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Selecting A Freewheeling Diode Solution For Lowest Losses With SiC MOSFETs

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Although earlier generations of power converters were limited by the switching speed and high losses of high-voltage silicon switches, new fast-switching and low-loss silicon carbide (SiC) MOSFETs and diodes greatly alleviate these constraints and offer designers the opportunity to create compact, superefficient power converters. In addition to more compact and efficient designs, the reduction in magnetics size made possible by high switching frequencies and simpler thermal management designs enabled by SiC's ability to operate at high junction temperatures can also help in reducing total system cost.

A standard phase-leg configuration, widely employed in many power conversion systems whether they are stepup or stepdown topologies, fundamentally consists of a switching device and a freewheeling device. This article discusses a few of the potential configurations available to implement the freewheeling device in a SiC-based system. These include use of a discrete SiC Schottky barrier diode (SBD), a SiC MOSFET's body diode, and a SiC MOSFET in combination with an additional discrete anti-parallel SiC SBD. The main objective here is to assess the impact of adding anti-parallel SiC SBDs to SiC MOSFETs on converter losses.

To that end, we've conducted a series of experiments to determine the switching losses produced by the three freewheeling device options. These experiments are described here in detail along with an analysis of the results and discussion of the tradeoffs of each freewheeling device option. Then, some guidelines are presented to help designers select the freewheeling diode solution that will minimize losses in their power converter applications. This discussion includes recommendations on how to size the anti-parallel SBDs, when their use is appropriate.

The Three Freewheeling Options

Fig. 1 presents three common freewheeling device solutions, each of which was studied in our research. SiC Schottky barrier diodes (SBDs) (Fig. 1a) offer the advantages of low switching losses due to their low reverse-recovery-charge characteristics, which are independent of di/dt, current level and temperature. However, their on-state voltage drop is relatively high, which results in relatively high conduction losses.

Using a half-bridge configuration and synchronous rectification can effectively reduce conduction losses and improve system efficiency. However, the body diode of a SiC MOSFET (Fig. 1b) is still a p-n structure, which makes it subject to reverse-recovery charge that is dependent on di/dt, current level, and especially temperature. The smaller thermal management solutions and wider operating-temperature margins presented by SiC devices means that SiC systems are likely to be operating at higher temperatures. Additionally, SiC systems will commonly see high di/dt transients and high current levels. All of these factors have an adverse effect that contributes to higher reverse-recovery charge and, ultimately, higher switching losses.

This article explores the impact of adding anti-parallel SBDs to SiC MOSFETs (as shown in Fig. 1c). Although this method is proven to provide favorable performance benefits, those benefits are not equal across all operating conditions; in some cases, the addition of an anti-parallel SBD actually penalizes system performance.

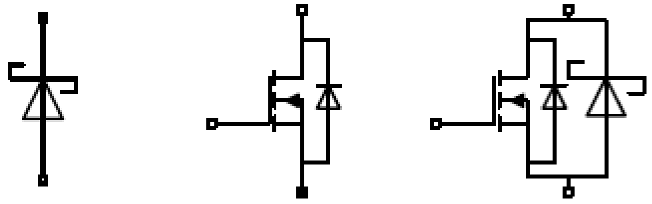

(a) SBD only (b) Body diode of MOSFET (c) MOSFET+SBD

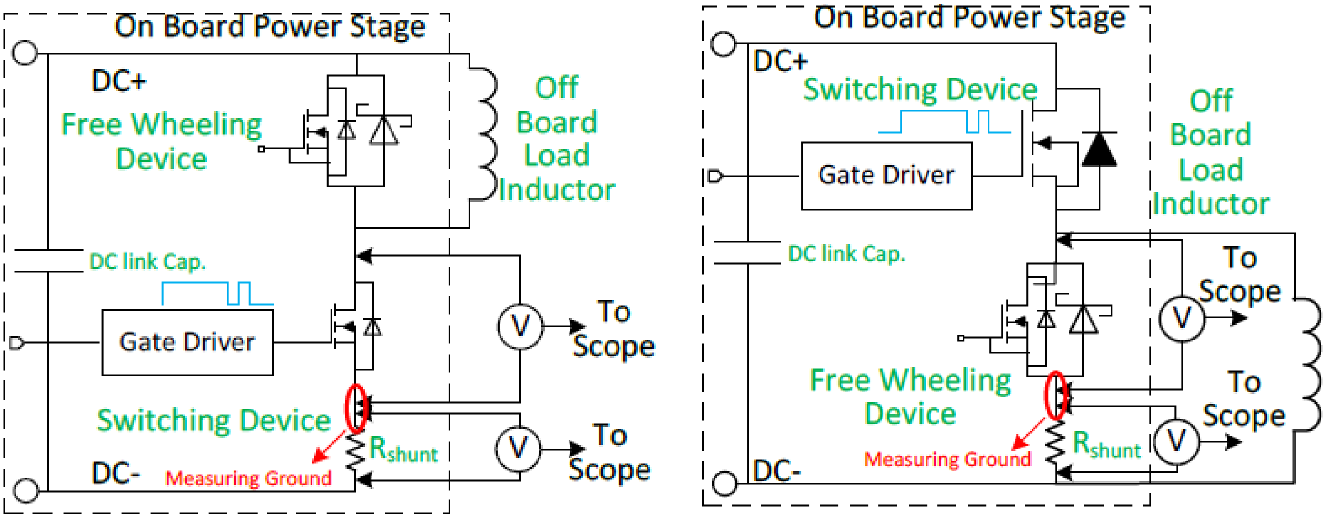
Fig.1. Three freewheeling device implementations.

We recently conducted a series of experiments to characterize SiC MOSFET body diodes and Schottky diodes for the purpose of comparing their loss and charge characteristics when implemented as different freewheeling device configurations at different temperatures. A pulse tester designed for dynamic characterization of SiC devices ensured accurate measurements of the fast-switching voltage and current.

Turn-on waveforms were compared under different temperatures with the different freewheeling device implementations. Turn-on loss and charge were calculated from the turn-on voltage and current. The results for the different freewheeling device combinations—SBD only (Fig. 1a) vs. MOSFET only (Fig. 1b) vs. MOSFET+SBD (Fig. 1c)—at different temperatures were compared to develop a design guideline for selecting a freewheeling diode solution to minimize switching losses.

Dynamic Characterization Board

A pulse tester optimized for dynamic characterization of SiC devices was developed to measure the switching loss of the switching device and the charge of the freewheeling diode. This dynamic characterization board allowed measuring voltage and current across switching devices and freewheeling devices separately by using different circuit configurations (Fig. 2). A half-bridge configuration with independent gate-driving circuits for each of the top and bottom devices was selected. This dynamic characterization board supported implementing both the top and bottom devices with only a SiC SBD, a SiC MOSFET only, or a SiC MOSFET with an anti-parallel SiC SBD. Our implementation of the board is shown in Fig. 3.



(a) (b)

Fig. 2. Switching loss measurement circuit (a) and charge measurement circuit (b) for comparing performance of the different freewheeling devices.

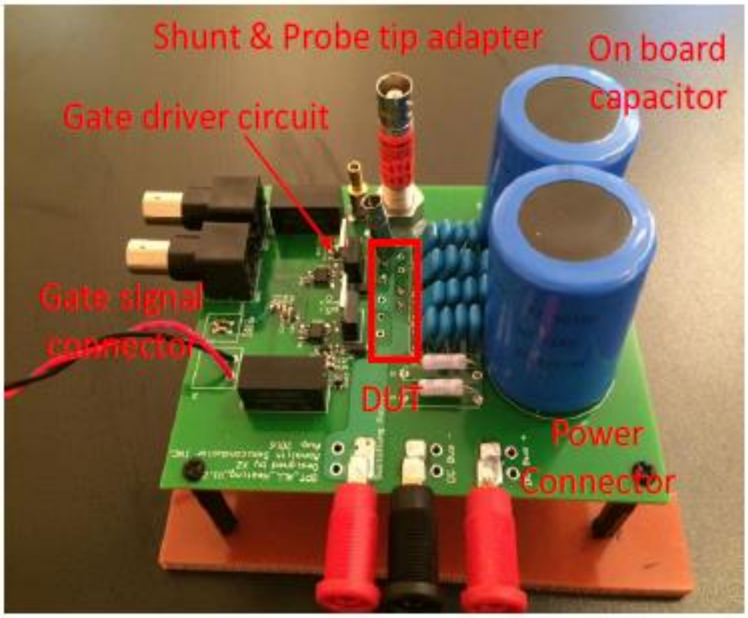


Fig. 3. Pulse test and dynamic characterization board.

The dynamic characterization board employs high-bandwidth, high-voltage passive probes and a co-axial current shunt to ensure accurate measurements for the bottom device position. For switching loss measurements, the bottom device switches with the top device freewheeling. The current and voltage characteristics for the bottom device were measured in order to calculate the switching losses. For device charge measurements, the top device switches with the bottom device freewheeling, then the current and voltage across the freewheeling bottom device were measured to calculate the charge.

Both voltage and current were measured with passive probes; all the probes were referred to the measuring ground as shown in Fig. 2. The test system's oscilloscope was not isolated; therefore, it was grounded to the system's measurement ground point. If the tester board's negative dc bus had been connected to dc power supply ground, circulating current in the system would have introduced errors to the current measurement. To reduce these errors, a dc link energy storage capacitor bank was incorporated into the system as shown in Fig. 4.

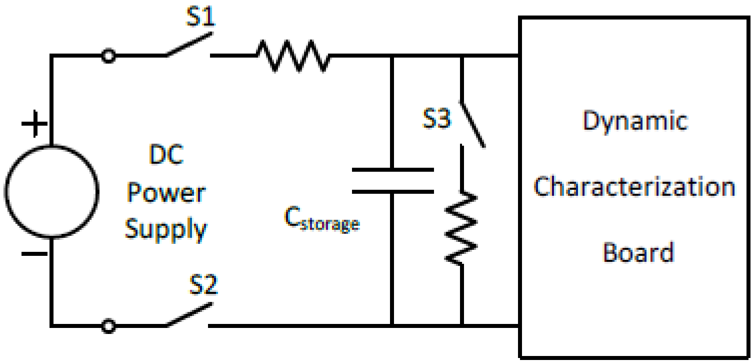


Fig. 4. Floating measurement circuit with dc link cap.

During the measurement, the dc link energy storage capacitor bank was charged to the required voltage and mechanically disconnected from the dc power supply to isolate the testing board; a single ground point was connected through the oscilloscope to eliminate errors introduced by circulating current through multiple grounding points.

Given that the output capacitance of SiC MOSFETs and SBDs is very low compared to silicon devices, a load inductor was designed with a single-layer winding to reduce the equivalent parallel capacitance (EPC) of the load inductor. In order to characterize the switching behavior of the devices under high temperature, the device was heated with a hot-air gun.

The full test setup (Fig. 5) included the capability to heat all the devices for loss and charge characterization at high temperatures. A double-pulse test signal was used to control the test conditions. The devices under test (DUTs) were a Littelfuse LSIC1MO120E0080 1200-V, 80-mΩ SiC MOSFET and a Littelfuse LSIC2SD120A10 1200-V, 10-A SiC diode (Fig. 6). All three freewheeling device combinations shown in Fig. 1 were characterized under these test conditions:

- Switching voltage: 600 V
- Switching current: 5 A to 40 A
- Driving voltage +20 V/-5 V
- External gate resistance: 5 Ω
- Testing temperatures: 25°C/100°C.

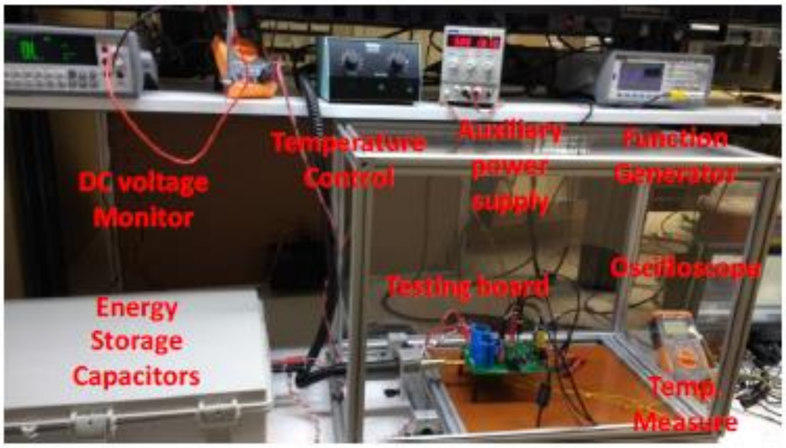


Fig. 5. Test setup.

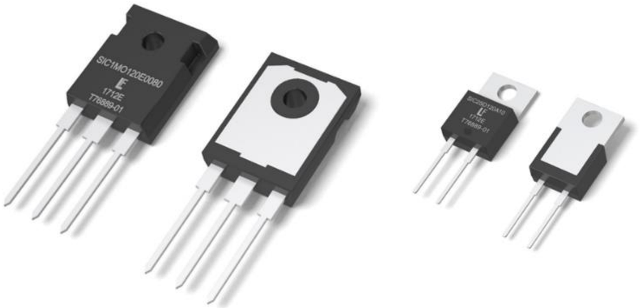


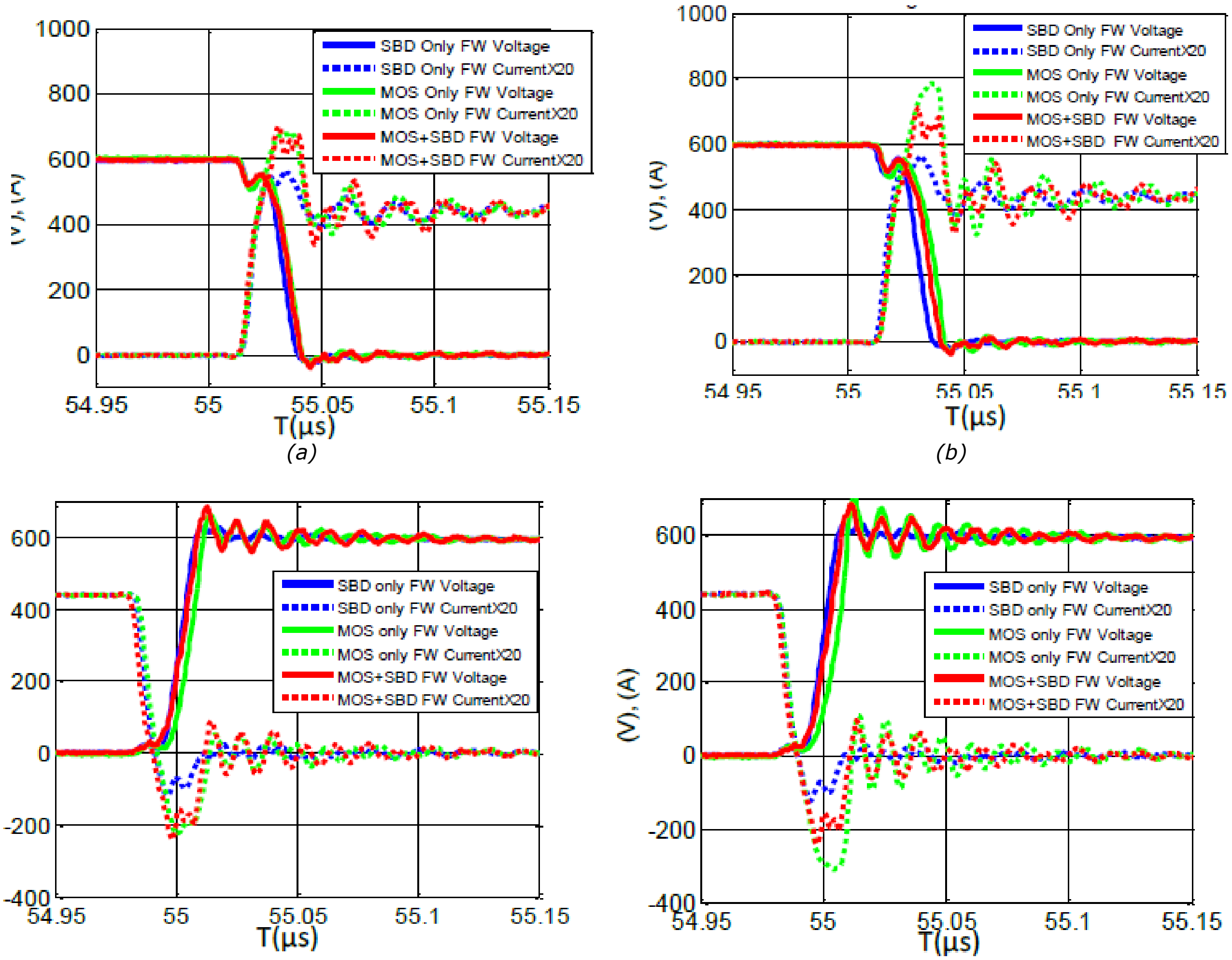
Fig. 6. The devices characterized were a Littelfuse LSIC1MO120E0080 series 1200-V, 80 mΩ, n-channel SiC MOSFET (left) and a Littelfuse LSIC2SD120A10 1200-V, 10-A SiC Schottky diode (right).

Switching Waveform Comparison

Fig. 7 shows the measured voltage and current across the switching device and the freewheeling device separately with different test temperatures and different freewheeling device implementations. It is clear that voltage transition waveforms are similar with different freewheeling diode implementations where the voltage rise time is within 10 ns, which demonstrates the high switching speed of SiC devices.

Ringing frequency was slightly different due to different parasitic inductances introduced by different freewheeling device implementations. However, the current transition waveforms were very different. The fast switching speeds of SiC MOSFETs cause current overshoot on the switching device during switching device turn-on due to the capacitive charge of the freewheeling diode.

At 25°C (Fig. 7, parts a and c), using the SBD only as the freewheeling device induced the smallest current overshoot. Using the body diode of the SiC MOSFET only and using the body diode of the SiC MOSFET with an additional anti-parallel SiC SBD each produced similar current overshoot. Overshoot for both of those configurations was larger than using only the SiC SBD.



(a) *(b)* *(c)* *(d)*

Fig 7. Measuring voltages and currents of switching and freewheeling devices. Voltages (solid lines) and currents (dashed lines) across switching device at 25°C (a), across switching device at 100°C (b), across free-wheeling device at 25°C (c) and across freewheeling device at 100°C (d).

When the temperature was increased to 100°C (Fig. 7 parts b and d), using only the MOSFET's body diode as a freewheeling device produced a significant increase in turn-on current overshoot. The current overshoot was temperature independent when an SBD or a MOSFET+SBD combination was used as the freewheeling device. Therefore, at 100°C, using the SiC SBD only as the freewheeling device still produced the smallest current overshoot; in contrast, using the body diode of the SiC MOSFET had the largest current overshoot.

These results verified that SiC SBDs only have capacitive charge; therefore, the current overshoot is independent of temperature. The body diode of the SiC MOSFET showed reverse-recovery phenomenon, given that the current overshoot—because it is a function of total charge [capacitive charge + reverse recovery charge]—increased with the temperature increase.

Comparison Of Switching Energy And Total Charge

Fig. 8 shows the voltage and current across the switching device for switching loss calculation. With careful deskew between voltage and current probes, the measured data was processed to remove dc components induced by the probe offset. With the processed data, the turn-on energy was calculated using equation (1).

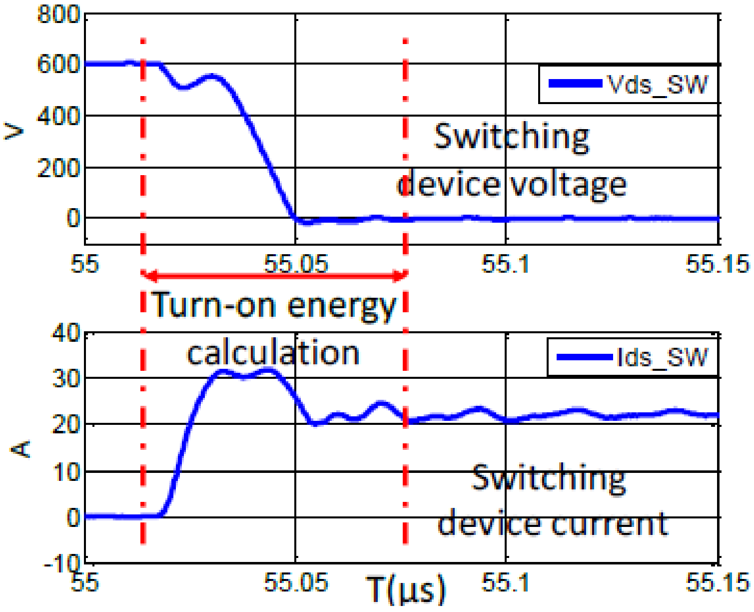


Fig. 8. Voltage and current across switching device for calculating turn-on loss.

$$E_{ON} = \int I(t) \times V(t)\, dt \tag{1}$$

The charge of the freewheeling device was calculated from the voltage and current across the freewheeling device as shown in Fig. 9.

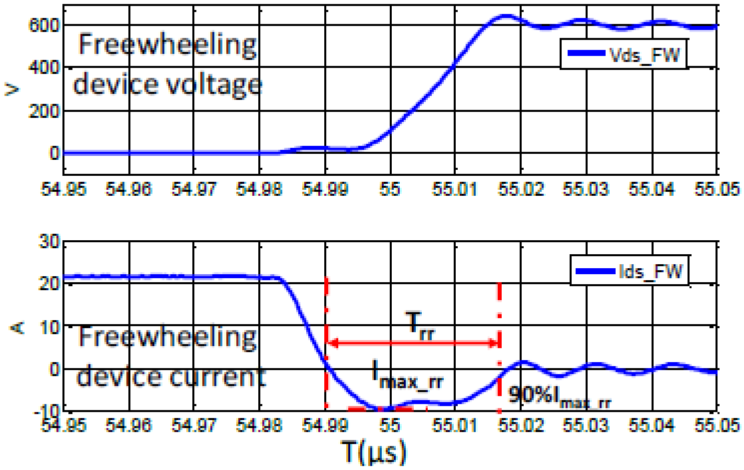


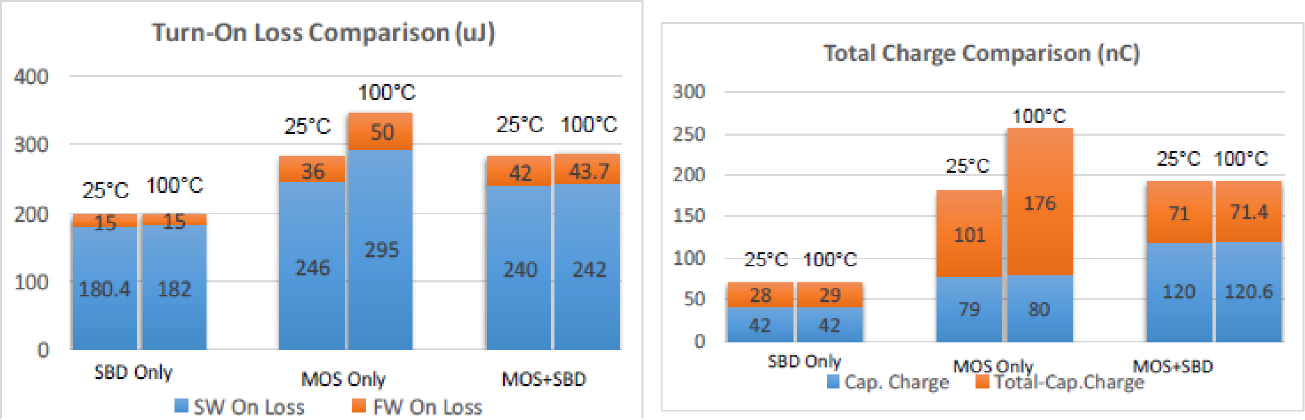
Fig. 9. Voltage and current across freewheeling device for device charge calculation.

The total charge (including capacitive charge, reverse-recovery charge and other possible charge) was calculated by the integration of the current through the freewheeling device during the switching period.

Fig. 10a shows the comparison of turn-on loss for switching and freewheeling devices under various test conditions. The results indicate that using a SBD alone as the freewheeling device has the smallest turn-on loss because it has the smallest total charge as shown in Fig. 10b. Additionally; this figure presents a “capacitive charge” characteristic, which is independent of temperature; therefore, the turn-on loss is also independent of temperature.

Using only the MOSFET body diode will increase turn-on loss due to the larger total charge. Moreover, the turn-on loss increases by more than 20% when comparing 100°C operating characteristics to 25°C operating characteristics. The total charge comparison also shows a significant increase at 100°C, which verifies the temperature dependency of the reverse-recovery charge phenomenon associated with the body diode. The reverse-recovery charge has an exponential relationship with temperature, which makes the turn-on loss even higher (more than 50%) at 150°C.

Adding an anti-parallel SBD to the MOSFET can reduce the high-temperature switching loss significantly. It may, however, increase the low-temperature turn-on loss a little due to the increase of total output capacitance. The addition of an anti-parallel SBD effectively eliminates the reverse-recovery charge associated with the SiC MOSFET body though, causing the freewheeling device then to exhibit temperature-independent total charge characteristics.



(a) *(b)*

Fig. 10. Turn-on loss comparisons (a) and the corresponding device charge comparisons (b) with different freewheeling device implementations. In the turn-on loss comparisons, the blue shading represents switching (SW) loss during SW device turn-on while the orange shading represents freewheeling (FW) loss during SW device turn-on. In the device charge comparisons, the blue shading is the capacitive charge calculated from device voltage while the orange shading is the total charge calculated from device current.

Choosing A Freewheeling Diode To Minimize Loss

In the loss and charge measurement, as shown in Fig. 10, an 80-mΩ SiC MOSFET (rated at 28 A at T_C = 100°C) is paired with a 10-A rated SiC SBD. With a 10-A SiC SBD only as the freewheeling diode, the switching energy during switching device turn-on is the lowest; however, the on-state voltage drop on the SiC SBD is relatively high. This results in relatively high conduction loss on SBDs compared with SiC MOSFETs. For applications with low duty cycles, the free-wheeling diode conducts most of the time, so system conduction losses will be high.

Using a half-bridge configuration and synchronous rectification can reduce conduction loss effectively. However, the test showed that the body diode of a SiC MOSFET is subject to total charge characteristics strongly influenced by di/dt, current level, and temperature. Adding an anti-parallel SiC SBD can reduce switching loss effectively, especially when the junction temperature is high. However, the rating of the anti-parallel diode needs to be optimized to minimize switching loss because capacitive charge—which contributes to the free-wheeling device total charge—and the IV characteristics—which relate to conduction losses—are correlated to device current rating.

The results shown in Fig. 11 indicate that using a diode with a higher current rating increases the current overshoot during switching. In this case, turn-on loss increased by 15% when a 20-A diode was used. Therefore, a lower current anti-parallel diode is preferred. However, the anti-parallel diode must be large enough to ensure that a majority of the current conducts through the anti-parallel SBD rather than the SiC MOSFET's body diode.

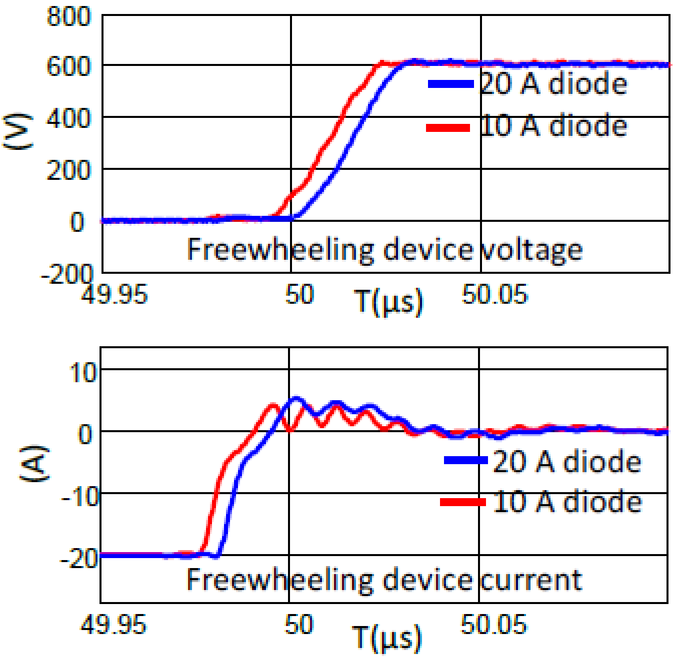


Fig. 11. Voltage and current across freewheeling device when using 10-A and 20-A rated anti-parallel diodes.

The recommended current rating can be derived by comparing the forward characteristics of the SiC SBD with the SiC MOSFET body diode, as shown in Fig. 12. If a 5-A diode is used as the anti-parallel diode when current is higher than 8 A, the voltage drop on the body diode will be lower than the voltage drop on the anti-parallel diode; in this case, adding an anti-parallel diode will not effectively reduce reverse-recovery loss during switching on because current will still flow through the MOSFET body diode.

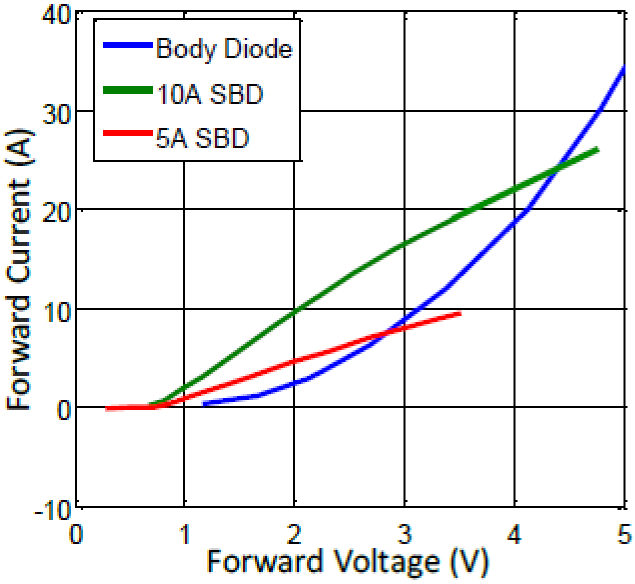


Fig. 12. Forward characteristic comparison between SiC SBD and SiC MOSFET body diode.

With a 10-A rated diode as the anti-parallel diode, the current limit increases to 24 A. For a 28-A rated MOSFET, this is a reasonable value, therefore, a 10-A anti-parallel diode should be selected for a 28-A SiC MOSFET. It should be noted that the current only flows through the anti-parallel diode during the turn-on transient and during the deadtime period. The current sharing will also depend on the parasitic inductance in the packaging of SiC MOSFET and anti-parallel diode and power loop layout design.

The static forward characteristic comparison only provides a guideline for selecting a proper anti-parallel diode based on current rating. After the deadtime, the SiC MOSFET will be turned on to conduct reverse current; therefore, the loss associated with the anti-parallel diode should be minimal. As a result, thermal management for the anti-parallel diode is usually not critical.

Summary

As these results show, using only an SBD as the freewheeling device produces the smallest current overshoot, but this implementation is subject to high conduction loss. The SiC MOSFET body-diode implementation is subject to reverse-recovery charge (even though the reverse-recovery behavior is less pronounced than in silicon devices) with switching losses that are dependent on working conditions.

Adding an anti-parallel SBD to the MOSFET offers the opportunity to reduce the dependency of switching losses on working conditions and improves system efficiency. However, this implementation will increase system cost and the device footprint. Moreover, the anti-parallel diode must be large enough to ensure that it conducts a majority of the current rather than the body diode of the SiC MOSFET.

About the Authors

In July 2016, Xuning Zhang joined Monolith Semiconductor as a principal application engineer, focusing on application of SiC devices. His research interests include high efficiency, high power density converter design, system EMI modeling and filter optimization, interleaving and multilevel converters, SiC device characterization and driving scheme optimization, high frequency system integration, and passive component design and optimization. Previously, Xuning served as a research scientist at CPES for two years, with research focusing on high efficiency high power density converter design and optimization with wide bandgap devices.

Xuning has authored and co-authored more than 40 papers for journals and leading international conferences. He has also presented several tutorial seminars during international conferences including APEC and ITEC-AP. Xuning received his bachelor's and master's degrees in electrical engineering from Tsinghua University, Beijing, China, and his PhD degree from CPES-Virginia Tech. He may be reached at xzhang@monolithsemi.com.

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For more information on designing with SiC MOSFETs and diodes, see How2Power's Design Guide, locate the Popular Topics category and select "Silicon Carbide and Gallium Nitride."