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PFC Efficiency Improvement Using SiC Power Schottky Rectifiers

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Almost all electronic applications need a power supply to convert the 90- to 130-V ac or 220- to 240-V ac mains voltage to dc voltage for powering integrated circuits and other devices within the applications. Today, the most popular kind of power supply is the switch-mode power supply (SMPS), which enables both high output-power levels and low standby losses.

With the recent introduction of new energy-saving regulations, power-supply designers are now confronted with stringent requirements for power efficiency. These requirements are forcing designers to consider the use of new power converter topologies and more-efficient electronic components such as high-voltage silicon-carbide (SiC) Schottky rectifiers.

Use of SiC Schottky rectifiers in place of comparable silicon rectifiers can improve the efficiency of the active power-factor correction (PFC) circuitry that's found in many SMPS designs. But to maximize the effectiveness of SiC Schottkys, power supply designers should understand the underlying technology and the key device parameters that must be considered when designing SiC Schottky diodes into an SMPS.

Market Forces

Increased environmental awareness has led governments to review their energy-saving requirements. In 1992, the Environmental Protection Agency (EPA) introduced the well known Energy Star program, which rewards companies whose products comply with the EPA's strict environmental requirements. Having the Energy Star label on a product label attests to that product's high level of energy efficiency, making the product more attractive to consumers. More recently, in 2004, a new program called 80 Plus was launched (Fig. 1).

Fig. 1 These labels appear on products that are certified to meet the Energy Star and 80 Plus energy-efficiency standards.

The 80 Plus program consists of an ambitious power-efficiency standard for desktop computers and servers and is divided into 4 categories called '80+', 'Bronze', 'Silver' and 'Gold' (see Table 1). In 2007, the Energy Star 4 program included the 80 Plus standard in its specification.

Parameter	Load	80+	Bronze	Silver	Gold
Efficiency	20%	80%	82%	85%	87%
	50%	80%	85%	88%	90%
	100%	80%	82%	85%	87%
Power factor	50%	0.9	0.9		

Table 1. The 80 Plus specification.

In July 2009, the upgraded Energy Star 5 specification was officially adopted by the European Commission and the American government. It requires desktop computer, laptop computer or server power supplies to comply with the Bronze level of the 80 Plus standard. Most power supply manufacturers are now asked to comply with that standard by their end-customers.

To achieve this level of performance, SMPS designers need to consider the efficiency improvements they can achieve using high-voltage SiC Schottky rectifiers. Switching from silicon rectifiers to SiC rectifiers may not (by itself) be sufficient to bring a particular power supply design into compliance with the 80 Plus requirements. However, the use of SiC Schottkys in combination with other design improvements can enable SMPSs designs to meet the efficiency goals.

Silicon-Carbide Technology

Silicon-carbide is a chemical compound of silicon and carbon. Its presence in nature is extremely rare. It was discovered in the 19th century and the first wide-scale production was achieved by Edward Goodrich Acheson in

1893. Silicon-carbide particles can be bonded together to form very hard structures (see Fig. 2), used in different applications such as automotive brakes or bullet-proof vests. The material's singular electrical properties also led researchers to study its use in electronic applications in the beginning of the 20th century.

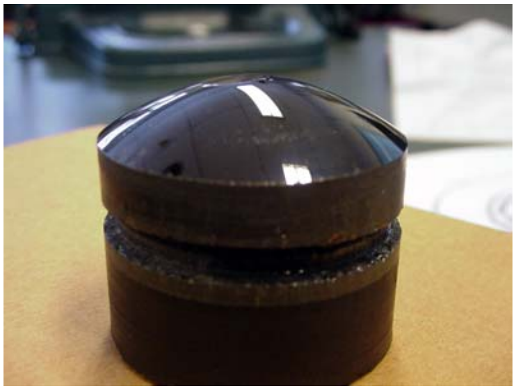

Fig. 2. Silicon-carbide ingot used for electronic component manufacturing.

One of the most remarkable properties of SiC is the fact that it is a wide-bandgap material, meaning that the amount of energy required to transfer an electron inside an atom from the valence-band to the conduction-band is very large compared to other common materials such as silicon (see Table 2).

Properties at 300 K, 1e15 – 1e16 cm^{-3} / Material	E_G (eV)	E_{BR} (V/µm)	Thermal conductivity (W/cm/K)	μ_N (cm²/V/s)
Si	1.12	20	1.5	1350
4H-SiC	3.26	200	4.5	800
Diamond	3.45	560	20	1900

Table 2. Key electrical properties of 4H-SiC compared to standard silicon and diamond.

Schottky-barrier rectifier diodes present the advantage of low forward losses and negligible switching losses compared to other technologies such as bipolar-structured rectifiers. However, the narrow bandgap (E_G) of standard silicon results in a low critical electrical field (E_{BR}), which limits its use in Schottky-barrier rectifier diodes to a maximum voltage of around 200 V (Fig. 3).

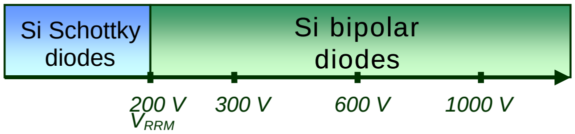

Fig. 3. Technological limit of the Schottky structure using standard silicon material.

Indeed, higher-voltage Schottky-structured Si-diodes (> 200 V) would require increasing the thickness and resistivity of the material leading to an increase of the dynamic resistance and the leakage current of the device, hence degraded performances (Fig. 4).

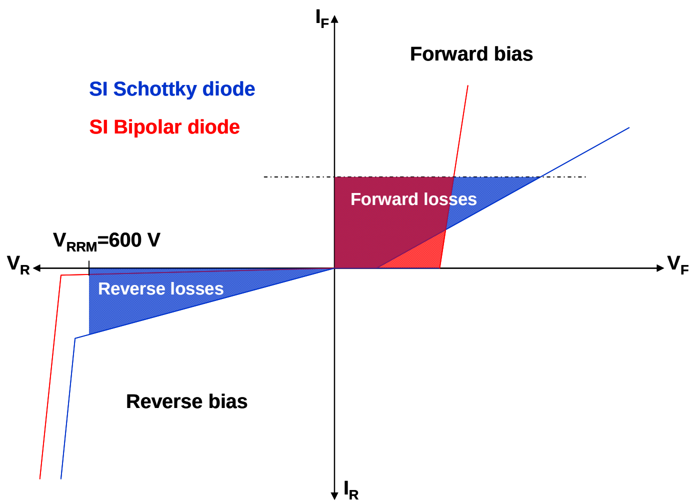

Fig. 4. Impact of the low critical electrical field of silicon on Schottky diode performance.

High-voltage rectifiers are generally used inside PFC circuits in switch-mode power supplies. In more and more cases, standard bipolar diodes no longer fulfill the stringent efficiency requirements.

The wide bandgap and high critical electrical field level of silicon-carbide led researchers to study its use in high-voltage rectifiers to improve their efficiency by designing Schottky-structured diodes.

Key Improvements With SiC Diodes In PFC circuits

Using SiC Power Schottky diodes in PFC circuits working in continuous mode allows a reduction in the recovery current of the boost diode compared to bipolar diodes (see Fig. 5). As a result, the turn-on power-losses inside the PFC MOSFET are reduced as can be seen in Figs. 6 through 10.

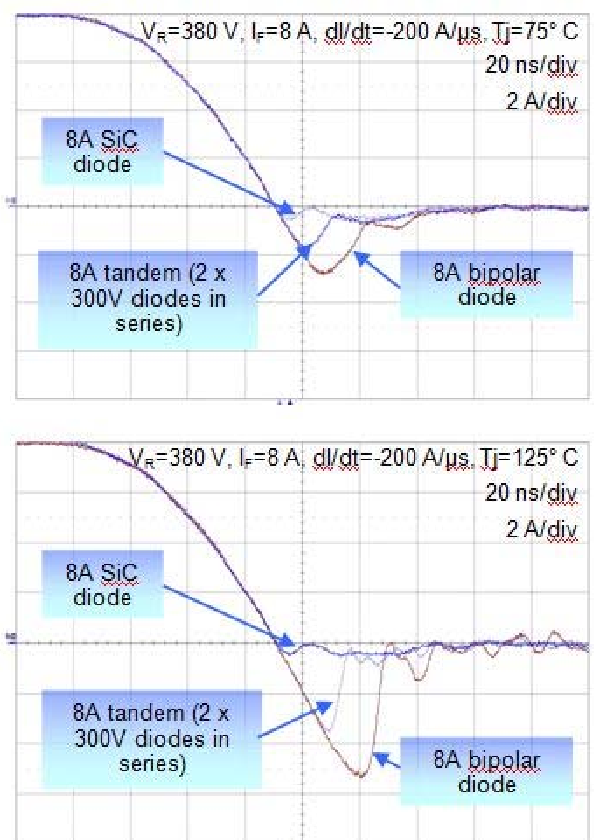

Fig. 5. Turn-off comparison between Si and SiC diodes for T_J=75°C and T_J=125°C.

One of the key benefits of SiC diodes is the fact that the turn-off characteristic remains almost constant when the temperature increases due to the capacitive nature of the recovery current. In contrast, the turn-off behavior of the bipolar diodes is characterized by an increase in the reverse recovery charge when the junction temperature increases.

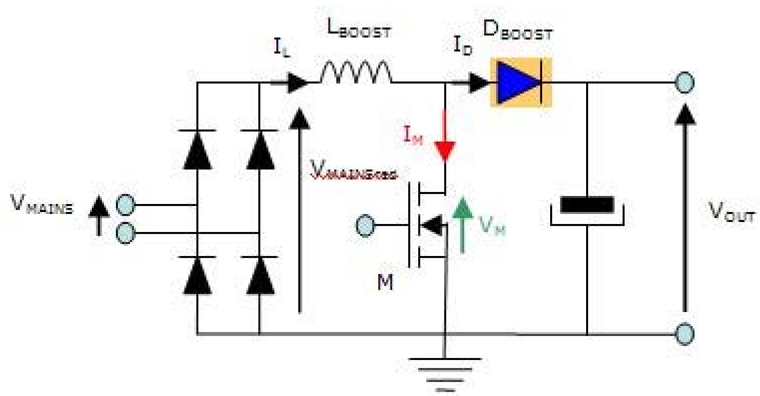

Fig. 6. Typical PFC circuit used in most switch-mode power supplies.

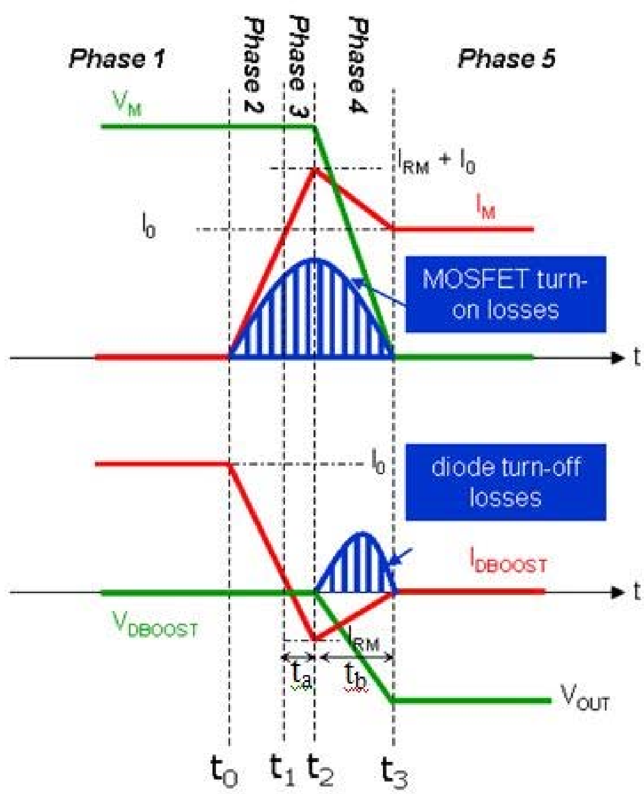

Fig. 7. Theoretical waveform of turn-on losses in the transistor ($E_{ON(M)}$) and turn-off losses in the diode due to the recovery current (I_{RM}).

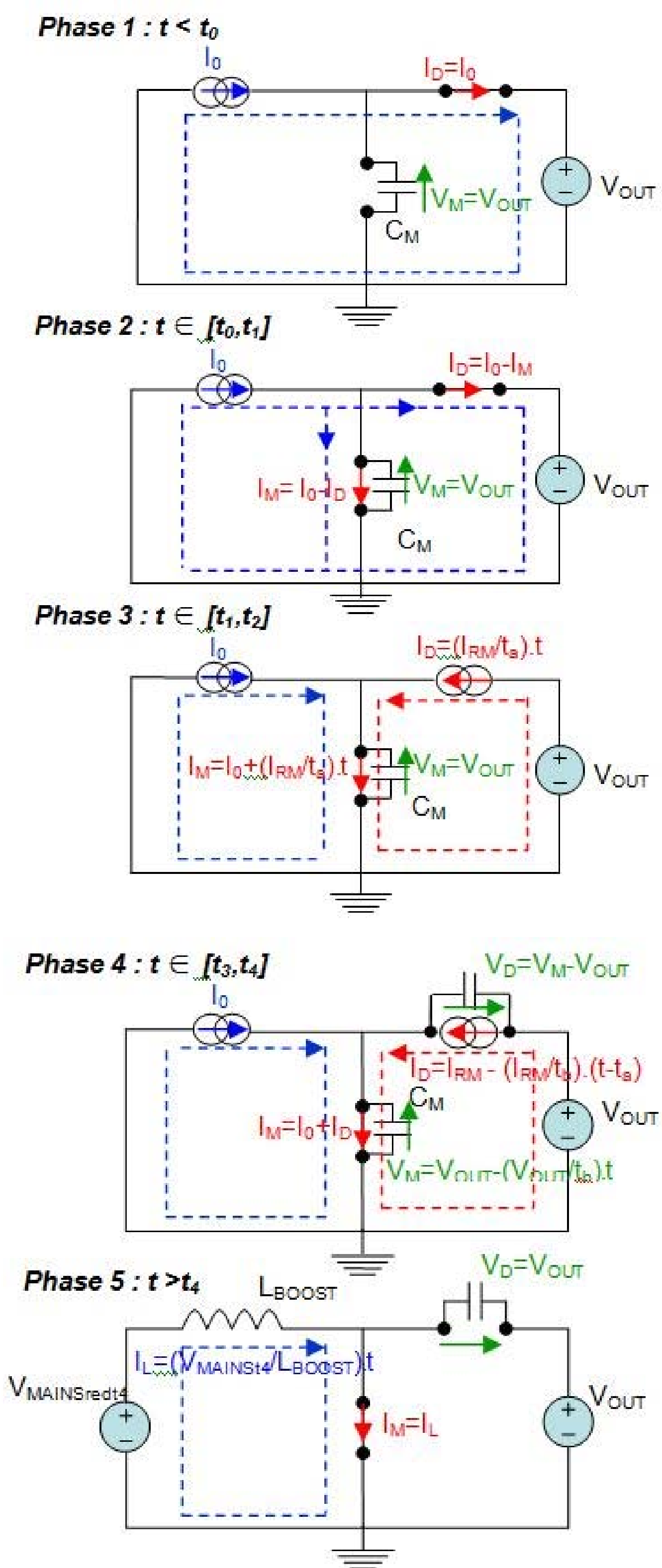

Fig. 8. Equivalent circuits for the turn-on phase of the transistor and turn-off phase of the diode with I_{RM} current in PFC circuit.

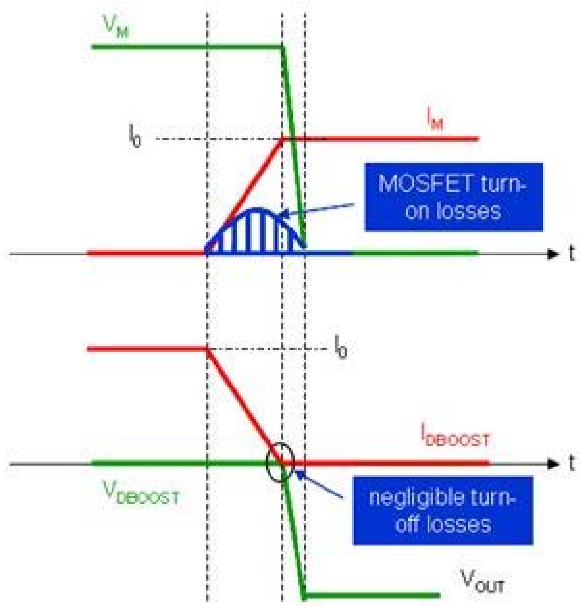

Fig. 9. Ideal waveform with SiC power Schottky rectifiers thanks to no I_{RM}.

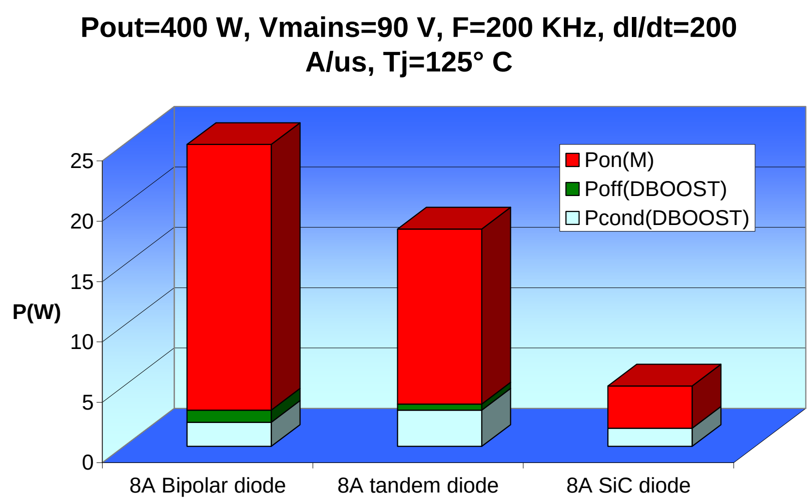

Fig. 10. Example power-loss comparisons for standard bipolar diodes, tandem diodes and SiC diodes.

Looking at Figure 10, the predominant power loss in the PFC is due to the turn-on of the MOSFET (Pon(M)). In this example, the use of the SiC diode allows a gain of about 4% efficiency compared to the standard bipolar Si diode.

Switching speed (dI/dt) is a key parameter for optimizing efficiency. Looking at Fig. 11, when using standard Si diodes, the turn-on power-losses of the MOSFET feature an optimized area corresponding to a certain switching speed. When using Si diodes, the dI/dt must be set taking into account the creation of electromagnetic interference (EMI). This sometimes forces designers to limit the switching speed.

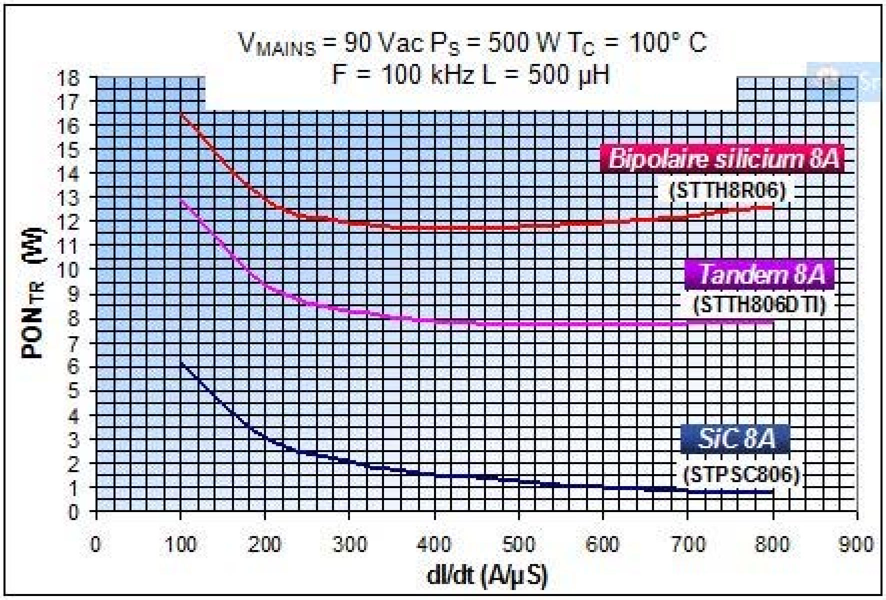

Fig. 11. Turn-on losses in the MOSFET versus dI/dt.

When using SiC diodes, the power losses always decrease when the switching-speed increases. Being naturally soft switching (due to capacitive recovery current), SiC diodes offer the possibility of switching the MOSFET at higher speeds and thus increase the converter efficiency. But even though the EMI generated by a SiC diode is lower than that of a Si diode, it still needs to be checked.

In Fig. 12, one can see that Si bipolar diodes suffer from a big decrease in efficiency linked to the recovery charge. SiC diodes feature a very low-efficiency variation. The small decrease is linked to the increase in the forward voltage-drop (V_F) of the Schottky and the resulting conduction losses.

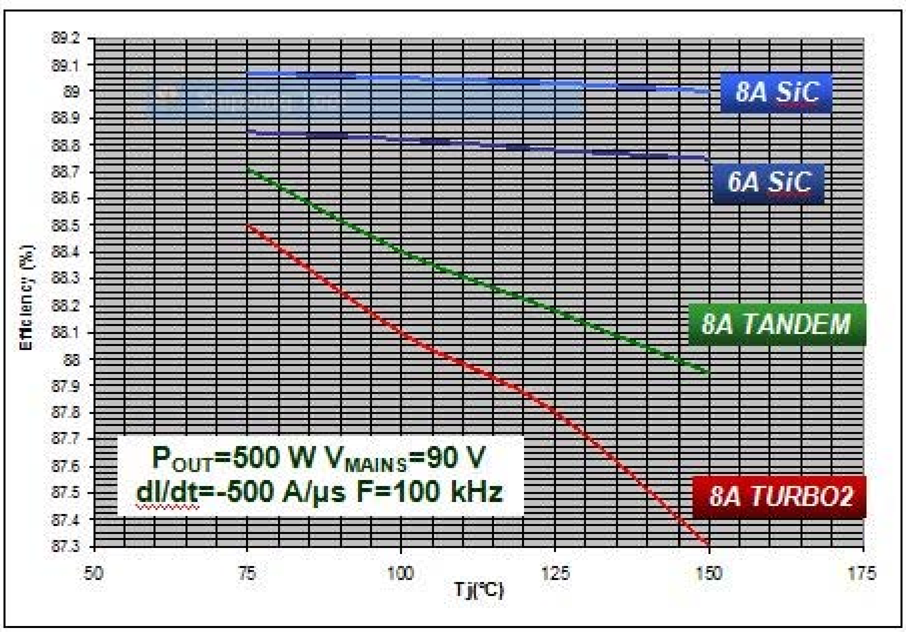

Fig. 12. PFC efficiency versus junction temperature with SiC diodes and standard Si rectifiers.

Considering that the switching losses of the MOSFET are much more important than the forward losses in the boost diode, the increase in the SiC Schottky's conduction losses versus temperature are not significant. Consequently, SiC power-Schottky diodes enable the PFC circuit to reach much higher efficiency levels than standard Si bipolar rectifiers, no matter the working temperature.

Besides improving efficiency, the SiC technology gives designers other options for optimizing the PFC circuit. For a given level of efficiency, SiC rectifiers allow an increase in the switching frequency of the PFC stage, which in turn reduces the size of passive components, snubber-circuits and EMI filters.

Designing A PFC With A SiC Boost Diode

One of the specific features of the SiC Schottky technology is the positive thermal coefficient that results in an increase of the diode's forward voltage when the junction temperature increases (see Fig. 13)

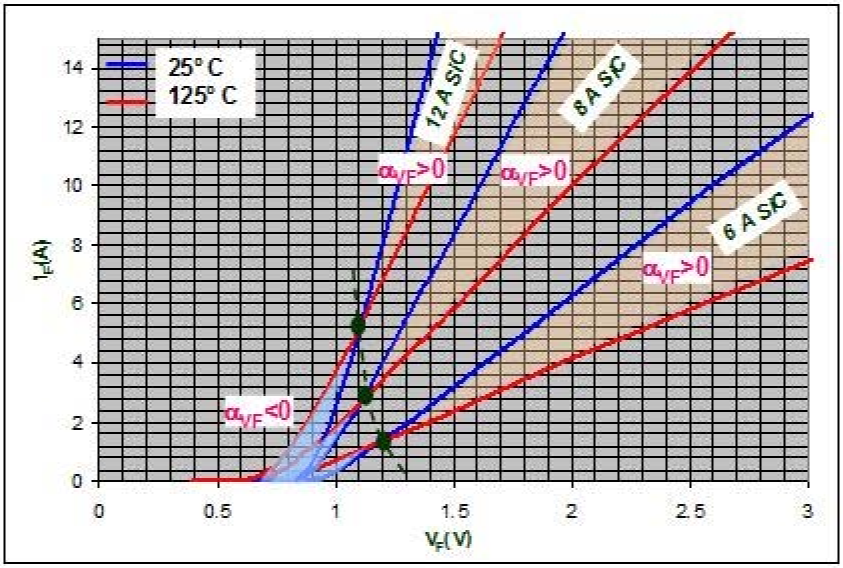

Fig. 13. Positive thermal coefficient effect on SiC diodes' forward voltage.

While the particular electrical properties of this semiconductor material enable power-supply designers to reach performance levels that were unexpected ten years ago, the positive thermal coefficient of SiC Schottky diodes can induce unusual behavior in the forward mode.

The fact that the forward voltage increases with the junction temperature means an increase of the forward power losses, hence a higher temperature and so on. A positive loop is then triggered that can lead to thermal instability at high overcurrent levels.

The surge current through the SiC diode can be particularly critical during transient phases such as power-supply start-up, power-line drop-out, and lightning surge as illustrated in Figs. 14 through 16. To guarantee safe operation of the component during these phases, designers must ensure that the diode's junction temperature remains below the maximum value specified in the absolute ratings of the datasheet (usually 175° C).

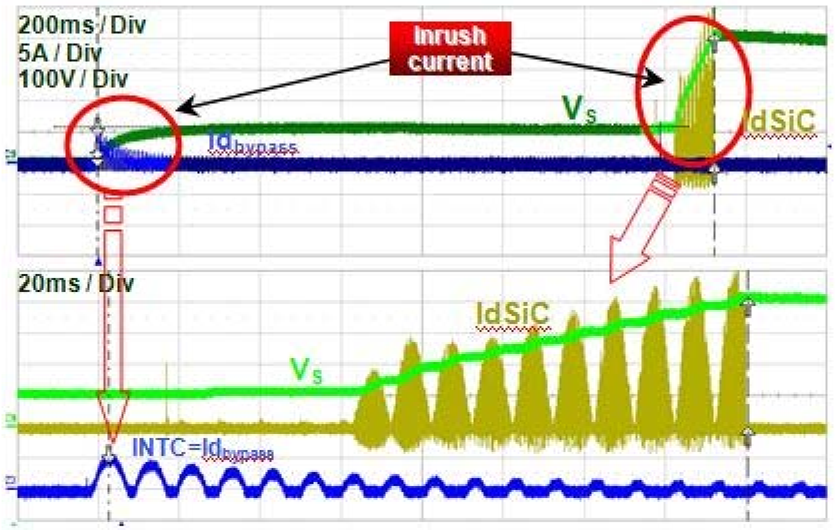

Fig. 14. Inrush current proportional to dVOUT/dt during the start-up phase.

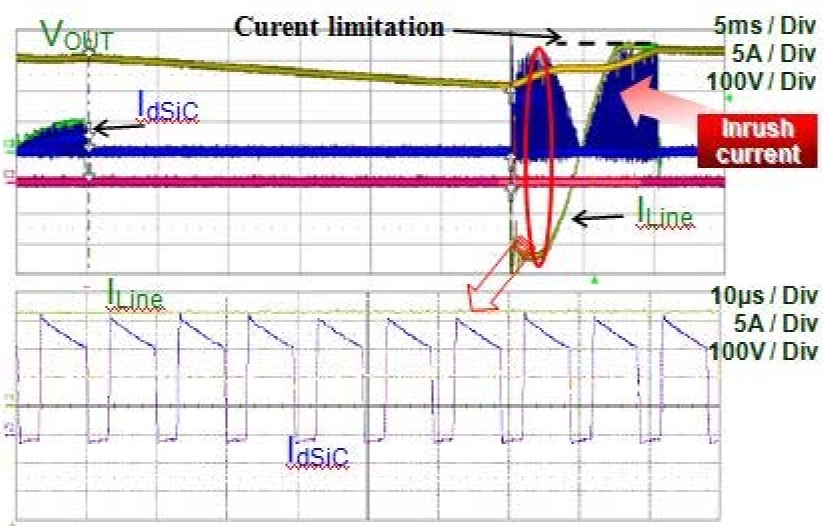

Fig. 15. Forward surge current through the boost diode during a line dropout.

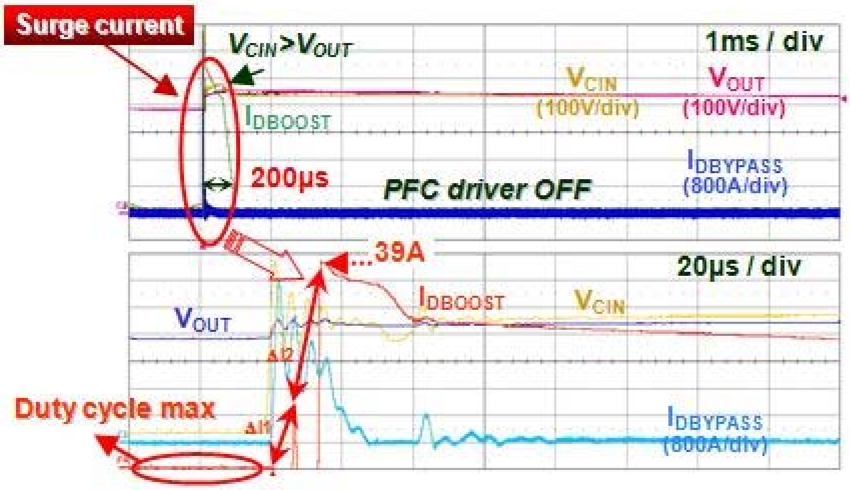

Fig. 16. High peak forward current through the boost diode during a lightning surge.

For simple current waveforms, estimating the junction temperature of the SiC diode through the thermal impedance curve given in the datasheet (Zth) is enough.

$$T_j(tp) = Zth_{(j-c)}(tp) \cdot P + Tcase$$

where P is forward loss dissipated in the diode (which should be calculated in the most critical situation with V_F at $T_{J(max)}$), Tcase is the diode case temperature, and Zth(j-c) is the thermal impedance from junction to case.

For more complex waveforms (due to the switching frequency), the use of an electrothermal model of the diode can help to simulate the junction-temperature increase with more precision. An example of an electrothermal model made with PSpice is presented in Figure 17. The diode model is integrated into a simplified model of the PFC, allowing simulation of the junction-temperature increase during the transient phases (startup and line dropout).

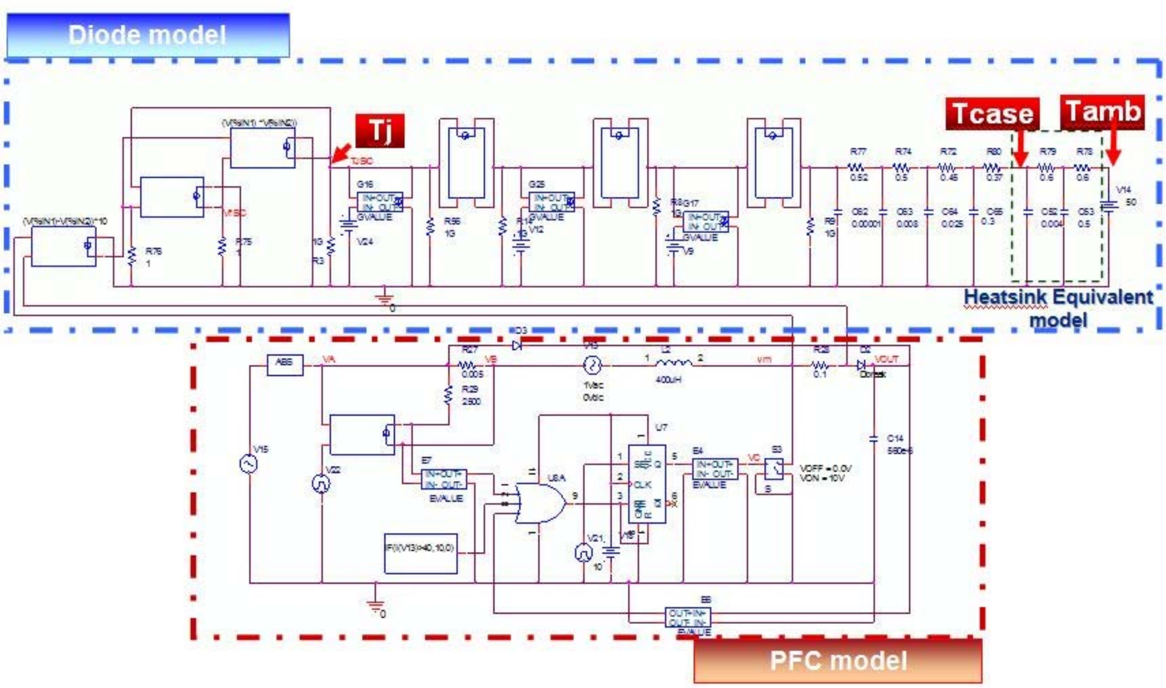

Fig. 17. Electrothermal model of the diode and electrical model of the PFC circuit.
(Click on the image to view enlarged diagram.)

Two simulation examples of the start-up phase under different start-up conditions are presented in Figure 18. In these examples, the circuit being simulated is a 650-W PFC operating at low line (90 V ac input) with C_S = 660 µF.

In Figure 18a, the maximum current through the SiC diode is 13 A with a soft start period of 60 ms (using the 'SoftStart' option of the PFC controller). The charging of the capacitance C_S from $\sqrt{2}$ x 90 V to 400 V is done in 120 ms. In this example, for a case-temperature of 90°C, the maximum junction-temperature is 101°C.

In Figure 18b, the soft-start period is reduced to 20 ms and the maximum amplitude of the current in the SiC diode is 50 A. The capacitance C_S is then charged in only 40 ms. In this example, the junction temperature of the diode exceeds the absolute rating of 175°C.

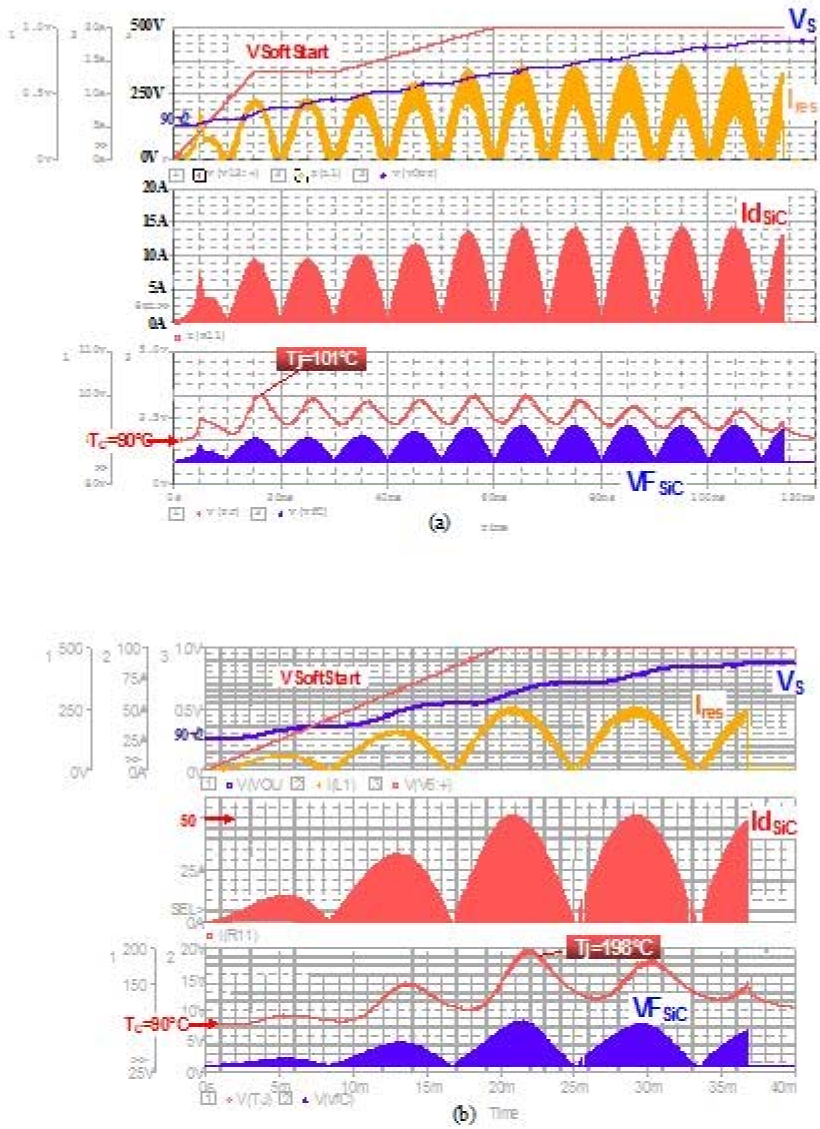

Fig. 18. Simulation of the SiC diode junction temperature rise.

Applying some basic design-rules can help avoid any trouble with SiC boost diodes during the transient phases of operation.

- Using a bypass diode connected between the bridge ouput and the output capacitor of the PFC is mandatory, especially during a lightning surge.
- Increasing the soft-start time as much as possible can help during the start-up phase.

- Use of a current-limit is highly recommended to protect the SiC boost diode during a line drop-out phase.
- Performance of lightning tests according to the IEC61000-4-5 standard is highly recommended. The most critical condition is at a 0° phase-shift angle with a maximum duty-cycle. In that case, the amount of current through the boost diode is maximum.
- Finally, the current rating of the SiC diode should be fine tuned to respect the absolute junction-temperature rating specified in the datasheet.

SiC And Beyond

Power Schottky diodes can reduce switching losses in the PFC MOSFET, the main source of power dissipation in the circuit, and thereby enable up to 4% increase in efficiency for the PFC circuit. Alternatively, they allow an increase in the switching-frequency of the power-supply so that the size of the magnetics can be reduced. This saves both space on the printed-circuit board and some raw materials.

All in all, SiC cannot be overlooked as an option when designing high-efficiency SMPS to save energy. However, these new diodes must be applied carefully because of their unusual behavior in forward-mode operation.

Adoption of SiC is just the first step on the path to higher efficiency for SMPSs. Researchers are now looking into other materials such as gallium-nitride (GaN), which will take efficiency-enhancing innovation a step further.

Literature:

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3. G. Comandatore, U. Moriconi “DESIGNING A HIGH POWER FACTOR SWITCHING PREREGULATOR WITH THE L4981 CONTINUOUS MODE”, AN628 1997

About the Authors

Frederic Gautier is an application engineer at STMicroelectronics, France. He has been an expert in switched-mode power supply applications and the industrial and power segments within the Application & System Engineering department since 1998. Frederic Gautier graduated with a technical degree in electronics and holds several patents in the switched-mode power supply domain within STMicroelectronics.

Cyril Borchard is a product marketing engineer responsible for rectifiers in the power segment at STMicroelectronics, France. He was previously in charge of marketing activities for rectifiers, protections, IPAD, thyristors and triacs in the consumer segment. In that scope, Cyril Borchard participated as marketing representative in the development of dedicated rectifiers for flat-panel displays (LCD and PDP) as well as specific protections and IPAD for consumer applications such as HDMI. Cyril Borchard holds a degree in Microelectronics and Automation from the Ecole Polytechnique de Montpellier.

For further reading on SiC Schottky rectifiers, see the How2Power Design Guide and search the Popular Topics category and select the Silicon Carbide and Gallium Nitride subcategory.