Performance Evaluation of a Schottky SiC Power Diode in a Boost PFC Application

Giorgio Spiazzi, *Member, IEEE*, Simone Buso, *Member, IEEE*, Massimiliano Citron, Michele Corradin, and Roberto Pierobon

***Abstract*—The performance of a 600 V, 4 A silicon carbide (SiC) Schottky diode (Infineon SDP04S60) is experimentally evaluated. A 300 W boost power factor corrector (PFC) with average current mode control is considered as a key application. Measurements of overall efficiency, switch and diode losses, and conducted electromagnetic interference (EMI) are performed both with the SiC diode and with two ultra-fast, soft-recovery, silicon power diodes, namely the RURD460 and the recently presented STTH5R06D. The paper compares the results to quantify the impact of the recovery current reduction provided by SiC diode on these key aspects of the converter behavior. Based on the experimental results, the paper shows that the use of SiC diodes in PFC designs may only be justified in high switching frequency applications.**

***Index Terms*—EMI, PFC, SiC diodes.**

I. Introduction

THE FIRST silicon carbide (SiC) power diodes have only recently become commercially available [1]. It is well known that the fundamental properties of this semiconductor material, such as its very high electrical breakdown field and its very high thermal conductivity, make it particularly suited to the manufacturing of power devices. However, due to technological limitations mainly related to the high defect density typical of the SiC crystal growing process and to the reduced size of the achievable wafers, SiC based power devices have been considered just a scientific curiosity for quite a long time. Even if demonstration devices have been presented in the literature now and then [2], SiC based Schottky power diodes have been available on the market only recently. The commercial availability of these devices has immediately generated an understandable interest in power electronics designers and some applications have already been described in the literature [3]–[6]. Given the device main features, such as the virtual absence of reverse recovery current and the stability of its performance with increasing operating temperature, it becomes interesting to quantitatively evaluate possible advantages of its adoption in typical applications, especially in terms of efficiency improvement and EMI reduction. In particular, the forward voltage drop of these diodes at relatively large currents is known to be significantly larger than that of silicon diodes, which makes the efficiency improvement issue worth investigating. The same can be said for the EMI aspect, where the absence of the recovery current peak may have an appreciable effect. This paper discusses the results of the comparative evaluation of a 4 A, 600 V SiC Schottky diode (Infineon SDP04S60, packaged in a P-TO220-3-1 case) and of two ultra fast soft-recovery diodes (RURD460, packaged in a TO251 case and STTH5R06D, packaged in a TO220AC case) with the same ratings. The key application for this type of rectifiers is the boost power factor corrector (PFC). We developed a 300 W, universal input voltage range boost PFC and evaluated its performance with the different diodes, measuring overall efficiency, switch and diode losses, and conducted EMI noise.

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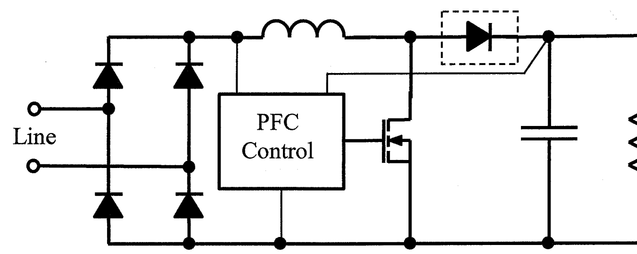

Fig. 1. Basic scheme of the Boost PFC.

TABLE I
CONVERTER RATINGS

Input voltage (RMS)	90-260 V
Output power	300 W
Output voltage	380 V
Switching frequency	70 kHz

II. Converter Description

Fig. 1 shows the basic scheme of the considered Boost PFC. The ratings of the converter are reported in Table I. These represent the typical characteristics of a PFC designed for a large variety of applications (e.g., telecom applications). A conventional and simple design procedure can be adopted to derive the necessary passive component values, required to guarantee the continuous conduction mode of operation for the converter during the whole line period and a suitable output voltage ripple. Also the selection of the required switch and diode is almost straightforward, given the current and voltage stresses. We then developed a simple two-layer printed circuit board (PCB) for the boost converter and tested on it three different diodes: the SDP04S60 SiC Schottky diode by Infineon (P-TO220-3-1 case, $R_{thJC} = 4.1\,^{\circ}C/W$), the widely used and well known RURD460 (TO251 case, $R_{thJC} = 3\,^{\circ}C/W$) and the STTH5R06D diode by ST Microelectronics, a 5 A, 600 V, low reverse recovery device, specif-

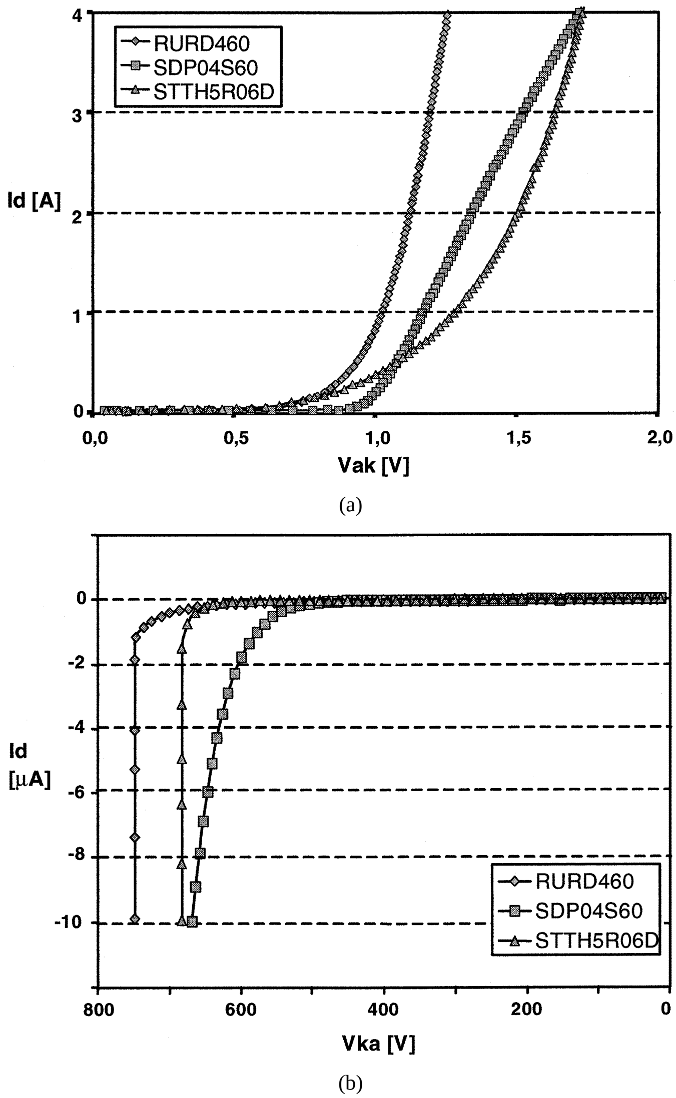

Fig. 2. (a) Measured forward and (b) reverse characteristics for the considered diodes.

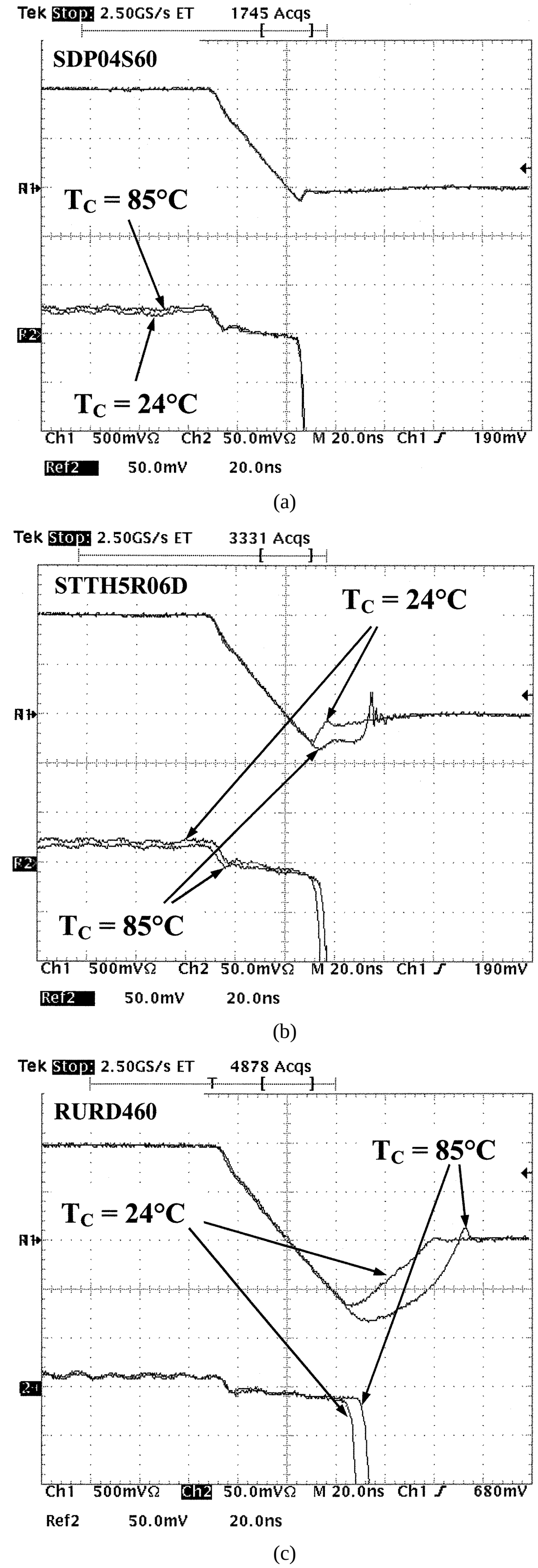

Fig. 3. Reverse recovery behavior at different temperatures. Top trace: diode current (5 A/div). Bottom trace: diode voltage (5 V/div). Timebase: 20 ns/div. (a) SDP04S60 diode (no appreciable change in the current waveform is revealed), (b) STTH5R06D diode, and (c) RURD460 diode. All measures performed at 400 V reverse voltage and 10 A forward current.

ically designed as a switching power supply free-wheeling diode (TO220AC case, $R_{thJC} = 3\,^{\circ}$C/W). It is worth underlining that the PCB layout was developed with great care, so as to minimize the generation of EMI [7]. Measurements of overall converter efficiency, switch and diode losses and conducted EMI have been done and are discussed in the following sections.

III. Diode Characterization

The diodes have been initially characterized to compare their basic parameters, namely the forward voltage drop, the breakdown behavior and the reverse recovery current. As can be seen in Fig. 2, the dc forward voltage drop of the SDP04S60 SiC diode is considerably higher than that of the RURD460 diode. The highest measured voltage drop is that of the STTH5R06D diode. All of these results can be considered in good agreement with the manufacturer data sheets. Fig. 2 also shows that the SiC diode behaves quite differently from both the Si diodes in reverse bias conditions, exhibiting an earlier breakdown current rise. However, in all cases the reverse leakage currents are well below the data sheets typical values. Fig. 3, instead, shows the recovery behavior of the three diodes for different case temperatures, namely 24 °C and 85 °C. While the effect of temperature variation is invisible in the case of the SDP04S60 diode, the RURD460 diode shows a peak recovery current increase of about 17%.

Correspondingly, its reverse recovery charge Q_{rr} increases by more than 50%. It is also possible to note the soft-recovery behavior of this diode, which requires about 60 ns (at room temperature) to get the current to zero. An intermediate behavior is shown by the STTH5R06D diode, whose peak recovery current is 50% smaller than the RURD460 diode's and similar to that of a low voltage Si Schottky diode. The temperature increase anyway, modifies its reverse recovery process which tends to become rather snappy and to induce oscillations (not visible at room temperature). This effect is also documented in [1]. Being a Schottky diode, the SDP04S60 device presents instead an almost negligible recovery current, mainly determined by its junction capacitance. From this standpoint its performance can be considered excellent. We tested all diodes at a 400 V reverse voltage and 10 A forward current, imposing a di/dt always above 300 A/μs. These are quite demanding operating conditions, which explains the relevant peak recovery current of the RURD460 diode. We also measured the diode voltage during the recovery process. As can be seen, all diode voltage waveforms present an initial step decrease, which is related to the current di/dt and to the package and test circuit parasitic inductances. An average value from about 5 to 7 nH can be estimated from the measurements, where the lowest value corresponds to the smallest package (TO251) of the RURD460 diode.

Based on these measurements, it is possible to expect the power losses on the SiC and on the STTH5R06D diodes to be predominantly conduction losses. Besides, the conduction losses of the RURD460 diode can be expected to be considerably lower than those of the other diodes, because of the difference in the forward voltage drop. On the other hand, the RURD460 diode is expected to have considerably higher switching losses, because of its slower commutation time. It is also expected to cause higher switching losses on the converter switch at turn-on, increasing the current level and the duration of the transition. The impact of these phenomena on the overall efficiency of the converter is examined in the following section.

IV. Efficiency Measurement

The considered diodes were all tested in the developed boost PFC board. We initially evaluated the effect of the diode recovery current on the switch current at turn-on. As can be seen in Fig. 4, in our application, the current peak at the moment of switch turn-on is considerably reduced by the use of the SDP04S60 diode [Fig. 4(a)] with respect to both the STTH5R06D diode [Fig. 4(b)] and the RURD460 diode [Fig. 4(c)]. As shown in the following, this reduces the commutation losses of the switch and also leads to a significant reduction of the generated common mode EMI. The results of the efficiency measurements are given in Tables II and III for 220 V_{RMS} and 110 V_{RMS} input voltage respectively. Total efficiency was measured by means of a WT210 Yokogawa Wattmeter. As can be seen, the power losses on switch and diode were also estimated, by means of temperature measurements. The measuring procedure consisted of two steps: at first

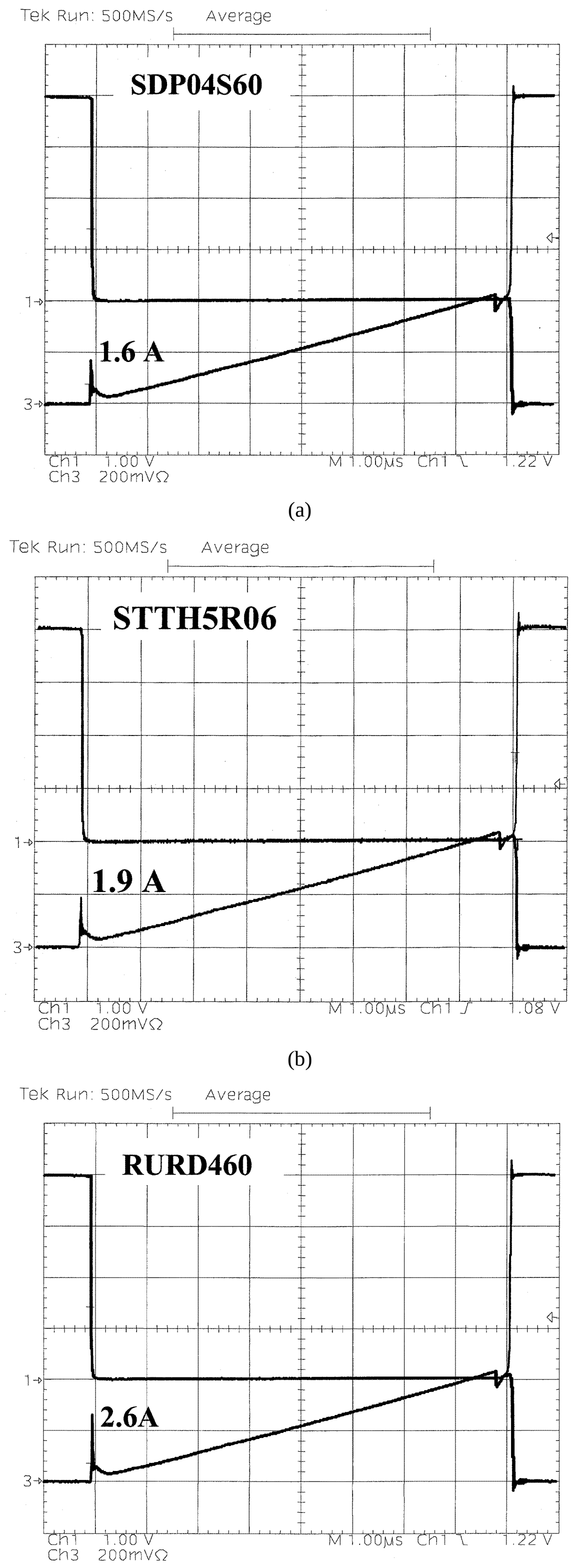

Fig. 4. MOSFET current and voltage waveforms during commutations. Voltage scale: 100 V/div. Current scale: 2 A/div. Timebase: 1 μs/div. Effect of diode recovery current for (a) the SDP04S60 (SiC) diode, (b) the STTH5R06D diode, and (c) the RURD460 diode.

the operating case temperature of each device was accurately measured, with a thermocouple, during normal operation; then, connecting the device to dc sources and maintaining

TABLE II
EFFICIENCY MEASUREMENT AT 220 V_{RMS}

	RURD460	STTH5R06D	SDP04S60
Input power [W]	312	311	311
Output power [W]	298	300	300
Efficiency	0.955	0.964	0.97
MOS losses [W]	5.1	3.4	3.0
Diode losses [W]	2.2	1.4	1.4

TABLE III
EFFICIENCY MEASUREMENT AT 110 V_{RMS}

	RURD460	STTH5R06D	SDP04S60
Input power [W]	314	323	320
Output power [W]	285	298	297
Efficiency	0.91	0.92	0.93
MOS losses [W]	13.2	8.2	7.8
Diode losses [W]	2.5	2.0	1.8

exactly the same set-up (i.e., without removing the device from the board and/or from the heatsink), the polarization of each device was accurately adjusted to get the same operating temperature. Power losses were finally calculated, based on the measured dc quantities. Though extremely time consuming, the procedure guarantees accurate results. The results confirm that the revealed efficiency improvement is tightly related to the reduction of the power losses on the metal oxide semiconductor field effect transistor (MOSFET) (IRFP450). The effect is even more evident when the 110 V input voltage is considered. It can be also noted that, in the case of the RURD460 diode at 110 V_{RMS} input voltage, the power losses on the switch reach a quite high absolute value, requiring a considerably bigger heatsink with respect to the other cases. An unexpected effect we found is the decrease in the output power measured in these conditions, which is possibly due to noise effects on the control integrated circuit, caused by the floating MOSFET heatsink. We suppose the common mode noise generated by the floating heatsink interfered with the controller, modifying its operating point. In fact, we observed a normal converter behavior when the heatsinks were all connected to ground. However, during measurements we kept the heatsinks floating in all cases. Finally, we must say that the losses on active devices represent roughly 50% of the converter total losses. Therefore, even a significant reduction of these, as is that offered by the SiC's diode adoption, only implies a small improvement of the overall converter efficiency. The important point is that the MOSFET operating temperature is significantly reduced, which implies the possibility of using a smaller heatsink. Another important point to be considered is that the reduction of the switching losses on the power MOSFET could allow a significant increase of the converter's switching frequency. While for the RURD460 diode the selected frequency (70 kHz) is close to the limit, the SDP04S60 and STTH5R06D diode could allow a significant increase of this parameter. As shown in [1], from this standpoint, SiC diodes can greatly improve the converter power density.

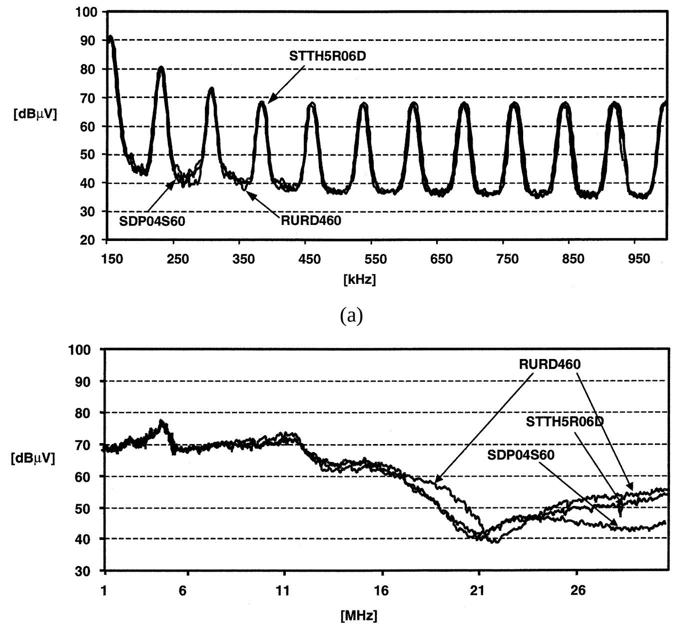

Fig. 5. Conducted EMI measurement at 220 V_{RMS} input voltage. (a) 150 kHz–1 MHz range. (b) 1 MHz–30 MHz range.

V. CONDUCTED EMI MEASUREMENTS

The conducted EMI generated by the PFC board was measured for the three diodes. No EMI filter was employed to reduce the noise injected into the line, to more clearly reveal the impact of the diode choice. The measurement set-up required the use of a standard line impedance stabilizing network (LISN) and of an EMC analyzer (Agilent E7401A). Great attention was paid to keep the layout of the board, the load and the cables connecting them, identical from measure to measure, so as to allow a fair comparison among the different outcomes. Results are shown in Fig. 5. As can be seen, the low frequency part of the considered spectrum (150 kHz–1 MHz) is almost unaffected by the diode substitution [Fig. 5(a). This can be explained considering the differential mode nature of the measured noise. This is characterized by well defined peaks at the harmonic frequencies of the modulation frequency and is related to the inductor current ripple, that is not affected by the turn-off behavior of the diode. On the other hand, the high frequency part of the spectrum (1 MHz–30 MHz), which is mainly related to common mode noise, is affected by the diode behavior [Fig. 5(b)]. In particular, the SDP04S60 diode guarantees a certain reduction of the injected noise with respect to both the STTH5R06D diode and the RURD460 diode, especially at frequencies above 24 MHz. The latter is the one exhibiting the poorest performance.

VI. CONCLUSION

The performance of a SiC Schottky diode (Infineon SDP04S60) has been evaluated in a typical 300 W boost PFC application. The diode has been compared to a couple of Si diodes (RURD460 and STTH5R06D). The experimental activity has revealed a positive impact of the SiC diode utilization in terms of achievable efficiency and EMI generation. This has been explained considering the significant reduction of the peak reverse recovery current typical of this type of diode with respect to Si diodes. However, recently introduced Si diodes, as the one considered here, offer a performance level very close to that of the SiC diode, both for the efficiency and the EMI generation, at least for usual switching frequencies (below 100 kHz). However, a considerable advantage could be achieved by using SiC diodes at higher switching frequency, taking advantage of their superior performance in terms of reverse recovery current. This could allow a significant increase of the converter power density.

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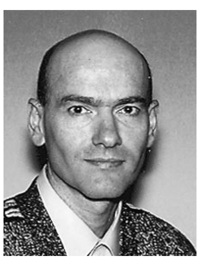

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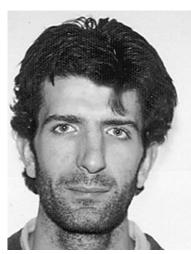

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