Efficiency improvement with silicon carbide based power modules

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Abstract

In the recent years, discrete SiC (silicon carbide) based devices have been introduced to the market. In this paper the utilization of SiC based diodes and switches in power modules will be presented, discussed and compared with Si-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 + 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 > 20 kHz.

1. Introduction

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 the recent years, SiC (silicon carbide) based Schottky diodes have been introduced into the market 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 point for SiC power devices, this emerging technology is also considered by many groups (see for example [3]) as ideal candidate for high power module applications. The main target of this paper is to get a better insight regarding the trade off between static and dynamic losses when moving from highly cost effective Si-based solutions to high performance but costly SiC based solution. For that purpose the following switch configurations are compared:

a) Si IGBT (Infineon IGBT^4) with Si free wheeling diode (Emitter Control^4)
b) Fast Si IGBT (Infineon IGBT^2) with SiC free wheeling diodes (Infineon 1200V SiC Schottky diodes)
c) 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].

2. IGBT power modules with SiC freewheeling 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]

First commercially available high power module containing SiC Schottky diodes as freewheeling diodes is a 600A, 1200V PrimePACK™ 2 IGBT power module with type designation FF600R12IS4F from Infineon Technologies as shown in Fig. 1:

Fig. 1. Infineon's high power module with integrated SiC schottky diodes as freewheeling diodes in PrimePACK™ 2 package.

The 1200V SiC diodes used are bare Schottky diodes with a p^+/p^- JTE edge termination structure and a Ti-Schottky barrier providing a barrier height of 1.27 eV 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 behavior of SiC Schottky diodes in combination with Infineon's fastest IGBT chips: S4 chip based on IGBT^2 technology.

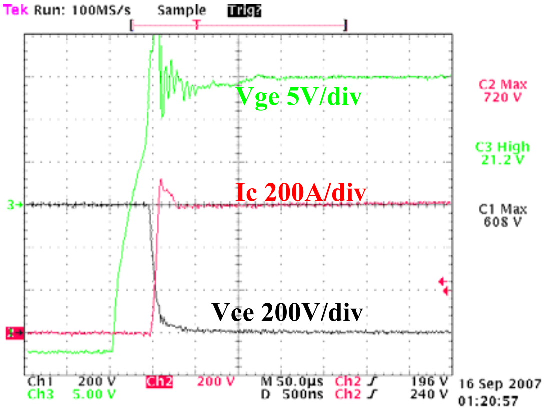

Fig. 2. Typical turn on behaviour of 1200V, 600A IGBT S4 Chip with 360A SiC Schottky diodes (Tj=25°C, Rg_on=0,5Ω)

Due to the absence of reverse recovery charge of SiC Schottky diodes, the turn on gate resistor of IGBT can be reduced dramatically to reduce turn on losses (As in the example, 0,5Ω is used). The reverse recovery current, as can be seen in Fig. 2, is reduced dramatically in comparison to Si based freewheeling diode. Following Fig. 3 shows typical switching loss of the module:

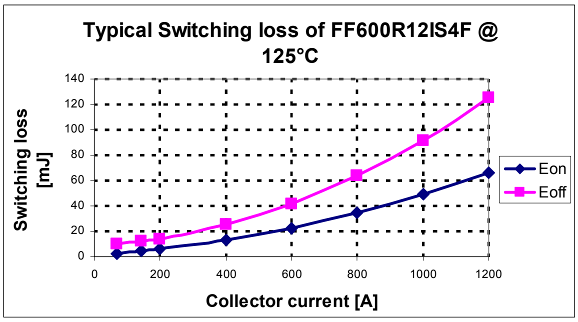

Fig. 3. Typical switching loss of PrimePACK™ 2 module FF600R12IS4F with SiC Schottky diodes.

With the reduction of turn on losses with SiC freewheeling diodes, the efficiency or the output power of the converter system can increase. This is very attractive for applications which take care of efficiency as first priority (e.g solar application). But efficiency is not the only benefit when using SiC freewheeling 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.

3. SiC JFET power modules

The conduction performance of Si-based MOSFETs is sharply dropping when the blocking voltage of the switch is getting 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]).

First prototype of a power module containing SiC JFET switches is an EasyPACK 2B module with H-bridge configuration. Fig. 4 and Fig. 5 show the circuit diagram and DBC layout of the module.

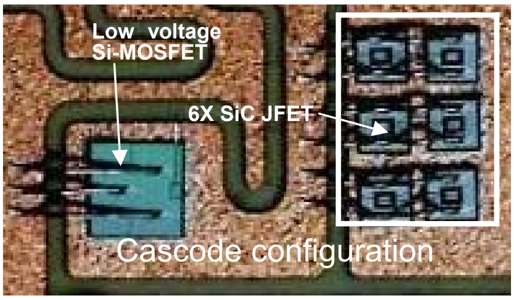

Fig. 4. DBC layout of EasyPACK 2B JFET cascode module

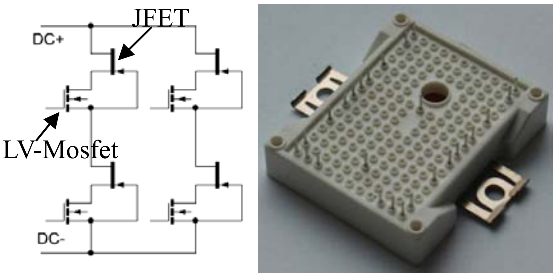

Fig. 5. Circuit diagram (left) and package (right) of EasyPACK 2B JFET cascode module

Infineon's 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 1200V SiC JFET. Each switch in the module contains 6 pieces of

SiC JFETs in parallel achieving a Rds_on in total of approx 70mΩ.

Figure 6 shows the static behavior of SiC JFET in combination with low voltage OptiMOS™ 2 in cascode configuration.

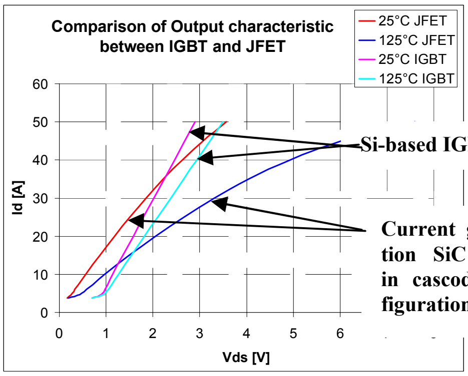

Fig. 6. Static characteristic of SiC JFET in cascode configuration @ 25°C, 125°C

Dynamic tests have been done with different gate resistor values (39Ω…82Ω). The results are shown in Fig. 7-8. The test conditions were: Tj=125°C, Id=40A, Vdc=600V, inductive load.

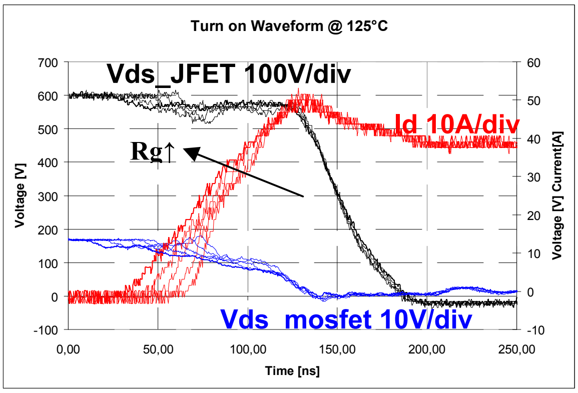

Fig. 7. Dynamic test waveforms of SiC JFET module: turn on @125°C

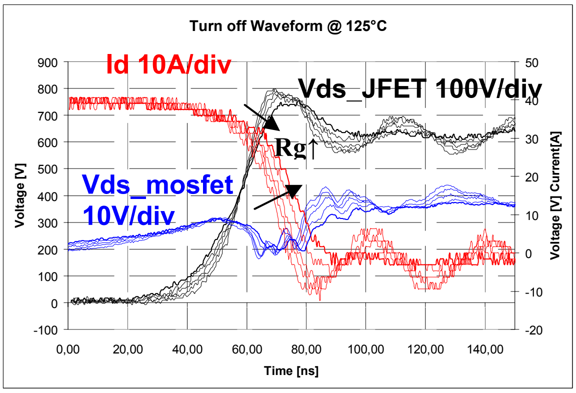

Fig. 8. Dynamic test waveforms of SiC JFET module: turn off @125°C

A comparison of dynamic losses to IGBT module is shown in Fig. 9:

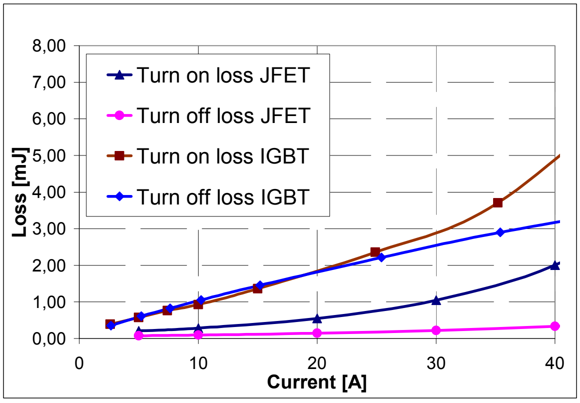

Fig. 9. Comparison of switching losses of the JFET module to a 25A, 1200V module with IGBT^4 (Tj=125°C, Vdc=600, Rg=39 Ω)

From the results it can be seen: 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 gate resistor.

4. Comparison between Si-based power modules and power modules utilizing SiC devices

Two possibilities of utilization SiC based devices in power modules have been presented in this paper. It is now interesting to compare the two different configurations to pure Si-based configuration. To serve this purpose, calculation of inverter losses based on [6] is used. The data of pure Si-based module was taken from datasheet of a 25A, 1200V IGBT4 module [7]. The measurements with IGBT+SiC Schottky diodes were performed on 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 introduced SiC JFET EasyPACK 2B module. The test conditions are: Tj=125°C, Vdc=600V, Irms=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 the following Fig. 10.

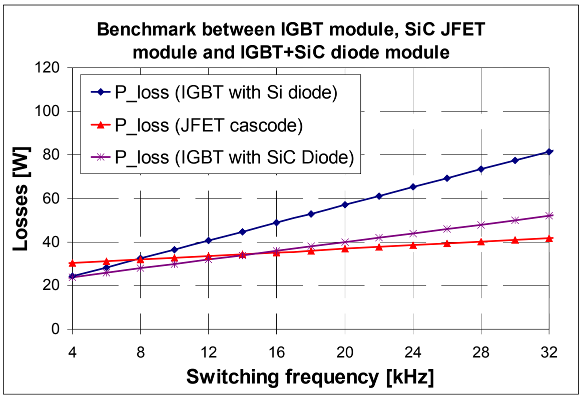

Fig. 10. Benchmark of total losses between IGBT module, SiC JFET module and IGBT+SiC diode module (Tj=125°C, Vdc=600V, Irms=21,2A, cosφ=0,8)

From the calculated results in this example, 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 utilizing SiC diode with IGBT if same output power is maintained. Utilizing SiC JFET can increase the efficiency by even 1,3%.
- For applications which treat power density as first priority, the output power of the converter at f_{sw}=20kHz can be increased by 31% by utilizing SiC diode if same semiconductor losses are maintained. Utilizing 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.
- Utilizing SiC diode with IGBT can increase the switching frequency of converter from 20kHz to 38kHz if same semiconductor losses are maintained. With SiC JFET, the switching frequency can be even increased to 70kHz with same losses. The increase of switching frequency can then decrease the size and cost of the output filter. The exact degree of size or cost reduction depends however on several other factors.

The utilization of SiC Schottky diodes or SiC JFETs can decrease the switching losses dramatically. The configuration of IGBT together with SiC diode as freewheeling 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 application, one can choose between these different configurations.

5. Conclusion

In this paper, modules utilizing 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 same converter design, the efficiency of whole system can be increased. Smaller heatsink or passive cooling system can be used.
- With same thermal design, the output power of converter can be increased. Power density of system can be increased.
- Increasing the switching frequency, the size of output filter and thus system cost can be reduced.

The first applications which can benefit from these advantages are those which need high efficiency (for example solar converter) or contain an output filter (for example medical equipment or UPS). In the long run and mainly depending on the cost and diameter development of silicon carbide base material, it is to believe that silicon carbide based power semiconductor will become the next generation of power semiconductors and bring a new wave of innovation into this field.

6. Literature

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