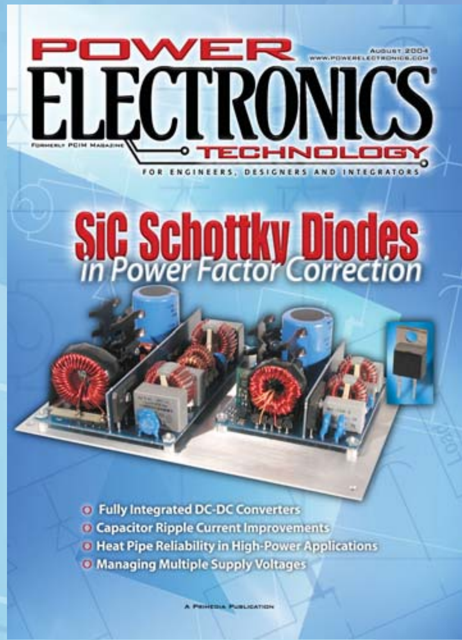
SiC Schottky Diodes in Power Factor Correction



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Efficiency gains resulting from the use of high-voltage SiC rectifiers in PFC boost converters can be used to increase power output, increase switching frequency for a smaller design or improve reliability. At the same time, SiC Schottkys can reduce EMI.

Active Power Factor Correction (PFC) is widely used in today's power supplies. Government regulations and customer requirements must be satisfied when designing these circuits. Increasingly, efficiency and power density are dominating the design tasks for a typical ac-dc converter. Designers also are being challenged to speed the design process and eliminate risk.

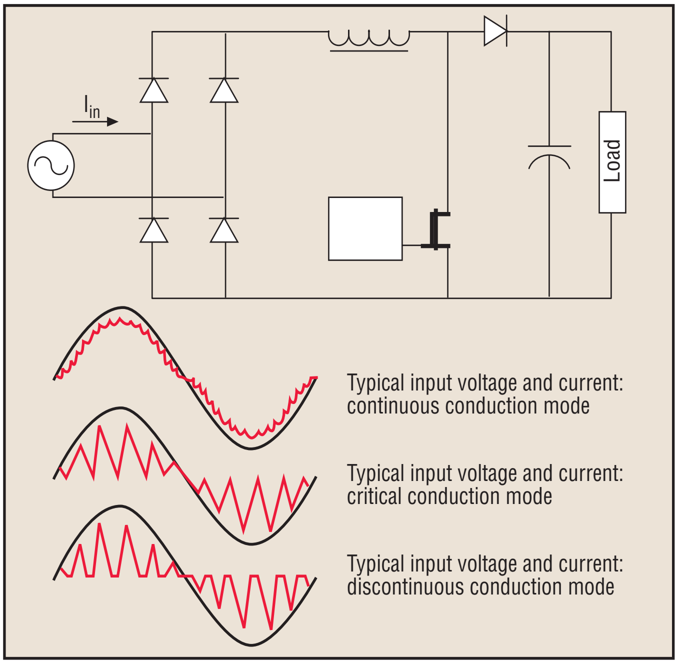

Fig. 1. *Comparison of conduction modes for a boost converter.*

As advances occur within the semiconductor market, it isn't always clear what the expected advantage is or how it will benefit a specific application. Often, the designer must change the design to fully realize the benefit of next-generation silicon. Engineers want less work, not more.

In recent years, work has been done to create power semiconductors based on a new and enabling semiconductor material. Silicon Carbide Schottky barrier diodes (SiC SBD) are the first of what undoubtedly will be many new power devices based on this unique material.

PFC Background

At power levels above approximately 200 W, most active PFC designs are continuous conduction mode (CCM) boost converters. It should be apparent that critical and discontinuous conduction mode converters suffer from large peak-to-peak current levels because the inductor current swings to zero each switching cycle. **Fig. 1** shows the three main conduction modes for a boost converter. The CCM not only limits peak current stress, but also will be easier to filter.

Along with the benefits of using CCM, certain drawbacks exist, the most notable being the losses and EMI generation associated with the turn-off of the boost diode.

Fig. 2 shows the typical MOSFET and diode currents for a CCM boost converter using an ultrafast high-voltage silicon rectifier. Note that the reverse recovery current of the diode shows up in the MOSFET drain current. This current will cause significant power dissipation in the MOSFET, along with increased EMI.

Obviously, areas exist where improvements in efficiency can be made. Consider a PFC circuit delivering 400 W while operating with 90-Vac input and 400-V output. The average output current will be 1 A, the average input current will be 4.94 A, and thus the average shunt current will be 3.94 A. This would lead to the conclusion that either the input or shunt path would be the best place to improve efficiency. What may

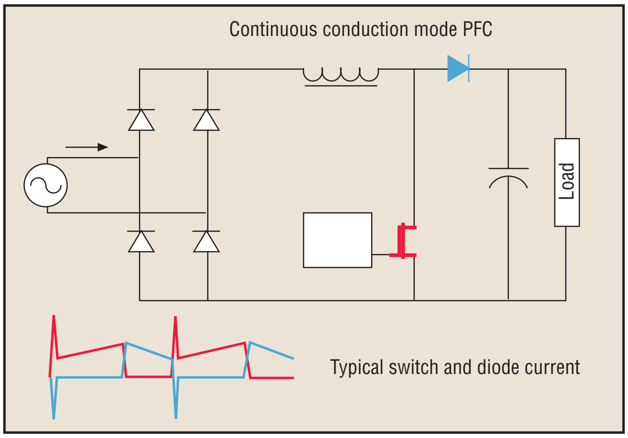

Fig. 2. *Typical MOSFET and diode current waveforms.*

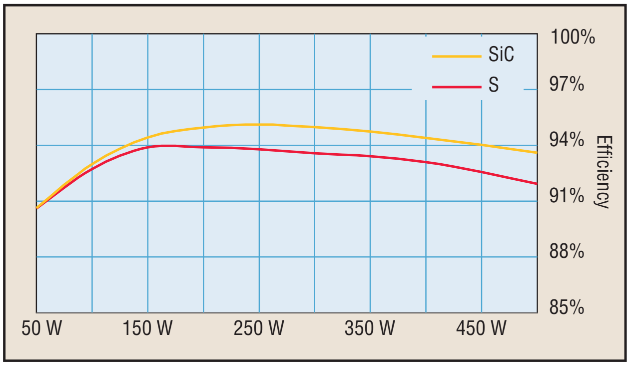

Fig. 3. *Low-line (90 Vac) efficiency comparisons for an 80-kHz, 500-W PFC front-end converter built with ultrafast Si rectifiers or Cree's*

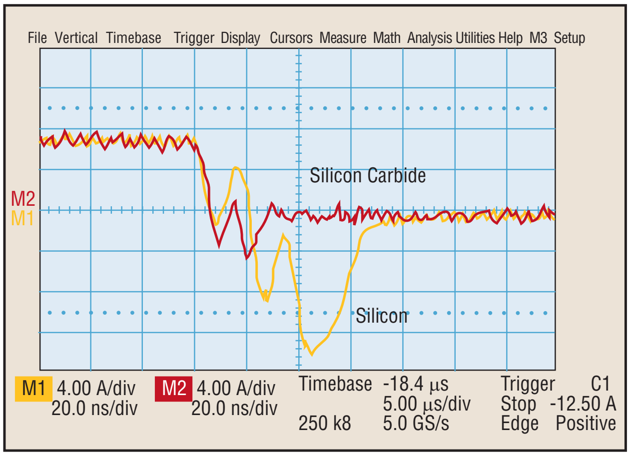

Fig. 4. *Low-line diode recovery currents in PFC front-end converter.*

not be clear is that shunt path improvements can come from changing the output diode.

Referring again to **Fig. 2**, we see that the recovery current from a standard ultrafast silicon diode produces a large current spike that must be dissipated in the shunt device. This current spike can be larger than the forward current in the diode. Also, this reverse current, like the MOSFET on-state resistance, increases with temperature, which can lead to thermal runaway conditions.

Cree Inc. has developed a line of high-voltage SiC SBDs available in current ratings from 1 A to 20 A at 600 V, 10 A to 20 A at 300 V, and 5 A to 20 A at 1200 V. The 600-V product line is well suited for PFC front-end designs.

SiC belongs to the wide bandgap group of semiconductor materials. This characteristic makes it ideal for creating high-voltage SBDs. In addition, much of the performance advantage of the silicon carbide versus silicon is enhanced at higher temperatures.

It's All About Efficiency

The key benefit of using SiC Schottky diodes is the lack of recovery currents. SiC SBDs have only a small stored capacitive charge. This lack of recovery current produces waveforms that have clean edges, reduced ringing and predictable losses. Often, snubbers used to limit reverse recovery currents and reduce EMI generation can be eliminated.

Efficiency is only one goal that challenges a power supply designer. Cost, weight, size and electrical performance are also foremost on the designer's mind. An efficient design can help meet these goals. Furthermore, a more-efficient design reduces heatsink requirements, which can lead to size, weight and cost savings.

Efficiency gains alternatively can be used to allow the delivery of higher power from the same design. Efficiency improvements also may allow the design of a cooler running power system. Cooler operation leads to improvements in system reliability. As you can see, it really is all about the efficiency.

To demonstrate possible gains, a 500-W PFC front-end was designed and tested. Performance was measured using ultrafast silicon rectifiers and Cree's SiC Schottky rectifiers. Although efficiency improvements are often a major design goal, this improvement could be used to enhance performance in other areas. Most notably, an increase in switching frequency can be obtained by trading some or all of the efficiency gain. Increasing the switching frequency will result in a smaller and lighter power supply. To evaluate this possibility, a second converter running at a higher frequency was designed and tested.

Input Voltage	90 Vac to 270 Vac
Output Power	500 W
Output Voltage	390 V

Table 1. *Converter ratings.*

Table 1 shows the basic ratings of the converters that were designed and tested. This PFC converter design would be typical of front-end power supplies designed for the server market.

Fig. 3 shows the measured efficiencies for an 80-kHz PFC converter at low-line input. The converter was designed to operate in CCM with a peak ripple current of 15% at low line. The graph shows the improvements that the SiC diode made. The improvements in efficiency are greatest at the higher loading, with an efficiency increase of 2%. This is a direct result of the reduction in recovery currents that are highest in the silicon diode at the highest loads. In comparison, the SiC diode charge recovery is independent of forward current.

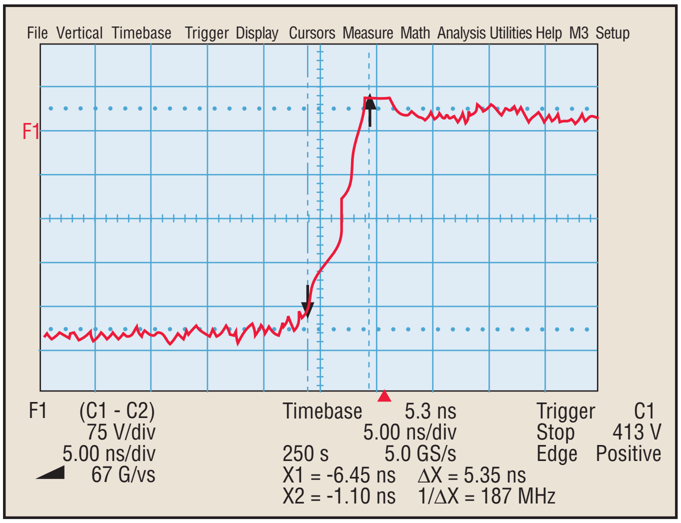

Fig. 5. *SiC Schottky turn-off slope in PFC front-end converter.*

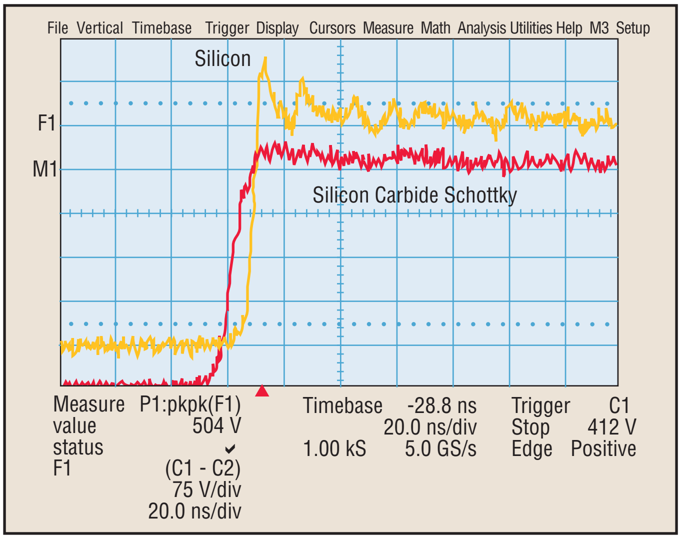

Fig. 6. *SiC vs. Si turn-off noise in PFC front-end converter.*

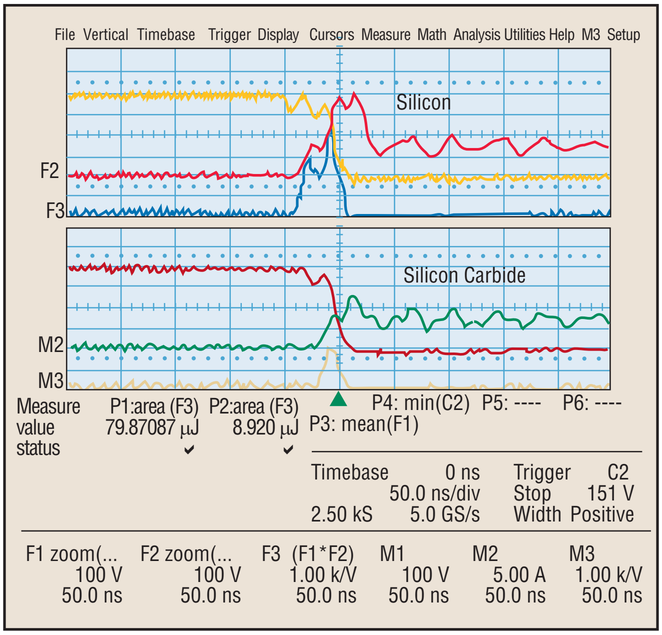

Fig. 7. *MOSFET turn-on loss in PFC front-end converter.*

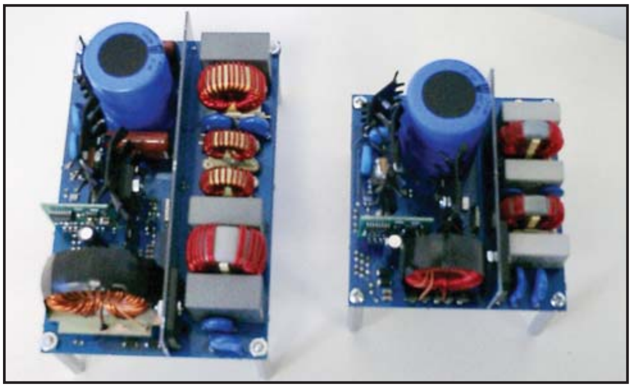

Fig. 8. *A size comparison of an 80-kHz PFC front-end built with Si rectifiers (left) and a 200-kHz PFC front-end with SiC rectifiers.*

Fig. 4 shows a comparison of reverse recovery currents. Note the small reverse current in the SiC SBD waveform. This small reverse current is the junction charging current from the junction capacitance. Of special note, this current is totally temperature independent.

The reverse recovery current in the silicon diode, like the on-state resistance in the MOSFET, will rise even further with increased temperature. These increases will cause switching losses to increase and possibly create a thermal runaway situation. Also note the di/dt of the diode current is approximately 1500 A/µs. The SiC Schottky recovery is independent of di/dt.

A paper has been written that questioned the dV/dt capability of SiC Schottky rectifiers.[4] The paper found that failure would occur under single pulse test conditions above 55 V/ns. On the contrary, **Fig. 5** shows the actual diode operation of Cree's *ZERO RECOVERY*™ rectifier in this converter with a voltage slope of 67 V/nS. This power supply has logged many hours of operation without issue.

Fig. 6 shows the turn-off edge for a SiC Schottky diode and an ultrafast silicon diode. The waveform offset and trigger point are skewed for clarity. You can see the advantage of zero recovery. The lack of recovery current in the SiC diode generates substantially less noise, which will lead to less EMI generation.

Fig. 7 shows the energy dissipation in the MOSFET switch caused by the recovery current in the boost diode. The silicon diode loss was 79.9 µJ, which translates to 6.4 W at 80 kHz and 16 W at 200 kHz. Compare that to SiC at 8.9 µJ or 0.7 W at 80 kHz and 1.75 W at 200 kHz. That's almost a 90% reduction in turn-on loss.

High-Frequency Operation

As stated earlier, improved efficiency could be used to create a power system with a higher switching frequency. The basic design goals were kept the same as the original silicon-based design, and the overall switching frequency was raised to the point where efficiency matched the original silicon design. The increase in switching frequency facilitates a reduction in the boost inductor size, as well as other switching-frequency reactive components.

What may be a surprise is the ability to reduce the size of the input EMI filter. Most EMI filter designs for low-frequency PFC circuits require additional differential mode inductance to create attenuation below the switching frequency. In contrast, higher-frequency designs can often rely on the leakage inductance of common-mode inductors to create low-pass filtering far below the operational frequency.

The design goal of increasing the switching frequency until the original efficiency was reached required somewhat of a trial-and-error process. As the frequency is increased, the boost inductor design must be modified and high-frequency filtering components changed. These, in turn, affect efficiency. The goal was achieved when the new converter efficiency was "close" to the original design.

Fig. 8 is a photograph of the final designs for the two PFC converters. As you can see, a major reduction in size was achieved. **Table 2** lists some basic comparative features between the low-frequency and high-frequency design. The high-frequency design is not only smaller, but also weighs 44% less than the low-frequency design.

The goal of this work was to design a PFC front-end that would use the efficiency gains from implementing a SiC Schottky diode to increase the switching frequency. **Fig. 9** shows the efficiency for an 80-kHz design using a silicon ultrafast diode and for a 200-kHz design using a SiC boost diode.

The efficiency curves shown in **Fig. 9** match closely, although the silicon diode is more efficient at light load and the SiC Schottky has a slight advantage in the medium to high loads.

	80 kHz	200 kHz	Delta
PCB	23.9 in^2 154.1 cm^2	14.8 in^2 95.5 cm^2	-38%
Volume	47.8 in^3 782.8 cm^3	29.6 in^3 485.1 cm^3	-38%
Weight	18.4 oz 521.6 gm	10.4 oz 294.8 gm	-44%
Density	10.5 W/in^3 0.64 W/cm^3	16.9 W/in^3 1.03 W/cm^3	+61%

Table 2. *Low-frequency Si vs. high-frequency SiC.*

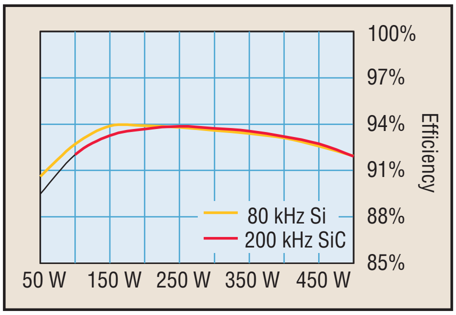

Fig. 9. *Efficiency of PFC front-end built using low-frequency Si-based design vs. high-frequency SiC-based design.*

Today, high-frequency operation of dc-dc converters is becoming commonplace. With the material advantages of SiC, PFC designs now can reap some of the benefits of higher frequency operation. With careful electrical design and PCB layout, reliable operation at high frequency is not only reasonable, but also improves overall system performance.

The ability to operate the front-end PFC converter and the downstream dc-dc converter at high frequency creates the opportunity for synchronous operation. Synchronous operation with leading-edge/trailing-edge modulation techniques can reduce EMI and the ripple current in the high-voltage bulk capacitor.

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4. *Acharya, K. and Shenai, K. "On the dV/dt Rating of SiC Schottky Power Rectifiers," Proceedings Power Electronics Technology Conference, October 2002, pp. 672-677.* **PETech**