

Demonstration of superior SiC MOSFET Module performance within a Buck-Boost Conversion System

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Abstract

This paper shows the performance of Infineon's new SiC MOSFET power module operating in a buck-boost conversion system. The fast switching characteristics of the module will be illustrated with the help of double pulse measurements which show dv/dt levels above $50\text{ kV}/\mu\text{s}$. A conversion efficiency of 99% has been measured at a switching frequency of 100 kHz. In addition a comparison to a Si IGBT based system has been made to evaluate the potential performance gain of using the Infineon SiC MOSFET module. Finally the performance increases achieved by the use of synchronous rectification, which has been tested up to a switching frequency of 500 kHz, will be delineated.

1. Introduction

As silicon (Si) based power semiconductors are reaching their technical limits in terms of switching performance, reliability and power density, power switches based on compound semiconductor materials are becoming the focus of a lot of interest for several applications like photovoltaics (PV), uninterruptable power supplies (UPS) and motor drives. Silicon carbide (SiC) is widely regarded as the most promising semiconductor material for power devices in the voltage range above 600V.

While SiC diodes are widely used in many applications¹, existing SiC MOSFETs have not yet achieved a similar level of acceptance in the power electronics market.

The main reasons for this lower acceptance level are the higher cost, unproven long term reliability [1] and additional design effort required to replace IGBTs with SiC MOSFETs [2].

This paper demonstrates the performance of a bidirectional buck-boost converter based on a new SiC MOSFET power module manufactured by Infineon. After characterization of the basic switching behavior using double pulse testing, functional tests have been performed to investigate the DC converter's performance under different operating conditions. A Si IGBT based converter is used as a reference system to compare the performance of equivalent Si and SiC based converters. The goal of this work is to evaluate the potential performance gains possible using a SiC MOSFET. A further target is the demonstration of the reduced

¹ E.g. Solar power inverters.

implementation effort for the shown power module in terms of driver circuit design and driving.

1.1. SiC MOSFET based DC/DC converter

The tested SiC module consists of a 50 A 1200 V half-bridge topology with each switch built with two 25 A chips in hard parallel connection. As integrated body diodes are implemented in the SiC MOSFET chips, no additional freewheeling diodes are necessary. An Easy1B [3] power module serves as package.

The passive components and PCB of the buck-boost converter have been designed with respect to the targeted switching frequency of 100 kHz. Figure 1 draws the circuit and implemented components of the converter.

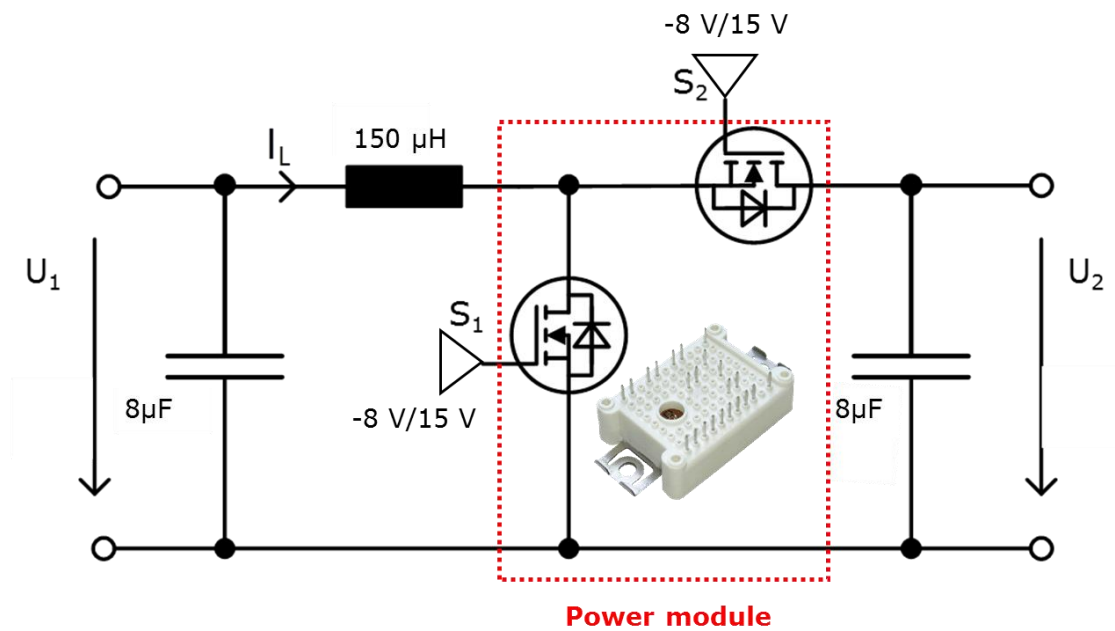


Fig. 1. Circuit of the investigated bidirectional buck-boost converter including the values of the implemented passive components and the driver voltages.

Film capacitances from Epcos [4] serve as input and output capacitors. A 150 μH inductor from Sumida [5], based on ferrite core technology, has been used as the DC choke. The two switches of the SiC MOSFET module are driven at -8 V/15 V using standard EiceDRIVER™ Compact [3] devices. The PCB consists of four 35 μm copper layers using FR4 as matrix material.

All the test data shown are with the system operating in boost or step up mode i.e. with the current flow as shown in figure 1.

2. Double pulse characterization

The following section describes double pulse measurements of the converter testing the switching behavior of S_1 . In this configuration a resistive load is connected across U_2 and S_2 is held off with $V_{\text{GS}} = -8 \text{ V}$. The external gate turn-on and turn-off resistance values are 1 Ohm.

2.1. Switching behavior

Figure 2 presents the turn-on and turn-off behavior of S_1 with U_1 at 600 V, I_d at 5 A, and a junction temperature of 25 °C i.e. room temperature RT.

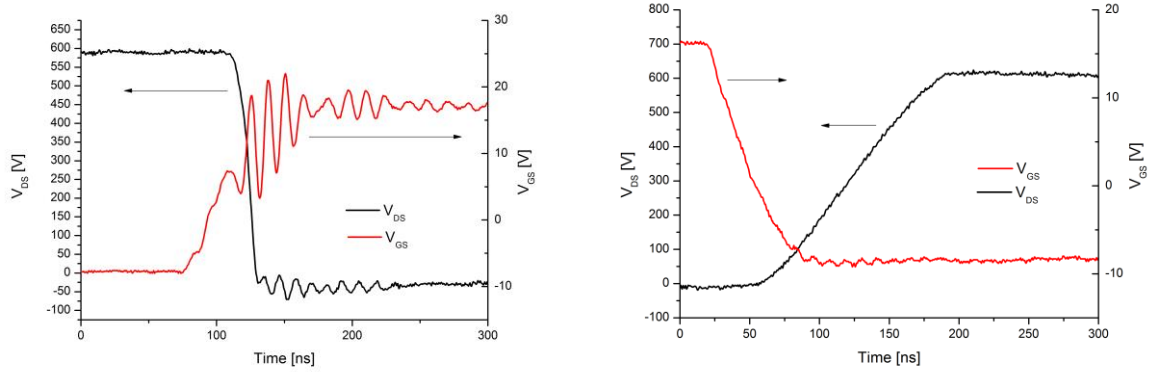


Fig. 2. (Left) Turn-on and (Right) turn-off behavior of S_1 at 5 A.

The gate-source waveform at turn-on shows some oscillatory behavior. These oscillations are caused by module internal inductance between the chip and the source auxiliary terminal where the measurements have been taken [6]. The switches themselves are turning-on properly which can be seen through the very low oscillations of V_{DS} during turn on. The dv/dt shown is at a high value of 40 kV/ μ s.

The turn-off at 5 A is much softer than the turn-on, as it can be seen in the right side of figure 2. Almost no oscillations of V_{GS} or V_{DS} are occurring. The dv/dt is at 5 kV/ μ s which is relatively low for a SiC switch.

As the turn-on switching is already very fast, the slow turn-off at 5 A does not represent the turn-off performance, which is possible with the presented SiC MOSFET. That is the reason why a further double pulse measurement has been performed at 30 A, which represents 60 % of the modules current rating. Figure 3 shows the waveforms of these measurements.

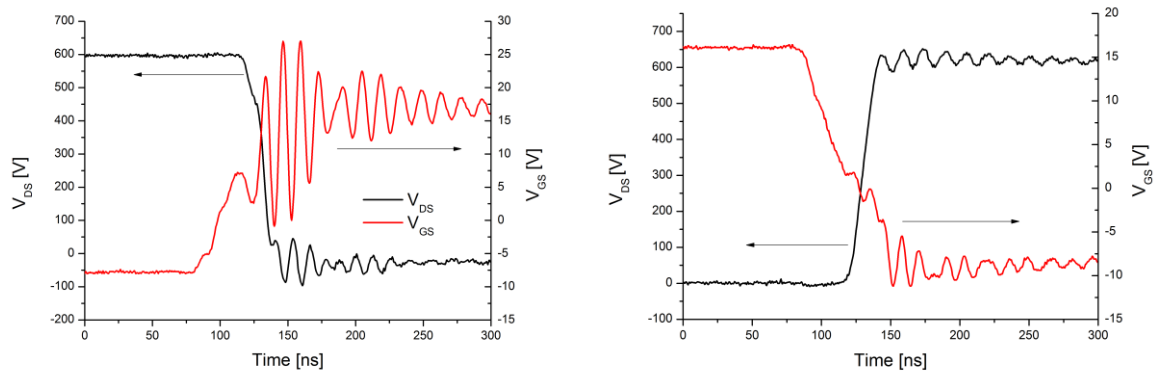


Fig. 3. (Left) Turn-on and (Right) turn-off behavior of S_1 at 30 A.

Again, strong oscillations are measured at the gate-source voltage during turn-on.

Nevertheless V_{DS} shows only a low level of oscillations indicating proper operation of the switches. The dv/dt values are 55 kV/ μ s during this turn-on and 34 kV/ μ s during turn-off showing the very strong influence of current and dv/dt during turn-off for this device.

Table 1 gives measurement values taken at different current levels.

Current [A]	dv_{on}/dt [kV/ μ s]	$\Delta V_{DS, on}$ [V]	dv_{off}/dt [kV/ μ s]	$\Delta V_{DS, off}$ [V]
5	40	-71	5	+24
10	52	-79	11	+33
20	50	-89	22	+40
30	55	-97	34	+52

Table 1. Over-voltage levels and dv/dt values at different currents.

As expected, the overvoltage increases with higher currents caused by higher di/dt levels during turn-on and turn-off. At turn-on currents higher than 10 A, dv/dt reaches a constant value of about 50 kV/ μ s. In the case of turn-off the dv/dt shows a large increase with the higher values of the switched current.

2.2 Investigation of parasitic high side turn-on

As the switching behavior of the investigated MOSFET is very fast, which can be seen by the high dv/dt values, it is important to investigate the possibility of parasitic turn-on of the upper switch. Figure 4 presents the gate-source voltage of the upper MOSFET during the turn-on of the lower switch.

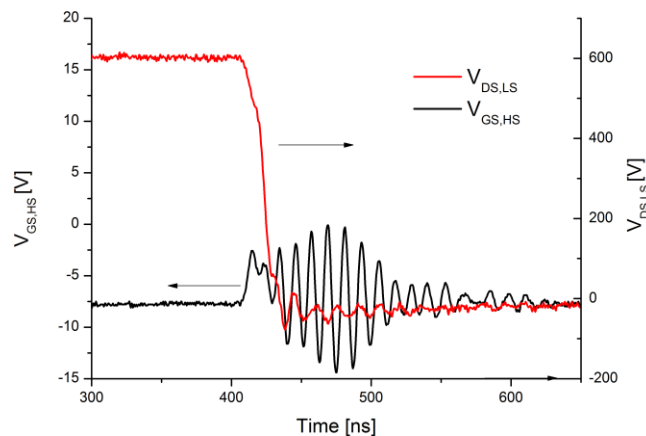


Fig. 4. Behavior of upper gate-source during turn-on of lower switch. I_d 30 A, U_1 at 600 V, RT and R_g 1 Ohm.

Under the conditions shown the dv/dt is >50 kV/ μ s. The high dv/dt causes voltage oscillations at the upper gate-source voltage. Nevertheless the measured gate-source voltage of the upper switch stays below 0 V and no parasitic turn-on is occurring as the threshold voltage is above 3 V. This indicates that at these high dv/dt levels -8 V is a good choice for the gate driver negative voltage.

As a conclusion of the double pulse investigations the fast switching of the investigated SiC MOSFET has been proven within the buck-boost converter. No parasitic turn-on of the upper switch could be detected even at 55 kV/ μ s. The measured gate-source oscillations are a consequence of the source inductance within the driver loop internal to the module and can be reduced with a negative feedback of the source potential towards the gate [7] connection. The switching performance of the MOSFET itself is not affected by this phenomenon.

3. Conversion Performance

For the measurement of the boost conversion efficiency a 100 Ohm resistor has been connected to the output. The input and output voltages and currents have been measured to calculate input and output power. The DC/DC converter is driven in conventional boost operation using S_1 as active switch and the integrated body diode of S_2 for freewheeling ($V_{GS,S2}=-8$ V). The switching frequency is 100 kHz using a duty cycle of 25 %. Figure 5 shows the slope of the efficiency at different input power levels.

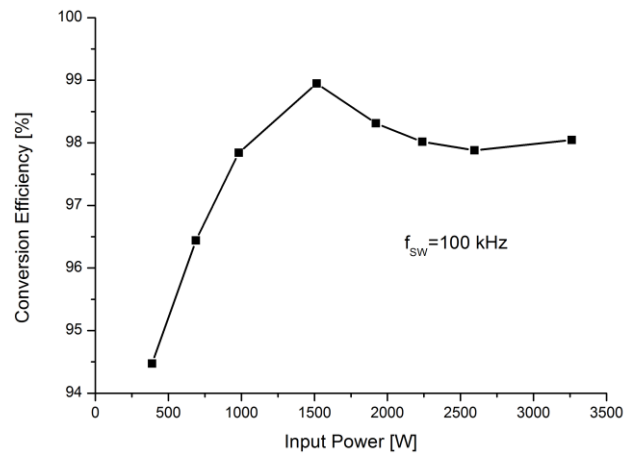


Fig. 5. Boost conversion efficiency as a function of input power.

A very high conversion efficiency of about 99 % at a rated input power of 1500 W can be measured. For a higher power rating up to 3500 W, the determined conversion efficiency stays about 98 %. No efficiency derating can be observed up to 3500 W. The slight efficiency increase between 2500 W and 3500 W occurs from the faster turn-off switching at higher current rating causing lower turn-off losses.

The slope of the power-efficiency curve may change for different duty cycles but the underlying high conversion efficiency of the converter at 100 kHz has been shown. These results give an impression about the potential of the SiC MOSFET module to operate at both high switching frequencies and conversion efficiency at the same time.

4. Benchmark performance comparison with Si IGBT based converter

The following section will compare the SiC MOSFET based unit with one using a Si IGBT. The focus of this study is the comparison of system size and efficiency.

4.1 Si IGBT reference characteristics

The Si IGBT based buck-boost converter uses the same circuit and passive component technologies as the SiC MOSFET based converter. As the switching losses of the selected IGBT4 and the antiparallel EC4 diode module are higher than the SiC MOSFET module losses, the targeted switching frequency of the Si IGBT solution is 16 kHz.

Consequently the size of the inductor as well as the size of the capacitors have to be increased to achieve the same voltage ripple as the SiC MOSFET solution (<1 %). Table 2 and table 3 compare the component dimensioning, the geometrical dimensions and the weight of both converters.

	Si IGBT based system	SiC MOSFET based system
f_{sw}	16 kHz	100 kHz
L	1000 μ H	150 μ H
C_{input}	42 μ F	8 μ F
C_{output}	40 μ F	8 μ F

Table 2. Component dimensioning of the Si IGBT and SiC MOSFET based DC/DC converter.

		SI IGBT Reference	SiC MOSFET Demonstrator
L	Size (H x W x L)	125 mm x 95 mm x 70 mm	70 mm x 55 mm x 40 mm
	Weight	3.20 kg	0.50 kg
Total	Size (H x W x L)	139 mm x 300 mm x 185 mm	84 mm x 206 mm x 134 mm
	Weight	3.77 kg	0.93 kg

Table 3. Weight and size of inductors and the total converters.

As the dimensioning of the passive components for the Si IGBT based converter is larger, the size as well as the weight is much higher compared to the SiC MOSFET based system. The main increase of weight and size is related to the larger inductor required for the Si IGBT reference.

Both systems have the same full power rating which results in the passive components for the SiC MOSFET solution having a four times higher power density (in W/kg).

A picture of both systems is presented in figure 6 to give an idea of the physical sizes of both designs.

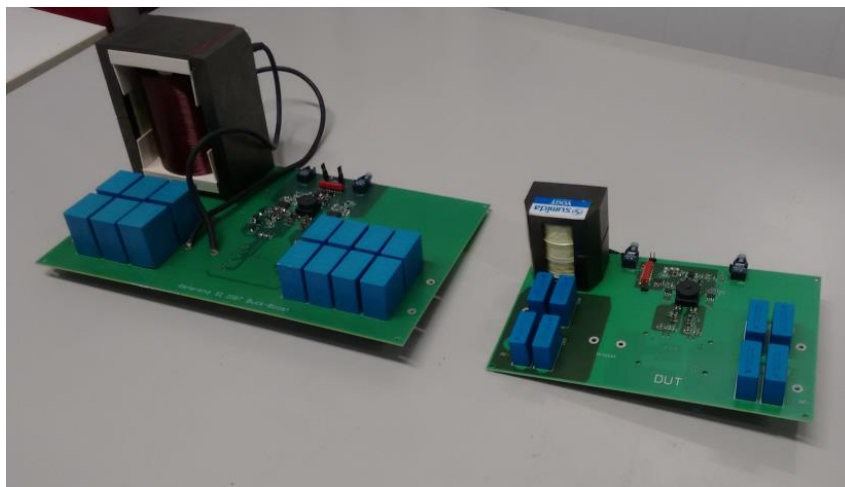


Fig. 6. (Left) Si IGBT and (right) SiC MOSFET based buck-boost converter.

4.2 Comparison of conversion performance

The test conditions for the comparison of conversion efficiency are similar to the conditions in section 3. Again, a 100 Ohm resistor serves as load. Both systems are driven as boost converters.

The conversion efficiency has been measured over a range of switching frequencies at an input power rating of 2000 W. The SiC MOSFET measurements have been taken under two different operating conditions. The first operating mode uses conventional switching as described in section 3. The second operating mode is to use S_2 in synchronous rectification mode to reduce the conduction losses of the body diode during the freewheeling portion of the cycle [8]. Figure 7 draws the efficiency results of these tests in a semi-logarithmic scale.

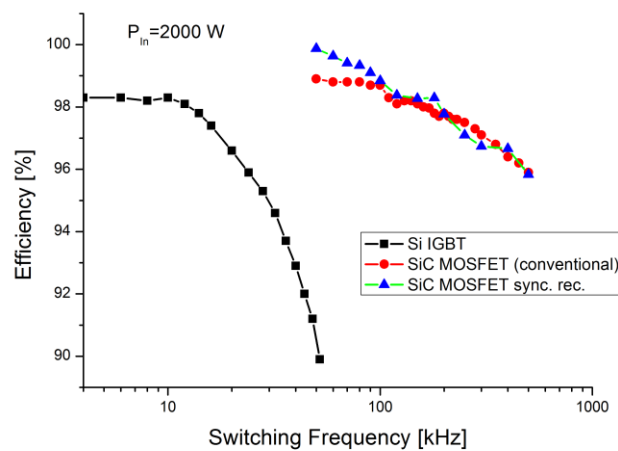


Fig. 7. Plot of the conversion efficiency the Si IGBT and SiC MOSFET based systems at different switching frequencies.

The measurement demonstrates the impressive performance jump from the Si IGBT to the SiC MOSFET. The Si IGBT based reference system only reaches an efficiency of 90 % at 50 kHz while the SiC MOSFET system achieves efficiencies beyond 99 % under the same conditions. The SiC MOSFET converter has been tested up to 500 kHz where the efficiency is still higher than 95 %.

The conversion efficiency of the SiC MOSFET demonstrator in the frequency regime up to 250 kHz can be increased by the use of synchronous rectification. This is due to the lower conduction losses as shown in Figure 8

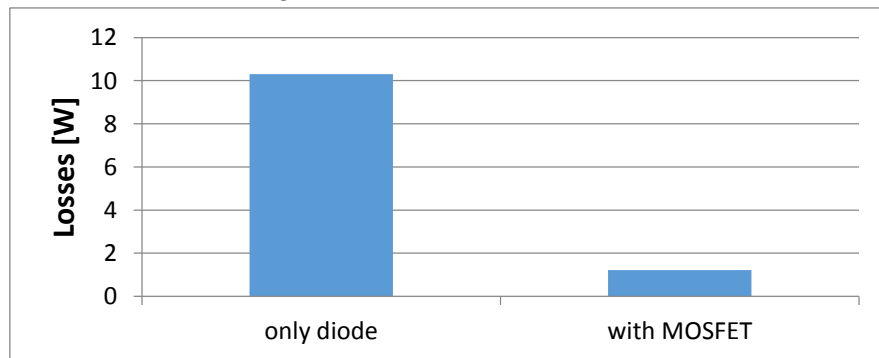


Fig. 8. Losses of the SiC demonstrator in bypass mode (S_1 turned off) with and without use of S_2 .

The presented results are for the case of 300 V input voltage and 6 A current. If both MOSFETs are turned-off, only the upper diode is conducting, leading to a loss of 10 W caused by the voltage drop at the body diode. If S_2 is turned-on, the channel of the MOSFET conducts the freewheeling current, which leads to a reduction of the voltage drop and the losses in the given example reduce to 1 W.

5. Summary and Conclusion

This paper gives an overview of the performance of Infineon's new SiC MOSFET power module operating in a DC/DC converter. The device demonstrates fast switching behavior of the module in the application without parasitic turn-on. The unit has achieved an efficiency of up to 99 % at a switching frequency of 100 kHz. The comparison with a Si IGBT based system clearly shows the potential advantages in terms of efficiency, size and weight.

In addition the gate driver of the SiC MOSFET was realized with a standard IGBT driver IC (EiceDRIVER™ Compact) at conventional drive voltages of -8 V/15 V. Even with this standard drive components; performance has been measured for operation up to 500 kHz.

Infineon is setting a milestone in power electronics with the introduction of its new generation of SiC MOSFET 1200 V modules. The outstanding performance and straight forward implementation are a big step towards improving the power density and performance in a wide range of power electronic devices like solar inverters, drive converters or power supplies.

The device and module design is targeting towards applications using switching frequencies up to 200 kHz, although the chip technology is able to be used at even higher frequencies provided the application will benefit from such an operation mode and auxiliary elements are available to run the full system at those values.

It has to be mentioned that we have investigated an early prototype SiC MOSFET module. The final product will be optimized in layout and performance with respect to effects like the source current feedback and other.

6. Acknowledgements

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7. References

- [1] Lelis, Aivars J., et al. *Electron Devices, IEEE Transactions on* 55.8 (2008): 1835-1840.
- [2] Fabre, Joseph, Philippe Ladoux, and Michel Piton. *Power Electronics, IEEE Transactions on* 30.8 (2015): 4079-4090.
- [3] Infineon Technologies AG, Neubiberg Germany
- [4] EPCOS AG, Munich Germany
- [5] Sumida AG, Obernzell Germany
- [6] Yin, Shan, et al *Power Electronics and Drive Systems (PEDS), 2015 IEEE 11th International Conference on*. IEEE, 2015.
- [7] Grbovic, Petar J. *Power Electronics, IEEE Transactions on* 23.2 (2008): 643-652.
- [8] Ji, H. K., and H. J. Kim. *Power Electronics Specialists Conference, PESC'94 Record., 25th Annual IEEE*. IEEE, 1994.