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CHARACTERIZATION AND COMPARISON OF SiC SCHOTTKY AND ULTRA-FAST DIODES IN A HARD-SWITCHING BUCK CONVERTER

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ABSTRACT

This research investigates the impact of the superior switching behavior of the SiC Schottky diode on the efficiency of a hard-switching buck converter. The outstanding characteristics of the SiC Schottky diode include high reverse voltage capability, absence of reverse recovery at turn-off, and a switching behavior independent to temperature, which find significant use in power electronics applications demanding fast switching frequencies and high converter efficiency. For benchmarking, we compare the performances of the SiC Schottky diode to a leading ultra-fast diode of comparable rating in a hard-switching buck converter with the load current, input voltage, switching frequency and diode turn-off dI/dt as the variable parameters. The important measurements include the diode and the FET switching and conduction losses as well as the buck converter efficiency trends with increasing load current, input voltage, switching frequency and diode turn-off dI/dt.

1. INTRODUCTION

There is a need to miniaturize DC-DC converter units in order to attain compatibility with the shrinking size of electronic devices. The reduction in size and weight of these converter units follows two major approaches as outlined in [1]. One approach is the reduction in the size of passive and magnetic components by increasing the switching frequency. Another is the reduction in power losses and the corresponding cooling requirements [1]. These goals are possible with the utilization of semiconductor devices that have minimal switching losses. The SiC Schottky diode is a new generation device belonging to the group of wide band gap semiconductors and as such, blocking voltages greater than 1 kV are possible [2]. Due to the inherent metal-semiconductor structure of the Schottky diode and the absence of minority carriers, there is no expected reverse recovery current when turning the diode off. These characteristics make it a suitable device in applications requiring high switching frequencies and large blocking voltages such as in power factor correction circuits. Coyaud, *et al.*observed that

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SiC Schottky diodes generate 4 times less switching losses than the usual ultra-fast rectifiers in a single-stage power factor correction circuit [3]. In another experiment, Lorenz showed that the efficiency of a 750 W active power factor correction circuit is almost independent of the switching frequency when the SiC Schottky diode is used as the boost diode as opposed to a significant drop in the circuit efficiency at higher frequencies when ultra-fast Si diodes are used [2]. The SiC material allows for low leakage currents because the resulting metal-semiconductor barrier is two times higher than that of Si [2]. With SiC, the Schottky diode specific on-resistance is smaller than with Si and GaAs even with higher blocking voltage capability due to a tenfold breakdown field strength. The thermal conductivity of SiC is comparable to copper allowing for higher device current density [2]. A comparison of the SiC and GaAs Schotky diodes shows that the SiC Schottky diode has lower voltage drop when conducting, which translates to lower power loss [4]. Another consequence of the wide band gap property of SiC is a very low intrinsic carrier density, which translates to a much higher temperature capability compared to Si. As discussed in [5], the temperature required to generate an intrinsic carrier density (electrons and holes) of 10^{13} cm^{-3} is around 800° C in SiC while it is only around 135° C in Si. With these benefits, the SiC Schottky diode can have superior performance over leading fast recovery diodes in switch-mode power supply applications, high frequency switching inverters and high voltage flyback converters [5].

Most of the studies found in literature on the superior switching performance of SiC Schottky diodes pertain to specific applications and there is no guarantee that the improvement in the converter efficiency may be significant for other voltage or current requirements. Furthermore, these studies often present a general description in the reduction of the diode and the corresponding FET switching losses, and they do not necessarily quantify the SiC Schottky diode's contribution to the improvement in the converter efficiency. We therefore present a thorough investigation of the switching performance of the SiC Schottky diode in comparison to leading ultra-fast diodes in a buck DC-DC converter of up to 225W with the input voltage, load current, switching frequency, and diode turn-off dI/dt as the variable parameters. The simplicity of the buck converter configuration and it's low parts count allow for the quantitative evaluation of the SiC Schottky diode's contribution to the improvement of the converter efficiency. For the actual benchmarking, we compare the performances of the D12S60 SiC Schottky diode and the STTA1206D ultra-fast. Both have the same current and voltage ratings, at 12A and 600V, respectively. The significant measurements include the trends in the diode and FET switching and conduction losses as well as the converter efficiency with increasing input voltage, load current, switching frequency, and diode turn-off dI/dt.

2. MATERIALS AND METHODS

The benchmark circuit for the characterization and comparison of the SiC Schottky diode against the ultra-fast is a buck DC-DC converter operated in the continuous mode. In order to achieve continuous-mode of operation, the buck inductor must be sufficiently large. We set the buck inductor at 1mH, based on the computations found in [6] to determine the minimum inductance value for continuous-mode operation. Fig. 1 shows the schematic diagram of the Buck converter setup. We perform an open loop testing of the diode in the buck converter and measure the switching losses on a cycle-by-cycle basis. The comparator circuit in Fig. 1 provides the necessary pulse-width modulation (PWM) waveform to switch the FET on and off. We can vary the PWM waveform frequency and duty cycle by adjusting the corresponding potentiometers in the comparator circuit. Fig. 2 shows a photo of the actual buck converter including the current and differential voltage probes. Fig. 3 shows the buck converter setup including test equipment.

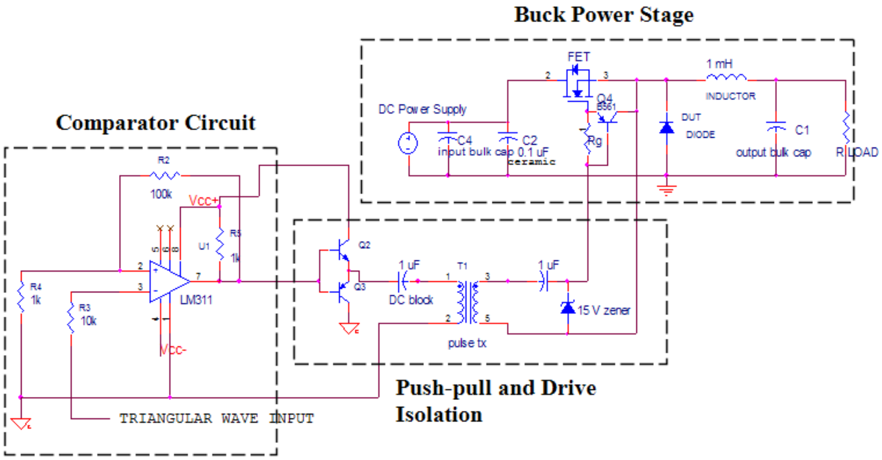

Figure 1. Schematic Diagram of Buck Converter Setup

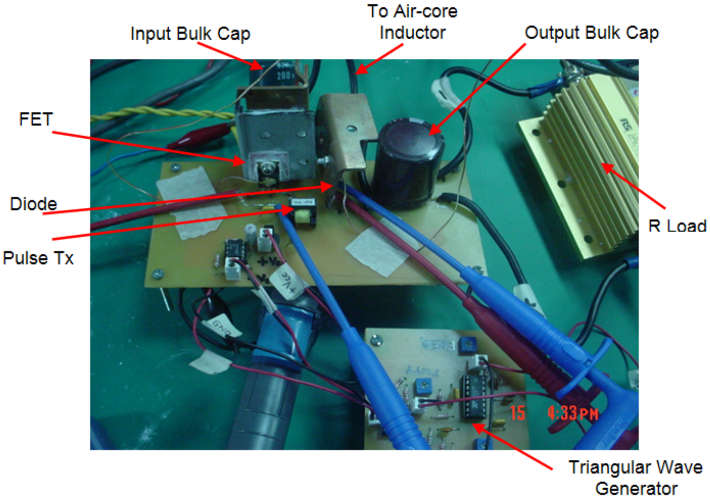

Figure 2. Photo of Buck Setup

The comparison of the SiC Schottky and ultra-fast diodes in all the experiments covers the turn-on and turn-off losses as well as conduction losses of the diodes. There is a pin-to-pin replacement of the SiC Schottky diode by the ultra-fast diode on the same circuit and with the same controlled parameters when comparing them. The experiments also include the

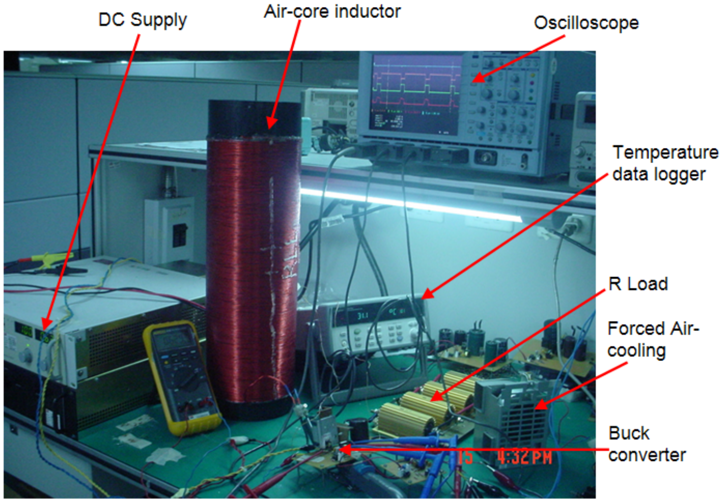

Figure 3. Buck Converter Test Setup Including Equipment

measurement of the FET switching and conduction losses as well as the converter efficiency for increasing diode forward current amplitude, switching frequency, input voltage, and diode turn-off dI/dt. The average switching loss per cycle from analytical computation is given as

$$P_{switching} = f_s \left(E_{turn-on} + E_{turn-off} \right) \tag{1}$$

which follows from the method in [7]. In equation (1), f_s is the switching frequency, $E_{turn-on}$ is the energy loss (usually in Joules) associated with the switching on of the diode or FET, $E_{turn-off}$ (usually in Joules) is the energy loss associated with the diode or FET turn-off. These expressions for energy are equal to the product of the values of the voltage and corresponding current multiplied by the fixed sampling time of the oscilloscope. Equation (1) gives the average switching losses (in Watts) over one switching period. Equation (2) gives the input-output power relationship while equation (3) gives the converter efficiency.

$$P_{in} = P_{out} + P_{total\ losses} \tag{2}$$

$$\eta = \frac{P_{out}}{P_{in}} \tag{3}$$

Fig. 4 illustrates the high-current-low-voltage testing of the diodes in the buck converter. For this testing, the load resistance is fixed at 3.626Ω, which is a parallel combination of two 10Ω resistors, a 22Ω resistor and a 33Ω resistor, each having 200W rating. The FET used in the high-current-low-voltage test is the IRF640N. This test maintains the switching frequency at 70 kHz, the input voltage at 60V, while increasing the diode forward current amplitude from 1A to 8A.

The high-frequency testing of the diodes in the buck converter varies the switching frequency within the 50 kHz to 270 kHz range and establishes the trend of the diode switching and

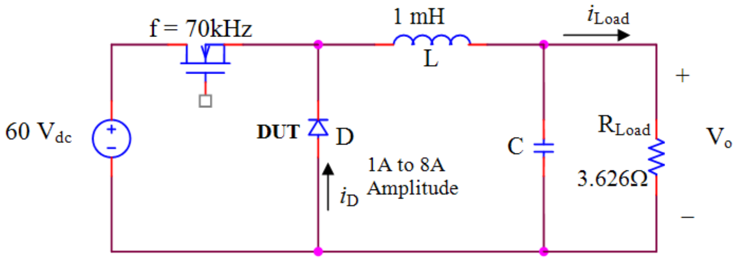

Figure 4. High-Current-Low-Voltage Testing of the Diodes in the Buck Converter

conduction losses and corresponding FET switching and conduction losses as well as converter efficiency versus switching frequency. Fig. 5 shows the buck converter for this experiment. In Fig. 5, the input voltage is 100 V_{dc} while the diode current is at a fixed peak value of 4A.

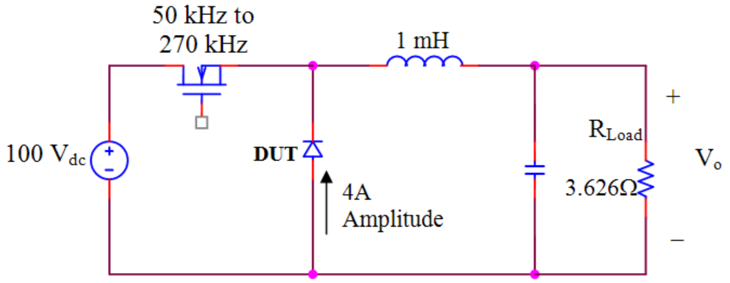

Figure 5. Testing of the diodes at different switching frequencies in the buck converter

Fig. 6 shows the setup for the high-voltage-low-current testing of the diodes in the buck converter circuit. The input voltage varies from 100 V_{dc} to 440 V_{dc} while the diode current is at a fixed peak value of 2 A. Setting the diode peak current at 2 A while increasing the input voltage requires decreasing the FET gate drive duty cycle for a fixed load resistance value of 33Ω. The switching frequency in this case is fixed at 70kHz. The FET used in this test is the SPP07N60S5.

Fig. 7 shows the setup for testing the diodes at different turn off dI/dt wherein R_G is variable. Varying the gate resistance allows for different turn-off dI/dt for the diode. The dI/dt and dV/dt experienced by the diode during turn-off follow from the relationship given by the dI/dt and dV/dt of the FET in equations (4) and (5), respectively

$$di/dt = I_{on}/R_G C_{iss} ln\left[\left(V_{GP} - V_{TH}\right)/\left(V_{GP} - V_{GS(on)}\right)\right] \quad (4)$$

$$dV/dt = \left[V_{GP} - V_{GS(on)}\right]/R_G C_{GD} \quad (5)$$

where

R_G = gate resistance

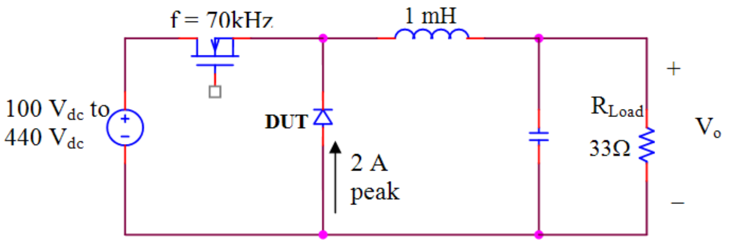

Figure 6. High-Voltage-Low-Current Testing of the Diodes in the Buck Converter

V_{GP} = positive gate pulse
$V_{GS(on)}$ = gate voltage required to support current I_{on} during saturation
C_{GD}, C_{iss} = parasitic capacitances of FET

The equations above are found in [8] and are also mentioned in [9]. Equations (4) and (5) state that for the same FET and diode forward current amplitude, an increase in R_G results in a proportional decrease in the FET turn-on rate and consequently, the diode turn-off rate. Fig. 7 illustrates that the variable diode turn-off dI/dt test maintains the input voltage at 100V, switching frequency at 70kHz and diode forward current amplitude at 3A. The load resistance value in this case is 3.626 while the FET used is the IRF640N. The gate resistance values are 12Ω, 27Ω, 51Ω, 75Ω, and 91Ω.

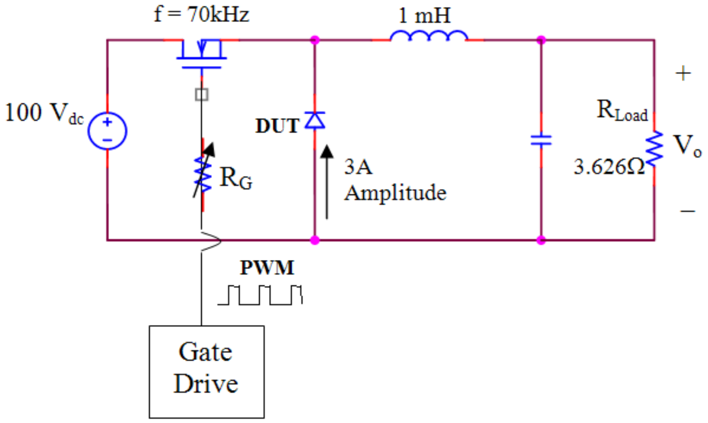

Figure 7. Testing of the diodes at different turn-off dI/dt in the buck converter

3. RESULTS AND ANALYSIS

This section presents the results of the comparison of the switching characteristics of the D12S60 SiC Schottky and STTA1206D ultra-fast diodes. Fig. 8 shows the turn-off waveforms of the STTA1206D ultra-fast while Fig. 9 shows those of the D12S60 SiC Schottky diode both at 5A diode forward current amplitude. It is evident from Fig. 8 that a large portion of the ultra-fast turn-off loss is due to its large reverse recovery. On the other hand, Fig. 9 shows that there is only a negligible displacement current at turn-off of the SiC Schottky hence, a smaller associated turn-off loss. Fig. 10 and Fig. 11 show the corresponding FET turn-on waveforms with the ultra-fast and with the SiC Schottky as the buck diodes, respectively. Since the switching intervals of the FET and the diode are complementary, we can see from Fig. 10 that the large ultra-fast reverse recovery spike during its turn-off is superimposed on the FET current during the latter's turn-on. On the other hand, there is no superimposed reverse recovery spike on the FET current at turn-on with the SiC Schottky as the buck diode. In other words, the absence of reverse recovery in the SiC Schottky diode not only minimizes its turn-off loss, but also the FET turn-on loss.

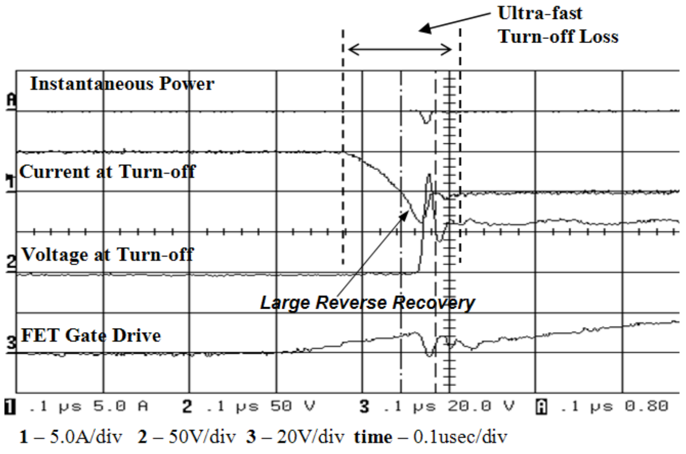

Figure 8. STTA1206D Ultra-fast Turn-off Waveforms

Fig. 12 shows a progressive increase in the ultra-fast's turn-off loss while there is a gradual increase in the SiC Schottky's turn-off loss with increasing forward current amplitude from 1A to 8A. As illustrated in Fig. 8 and Fig. 9, the difference in the trends is primarily due to the reverse recovery behavior, which also increases with forward current amplitude. The ultra-fast turn on loss in Fig 13 is consistently higher than that of the SiC Schottky diode due to an effectively larger forward recovery voltage spike at turn on as discussed in [8].

Figs. 14 and 15 show the FET turn-on and turn-off losses, respectively. In Fig. 14, we see a noticeably higher FET turn on loss with the ultra-fast diode that reaches around 0.3W at higher current settings. This is due to the superimposed ultra-fast reverse recovery spike on the FET current at turn-on as illustrated in Fig. 10. On the other hand, there is only a minimal displacement current superimposed on the FET current at turn-on with the SiC Schottky as

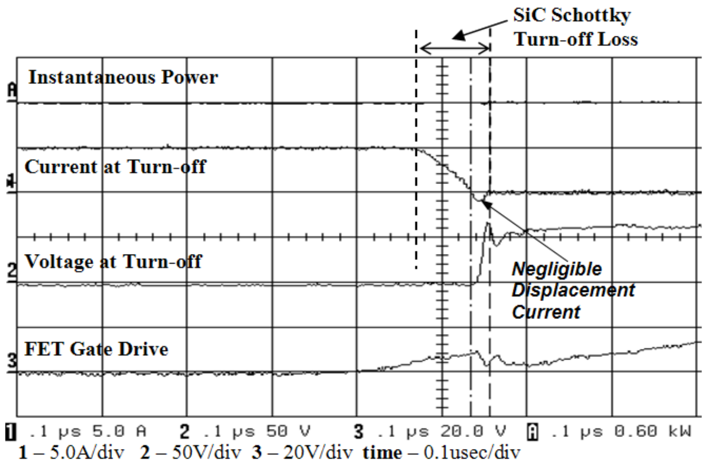

Figure 9. D12S60 SiC Schottky Turn-off Waveforms

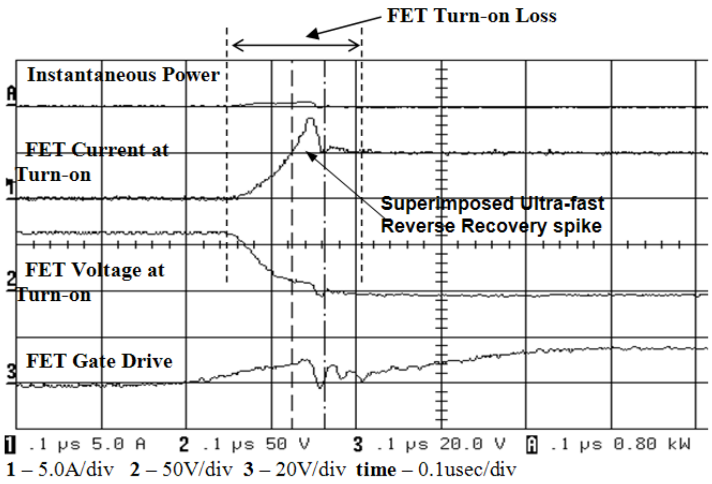

Figure 10. FET Turn-on Waveforms with STTA1206D Ultra-fast as Buck Diode

previously shown in Fig. 11.

In Fig. 15, the lower FET turn-off loss with the SiC Schottky is due to the effect of the latter's relatively lower forward recovery voltage spike (during diode turn-on) compared to that of the ultra-fast, which is also reflected in the FET's turn-off voltage.

The actual measured efficiency values in Fig. 16 shows that the efficiency with the SiC Schottky as the buck diode is higher by about 1% than that with the ultra-fast. The minimal efficiency improvement with the SiC Schottky is due to comparable conduction losses with that of the ultra-fast, which dominates in the total losses especially in high current applications. Figs. 17 and 18 show the diode and FET conduction losses, respectively. The diode conduction

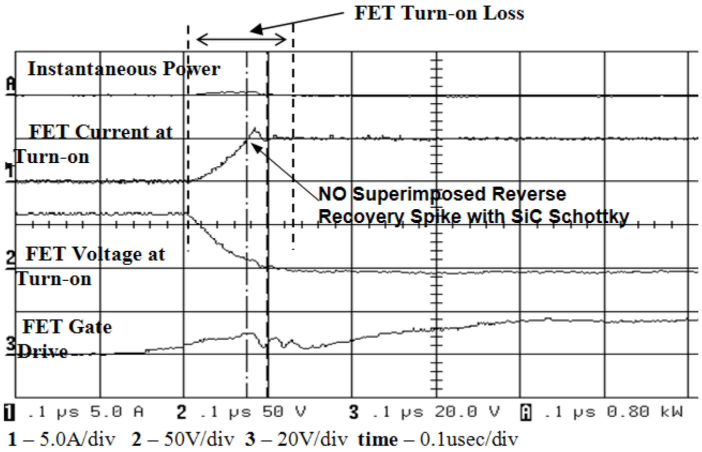

Figure 11. FET Turn-on Waveforms with D12S60 SiC Schottky as Buck Diode

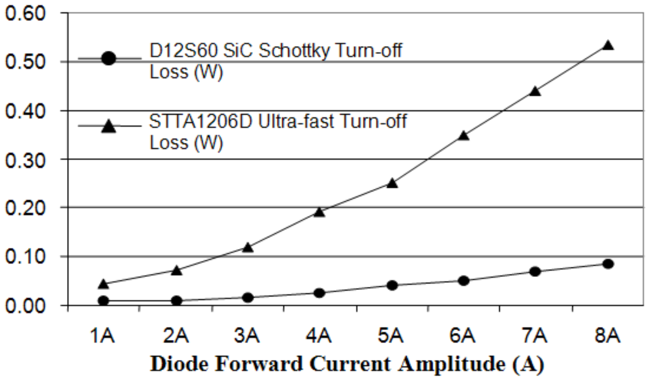

Figure 12. Diode Turn-off Losses in the Buck High-Current-Low-Voltage Test

losses in Fig. 17 reach up to about 3.7W, while Fig. 18 shows that the FET conduction losses reach up to 5.5W at high forward current settings.

Fig. 19 and Fig. 20 shows the diode and FET total switching losses in the high frequency test, respectively. In Fig. 19, there is a remarkable increase in the ultra-fast total switching loss with frequency while there is only a negligible increase in the SiC Schottky total switching loss. The ultra-fast total switching loss versus switching frequency in Fig. 19 rises with a slope of 128mW/20kHz. On the other hand, the SiC Schottky total switching loss rises gradually with a slope of 17mW/20kHz. In Fig. 20, the FET total switching losses with the SiC Schottky as the buck diode is consistently smaller than that with the ultra-fast by about 0.8W especially at switching frequencies above 150kHz.

The plots in Fig. 21 show that there is an evident drop in the buck converter's efficiency from about 80.7% at f = 50kHz to 72.4% at f = 270kHz in the case with the ultra-fast as

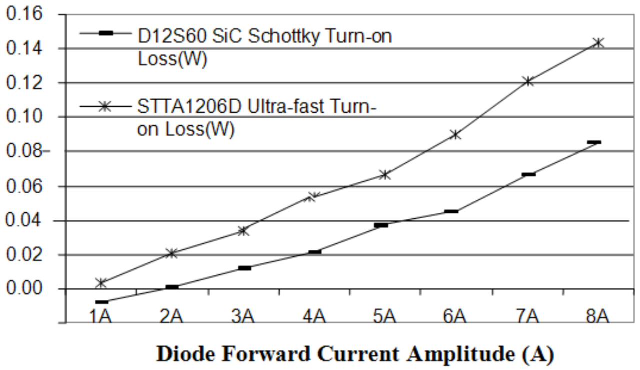

Figure 13. Diode Turn-on Losses in the Buck High-Current-Low-Voltage Test

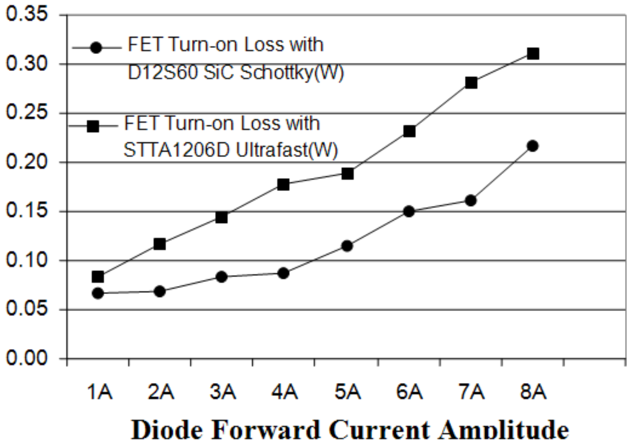

Figure 14. FET Turn-on Losses in the Buck High-Current-Low-Voltage Test

the buck diode. On the other hand, there is a relatively gradual decrease in the converter's efficiency from 80.7% at f = 50kHz to 77% at f = 270kHz in the case with the SiC Schottky as the buck diode.

Fig. 22 shows that the SiC Schottky turn-off loss becomes comparable to that of the ultra-fast at higher voltages starting at 350V. This is due to a significant increase in the SiC Schottky displacement current at large reverse voltages. The displacement current in the SiC Schottky at turn-off is due to its capacitive behavior as given by equation (6):

$$C(V,S) = S\sqrt{\frac{qNd\epsilon_{SiC}}{2(V+V_{Barrier})}} \tag{6}$$

where V is the reverse voltage across the diode and S is its junction surface [3]. The energy

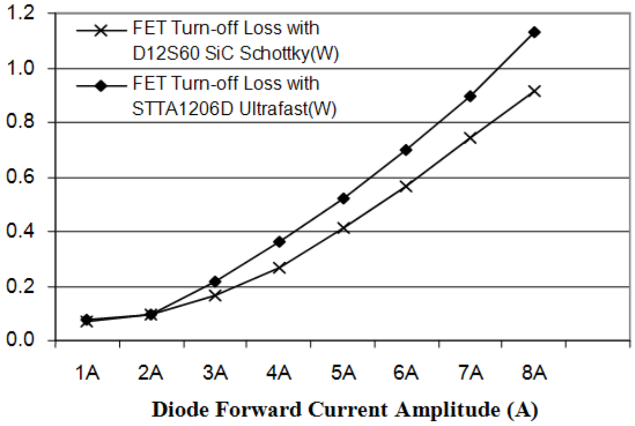

Figure 15. FET Turn-off Losses in the Buck High-Current-Low-Voltage Test

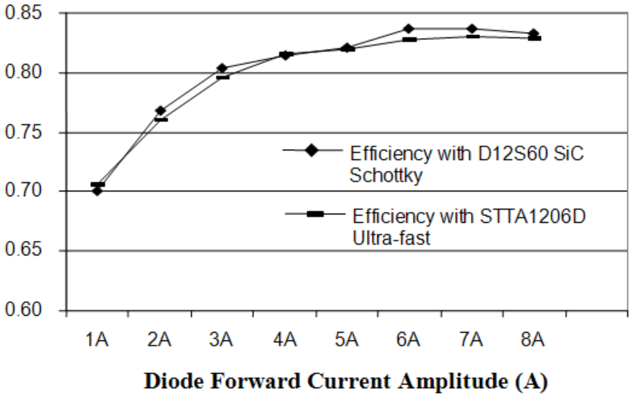

Figure 16. Efficiencies in the Buck High-Current-Low-Voltage Test

associated with this capacitive behavior is given by equation (7)

$$E = kV^{\frac{3}{2}} \tag{7}$$

where V is the reverse voltage across the diode. This means that at large reverse voltages and small forward current levels, the SiC Schottky turn-off loss due to its displacement current becomes comparable to, or may even exceed, the turn-off loss due to the ultra-fast's reverse recovery. This is particularly the case since there is only a minimal reverse recovery in the ultra-fast especially at low forward current levels. Fig. 23 shows that the corresponding FET turn-on loss with the SiC Schottky as the buck diode is still consistently smaller than that with the ultra-fast.

In Fig. 24, there is generally a 1% to 2% efficiency improvement in the buck converter for the high-voltage test with the SiC Schottky. This is closely related to the minimal FET turn-on

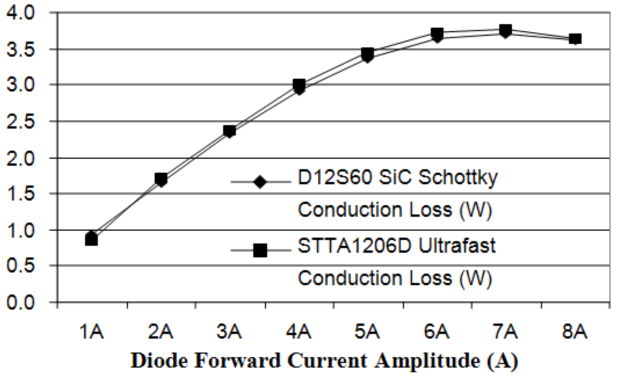

Figure 17. Diode Conduction Losses in the Buck High-Current-Low-Voltage Test

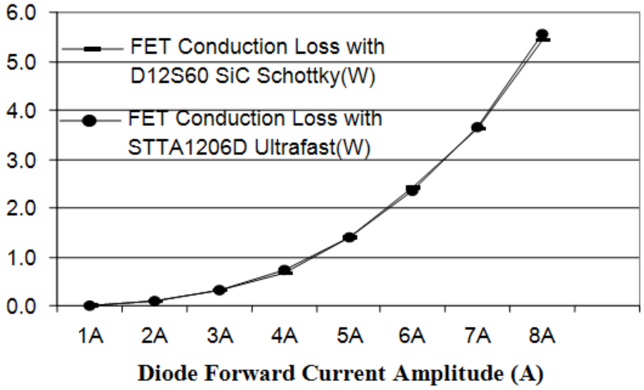

Figure 18. FET Conduction Losses in the Buck High-Current-Low-Voltage Test

losses with the SiC Schottky as the buck diode.

As explained in the Materials and Methods section, we can vary the diode turn-off dI/dt rate by varying the gate drive resistance, R_g. Increasing R_g tends to slow down the drive, hence a slower dI/dt rate. Fig. 25 shows the trends of the diode turn-off dI/dt with increasing gate resistance from 12Ω to 91Ω. We take note that the slope represented by the turn-off dI/dt is negative.

Figs. 26 and 27 show the diode and the FET total losses, respectively. In Fig. 26, we can see that the SiC Schottky total loss is relatively independent of the turn-off dI/dt rate, while that of the ultra-fast varies significantly. This is because the ultra-fast reverse recovery, and consequently its switching loss, varies with the turn-off dI/dt rate. On the other hand, the capacitive behavior of the SiC Schottky, which is expressed in equation (6), makes its displacement current and turn-off loss independent of the applied dI/dt rate.

Fig. 27 shows that the FET total loss with the SiC Schottky in the variable turn-off dI/dt test is still consistently smaller than the case with the ultra-fast. Fig. 28 shows the corresponding

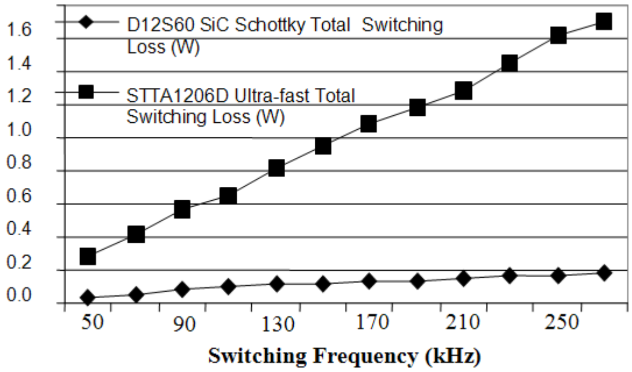

Figure 19. Diode Total Switching Losses in the Buck High-Frequency Test

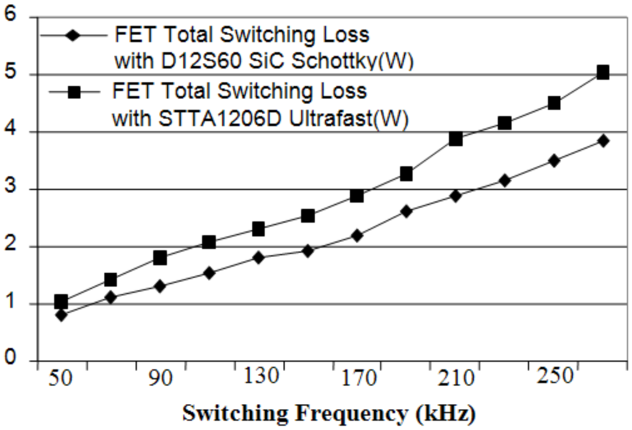

Figure 20. FET Total Switching Losses in the Buck High-Frequency Test

efficiency trends for the variable diode turn-off dI/dt test.

4. CONCLUSIONS AND RECOMMENDATIONS

The results of the experiments in this research provide a thorough benchmarking of the SiC Schottky diode against the ultra-fast in the buck converter in terms of electrical parameters such as the switching and conduction characteristics. This research also includes an assessment of the impact of the superior switching performance of the SiC Schottky diode on the converter efficiency. The following are the significant conclusions derived from the detailed comparison of the SiC Schottky and ultra-fast diodes in the buck converter:

(a) The absence of a reverse recovery current in the SiC Schottky decreases not only its switching loss but also that of the FET, particularly the FET turn-on loss.

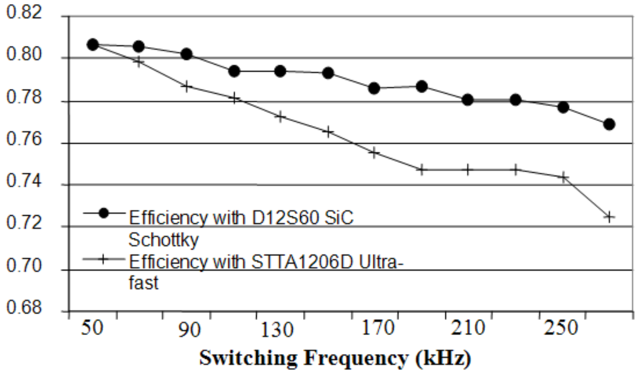

Figure 21. Efficiencies in the Buck High-Frequency Test

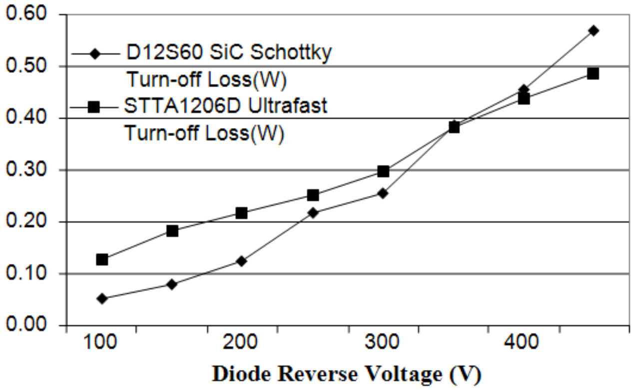

Figure 22. Diode Turn-off Loss in the Buck High-Voltage-Low-Current Test

(b) The relatively smaller Schottky diode forward recovery voltage overshoot results in a smaller Schottky diode turn-on loss compared to the ultra-fast. As a consequence, there is also a smaller FET turn-off loss with the SiC Schottky.

(c) There is a remarkable difference between the ultra-fast and SiC Schottky turn-off losses due to the reverse recovery behavior especially in high current applications with the ultra-fast turn-off loss reaching as much as 6 to 12 times that of the SiC Schottky at forward current amplitudes greater than 4A. However, due to comparable conduction losses, the converter efficiency improvement with the SiC Schottky diode is minimal and is only less than 1%.

(d) For similar current and voltage requirements, there is a marked improvement in the converter efficiency with the SiC Schottky diode especially with more aggressive switching frequencies. The ultra-fast switching loss is consistently 6 to 9 times higher than that of the SiC Schottky. At switching frequencies greater than 150kHz, the overall converter

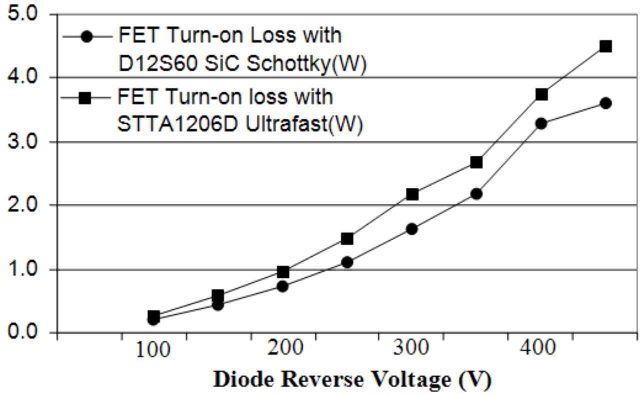

Figure 23. FET Turn-on Losses in the Buck High-Voltage-Low-Current Test

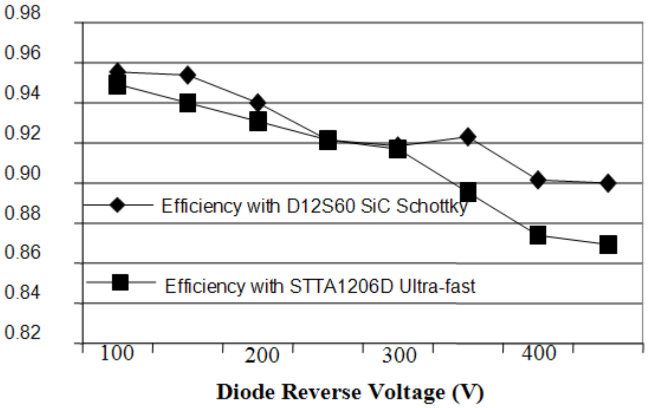

Figure 24. Efficiencies in the Buck High-Voltage-Low-Current Test

efficiency with the SiC Schottky is higher by 3% to 4% than that with the ultra-fast.

(e) The capacitive behavior of the SiC Schottky that is dictated by the reverse voltage across it, results in a large turn-off loss especially in high voltage applications wherein it is exposed to high reverse voltages. In other words, the SiC Schottky turn-off loss becomes comparable to that of the ultra-fast particularly in high voltage and low current applications such that the small diode forward current amplitude only results in minimal ultra-fast reverse recovery that is just comparable to the SiC Schottky displacement current. However there is still an improvement of 1% to 2% in the converter efficiency at high voltage settings with the SiC Schottky due to the effectively smaller FET turn-on losses; and

(f) The capacitive behavior of the SiC Schottky and the absence of a reverse recovery current make its turn-off loss independent to its turn-off dI/dt rate. In particular, the

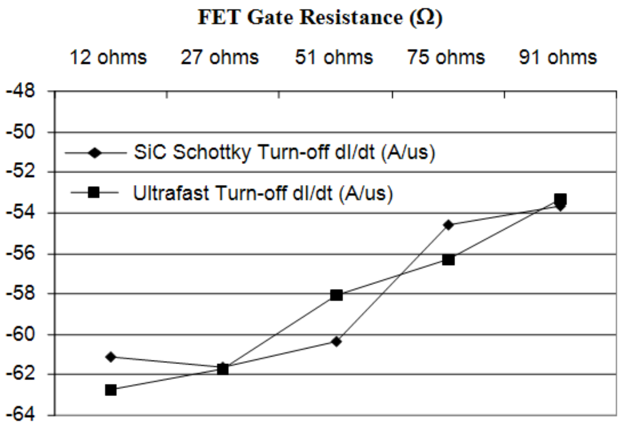

Figure 25. Diode Turn-off dI/dt Rates in the Buck Variable Diode Turn-off dI/dt Test

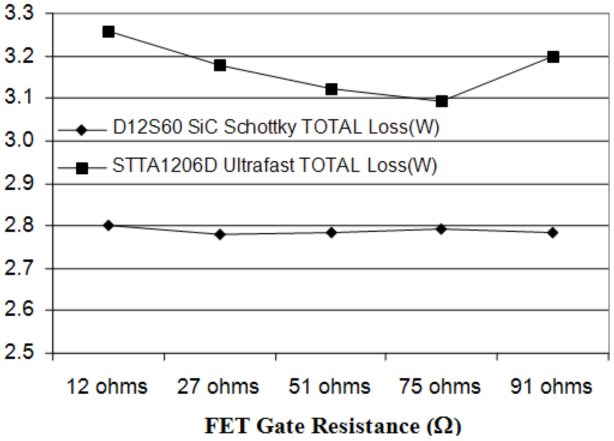

Figure 26. Diode Total Losses in the Buck Variable Diode Turn-off dI/dt Test

capacitive behavior of the SiC Schottky makes its turn-off loss dependent only on the reverse voltage. On the other hand, the ultra-fast has an effectively larger peak reverse recovery and shorter reverse recovery time at faster turn-off dI/dt rates, which results to correspondingly higher ultra-fast turn-off losses.

One possible area for further research is the impact of the absence of reverse recovery peaks in the SiC Schottky on the reduction of the converter's generated EMI (electromagnetic interference). In general, the ultra-fast reverse recovery overshoot is rich in harmonic content such that more aggressive switching and larger peak reverse recovery current may pose EMC (electromagnetic compatibility) problems. Another area of interest is high temperature applications of the SiC Schottky diode given that its switching characteristics are independent to temperature within its safe operating area.

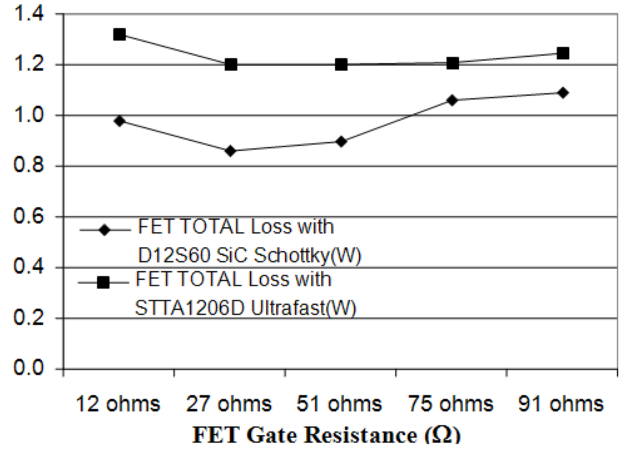

Figure 27. FET Total Losses in the Buck Variable Diode Turn-off dI/dt Test

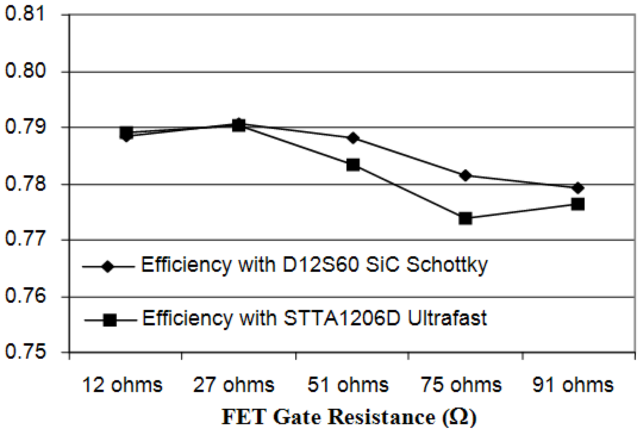

Figure 28. Efficiencies in the Buck Variable Diode Turn-off dI/dt Test

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NOMENCLATURE

Symbol	*Description*
FET	Field-Effect Transistor
SiC	Silicon Carbide Schottky
I_{on}	Full Conduction Current in Amperes
GaAs	Gallium Arsenide
E	Energy in Joules
V	Voltage in Volts
Si	Silicon
DUT	Device Under Test
R_G	Gate Drive Resistance in Ohms
V_{TH}	FET Threshold Voltage