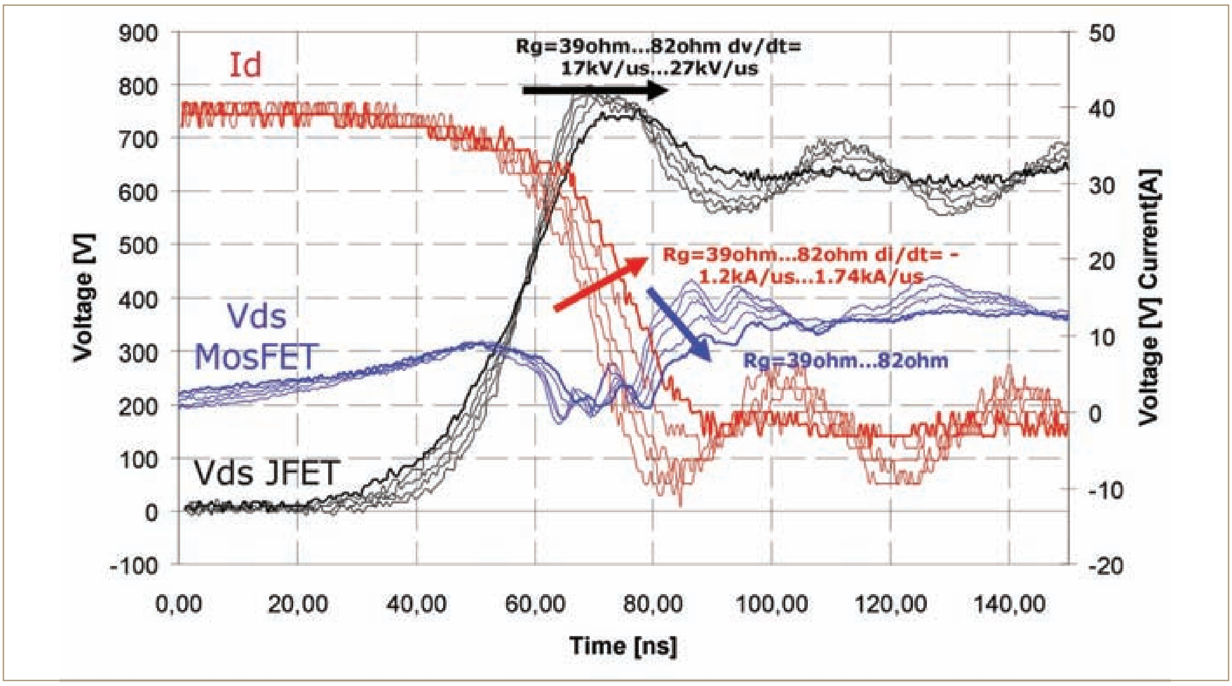


Figure 6: Dynamic test waveforms of SiC JFET module at turn-off

that the turn-on losses are quite low due to the low reverse recovery charge of the body diode.

The turn-off losses are very low, caused by the absence of minority carriers in JFETs similar to MOSFETs. Another advantage is that the di/dt slope during turn-off can be fully controlled simply with variation of the gate resistor.

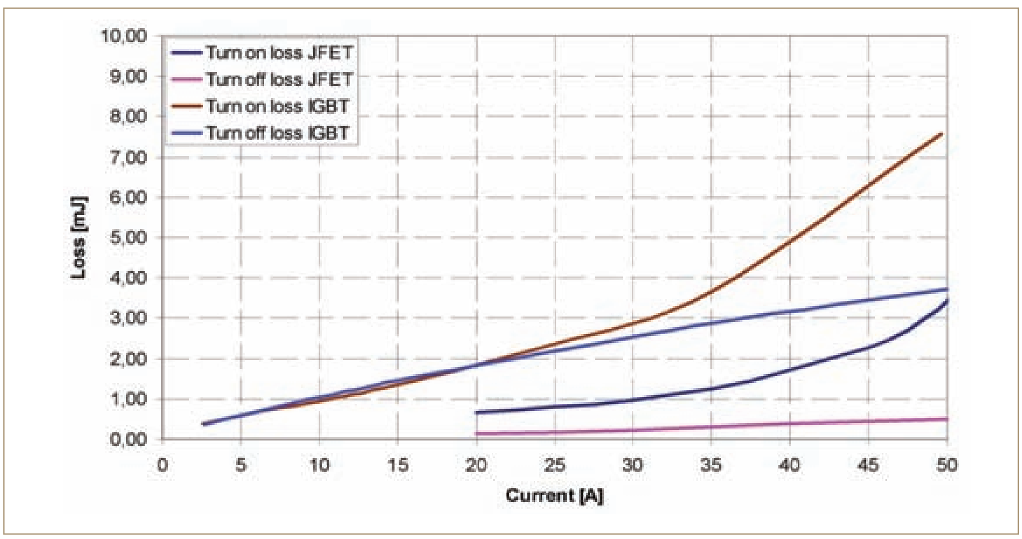
Comparison between Si- and SiC-based power modules

Two possibilities of SiC based devices in power modules have been presented in this article. It is now interesting to compare the two different configurations to pure Si-based configurations using calculation of inverter losses [6].

The data of a pure Si-based module was taken from the datasheet of a 25A/1200V IGBT4 module [7]. The measurements with IGBT plus SiC Schottky diodes were performed on a 25A/1200V IGBT4 module, together with the introduced 15A/1200V SiC Schottky diodes. The measurement of SiC JFET in cascode configuration was performed with the SiC JFET EasyPACK 2B module under test conditions of T_j= 125°C, V_{dc}= 600V, I_{rms}= 21.2A, cosφ = 0.8. The Gate resistor value for each configuration has been chosen to have the minimal possible switching losses. The derived results are shown in Figure 8.

From the calculated results, the advantages of SiC based devices can be observed immediately. For applications which treat efficiency as first priority, the efficiency of the converter at f_{sw} =20kHz can be increased by 1.1% by utilising SiC diode with IGBT if the same output power is maintained. Utilising SiC JFET can increase the efficiency by even 1.3%. For applications which treat power density as the first priority, the output power of the converter at f_{sw} =20kHz can be increased by 31% by utilising SiC diode if the same semiconductor losses are maintained. Utilising SiC JFET can increase the output power by 28%. Under these conditions, the IGBT/SiC diode combination outperforms the JFET, due to lower conduction losses of the IGBT compared to the unipolar JFET device. Utilising SiC diodes with IGBTs can increase the switching frequency of a converter from 20 to 38kHz if the same semiconductor losses are maintained. With SiC JFET, the switching frequency can even be increased to 70kHz with the same losses. The increase of switching frequency can then decrease the size and cost of the output filter. However, the exact degree of size or cost reduction

Figure 7: Comparison of switching losses of the JFET module to a 25A/1200V module with IGBT4 (T_j= 125°C, V_{dc}= 600V, R_g =39Ω)



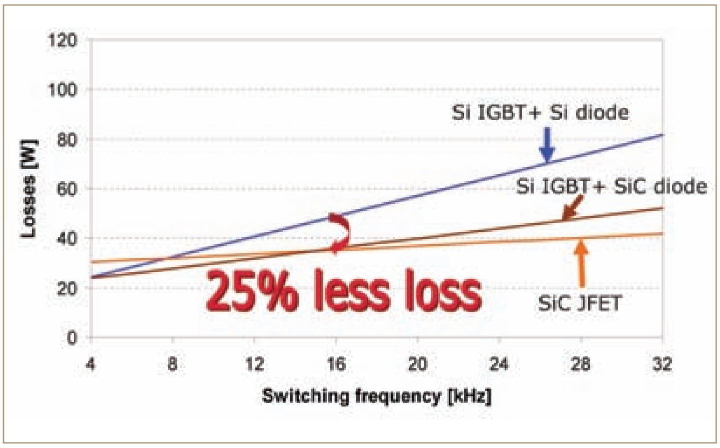


Figure 8: **Benchmark of total losses between IGBT module, SiC JFET module and IGBT+ SiC diode module (T_j = 125°C, V_{dc} = 600V, I_{rms} = 21.2A, cosφ = 0.8)**

depends on several other factors.

The utilisation of SiC Schottky diodes or SiC JFETs can decrease the switching losses dramatically. The configuration of IGBT together with SiC diode as free-wheeling diodes combines the superior conduction performance of IGBT chips with the ultra-low reverse recovery losses of SiC Schottky diodes. Even lower switching losses can be achieved with SiC JFET. Due to the missing conductivity modulation in the unipolar component, the conduction losses of the SiC JFET, however, are slightly higher than IGBTs (trade-off between chip area and cost). According to the switching frequency or the requirements from applications, one can choose between these different configurations.

Conclusion

Modules utilising SiC devices (Schottky diodes, JFET) are presented. The performance of these modules compared to Si-based power modules is demonstrated and discussed. From the results, it is clear to see the benefits of utilizing SiC devices. With the same converter design, the efficiency of the whole system can be increased. A smaller heatsink or passive cooling system can be used. With the same thermal design, the output power of the converter can be increased or the power density of the system can be increased. Increasing the switching frequency, the size of output filter and thus, system cost, can be reduced.

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