

DC-DC CONVERTER USING SILICON CARBIDE SCHOTTKY DIODE

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Abstract—

Silicon carbide (SiC) is the perfect cross between silicon and diamond. The crystal lattice of SiC is identical to silicon and diamond, but, exactly half the lattice sites are occupied by silicon atoms and half by carbon atoms. Like-diamond SiC has electronic properties superior to silicon, but, unlike diamond it is also manufacturable. The thermal leakage current (dark current) in SiC is sixteen orders-of magnitude lower as well. As temperature increases, the leakage current increases, but, the temperature where the leakage current would disrupt circuit operation is over 1000 °C in SiC, compared to about 250 °C in silicon. The SiC electronic revolution began in the early 1990's when single-crystal wafers became commercially available for the first time. During the intervening years, many different electronic devices have been demonstrated in SiC, with performance often exceeding the theoretical limits of silicon. These include pin diodes, MOS field-effect transistors (MOSFETs), metal-semiconductor field-effect transistors (MESFETs), and bipolar transistors (BJTs), as well as specialized devices such as CCD imagers, Schottky diodes, static induction transistors (SITS) and impact-ionization- avalanche-transit-time (MATT) microwave oscillators. These early digital logic gates and linear elements are based on n-channel MOS technology, but, quickly followed by more sophisticated CMOS integrated circuits.

Key words: Silicon Schottky diode, Silicon Carbide Schottky diode, MOSFET

1 Introduction

Semiconductor power devices, especially diodes play important role in switching response. Low power dissipation on the switching devices will give rise to highly efficient power electronic system. For example, if a semiconductor device operates in a linear mode such as in power amplifiers of in linear regulators, it is expected that some amount of energy will be lost in the power circuit before its energy reaches the output. High efficiency of power converter requires a minimal loss of this energy from source to load. One of the energy can be easily dissipated in the diodes in terms of heat leading to a lower efficiency of the converter [1].

The unipolar Silicon Schottky (Si) and Silicon carbide Schottky (SiC) diodes are commonly used in power converters circuits. In spite of both diodes come from the same unipolar family, the issues of higher switching losses with

regards to reverse recovery losses have yet been solved. Nevertheless, the new SiC diode has emerged in the market in recent years where they are expected to improve the efficiency of the converter by allowing a further reduction in reverse recovery energy losses and hence increasing the performance. The additional substance of carbide element in the power Schottky diode may eventually lower the reverse charge current and thus, improve the overall transient response in the converter. An ideal semiconductor device would inhibit large breakdown voltage, low voltage drop in the on-state, high switching speed and low power loss. However in order to increase the performance of a semiconductor device, several additional doping enhancements will be added during the fabrication stage, where the characteristics of the device will altered by adding some impurity atoms to the pure semiconductor material. Today's technology requires extensive research to develop more powerful devices, not only to have lower switching losses, higher efficiency but also improve reliability. For this reason, power losses in the device must be put into consideration. The main contribution in this work is to verify that SiC high power diode having larger energy bandgap can indeed produce better results in DC-DC converter. The analyses are mainly done using circuit simulator.

2. Silicon Schottky Diode Family

The Silicon Schottky diode of Schottky barrier diode is widely used as a mixer or detector diode. In addition to its low forward voltage drop, it may lead to lower levels of power losses in the circuit [2]. Since Si diode is a unipolar device, the current transport is mainly due to majority carriers and therefore the speed is faster. In addition, it has low turn-on voltage, high frequency capability and low capacitive effect [3]. SiC diode is a wide-bandgap (WBG) semiconductor family from III-V group. It has the advantages in faster recovery times as well as no dependence on temperature [4] and has the potential to operate more efficiently. In Si diode however, the temperature may rise due to the increasing in electron's thermal energy leading to higher peak reverse recovery current [5]. This eventually gives higher power loss in the device.

In addition to smaller package and higher weight, SiC diodes also have higher critical field and barrier heights compared to Si diode. This results in reduced on-state resistance and lower leakage current or SiC diode [6]. It also has been demonstrated that the SiC diode has the potential to improve power FET performance [7]. Its energy bandgap is

three times higher than Si and ten times higher in electrical breakdown strength. Therefore, SiC can operate at operating voltage of 20 times with current densities up to 400 times higher than Si diode [8]. SiC Schottky diode has a small forward voltage and the reverse breakdown voltage cannot be made too high (currently about 200 V). It is used for rectification of power supplies for low voltage and high current applications or in high frequency systems due to its small reverse recovery time.

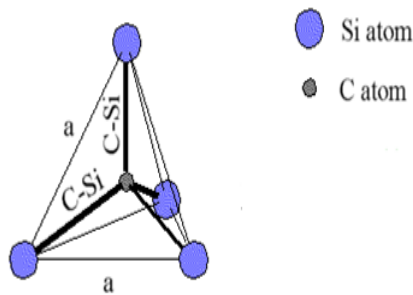


Fig.1 The tetragonal bonding of a carbon atom with the four nearest silicon neighbors. The distance a and C-SiC are approximately 3.08\AA and 1.89\AA respectively.

Fig. 1 shows four Si atoms made a covalent bonding with a single Carbon © atom to form a SiC. The C atom is located in the middle of the structure and the distances between all atoms which marked C-Si are equal. The SiC possess increase tolerance to radiation damage, marking it a material suitable for defense and aerospace applications. Due to high tolerance of temperature in SiC, it is chosen in various industries, such as aircraft, automotive communications, power and power spacecraft.

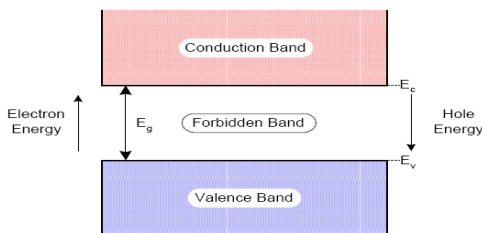


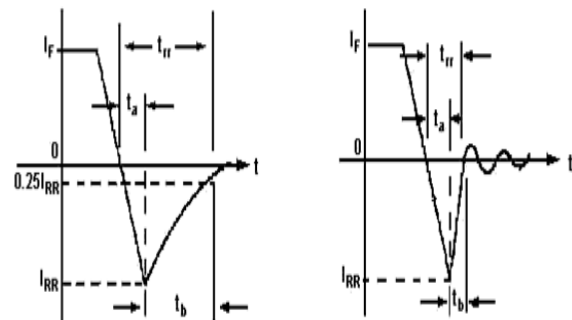
Fig. 2 Energy Band Diagram of a Semiconductor.

The characteristics of SiC diode as a wide bandgap semiconductor device results in a more energy to excite the electron from its covalent bond during turn-off compared to Si. Referring to Fig. 2, the wide bandgap is measured from the distance between the conduction band and valance band. An insulator would have a larger bandgap that would take lots of energy for the electrons to travel from the valence to conduction band while a conductor would have no forbidden band. The energy is calculated from the difference between

both bands. The wider the bandgap, more thermal energy is required to excite the electrons enabling the device to operate at higher temperature without affecting its electrical properties.

3 Reverse Recovery

Reverse recovery is one of the properties in a diode. It can be a factor in determining the efficiency of the applications. When a diode has been conducting in a forward bias long enough for it to establish steady, there will be charges due to the presence of minority charge carriers. This charge must be removed to block in reverse direction.



a. Soft recovery

b. Abrupt recovery

Fig. 3 Reverse Recovery Current Characteristic

The characteristics of reverse recovery current experienced by a diode is represented Fig. 3 above, t_{rr} represents the reverse recovery time, I_{rr} is the peak reverse current whilst t_a is the transition time due to charge stored in depletion region of the p-n junction and t_b is the time for the current to relax to zero. The peak reverse recovery current depends on the falling rate of change in current during turn-off. In SiC diode, there will be less or none reverse recovery current due to its ability to immediately remove stored charge. However, there are differences observed during the recovery from the peak values. This is merely reflected from different device's fabrication techniques.

Normally, in SiC, the rising current rate takes a longer time (t_{rr}) as shown in part (a) in Fig 3. This eventually reduces the turn-off speed. In other SiC type, The speed can also be slightly faster due to smaller t_b but with the cost of higher dissipation. This can be seen in part (b) as oscillation exists during the end stage of turn-off time. In addition, if the falling current rate during the beginning of turn-off time is high as in the case of non-schottky diode, the reverse current would also be high, leading to both high power dissipation and lower in turn-off speed.

4 Diode characteristics

4.1 Static Characteristics

The I-V and reverse current are among the static characteristics of the device. Due to higher level of majority carrier injection in Si diode, this causes a lower voltage drop and hence smaller capacitance to bias the junction for turn-on process. This is the only advantages of Si diode compared to SiC. Here, SiC diode requires a higher voltage to forward bias the device. Apart from that, SiC diode can handle larger reverse voltage as compared to Si.

4.2 Dynamic Characteristics

The characteristic that changes with time is inherited in both devices. Si and SiC diodes are compared in terms of the reverse recovery time, reverse recovery current and corresponding switching losses. The comparisons in dynamic characteristics between two devices are tabulated in Table I. The SiC and Si diodes used are of part number UPSC600 and B530C respectively.

Table I. Comparison of Dynamic Characteristics

Characteristics	SiC Schottky (UPSC600)	Si Schottky (B530C)
Reverse Recovery Time	Time Unchanged with temperature variation	Increases as temperature increases
Reverse Recovery Current	Negligible	Increases as temperature increases
Switching Losses	Low	Slightly higher

Table I shows that SiC diode has advantages in all dynamic characteristics. Si diode suffers from higher reverse recovery current and switching losses. This clearly indicates that additional carbide substance in the device may improve switching speed and reduce power dissipation.

5. DC-DC CONVERTER (CHOPPER)

5.1 Simulation of DC-DC converter

Fig. 4 shows the circuit diagram of DC-DC converter using SiC Schottky diode and Fig. 5 shows Si Schottky diode V_1 provides a pulse signal to the FET (M_1) and the signal will appear at V_{gs} . The signal will then forward bias the gate-source junction of the MOS FET. As a result, the MOSFET is turned on. At this time, current will develop in L_{load} and increase to its peak value. There is no current flowing in the DUT (D_{1-SiC}) yet. When MOSFET is turn off, the charged inductor current will be discharged through the low impedance path, $D_{1-SiC}-R_{load}$. This process repeats in the next subsequent switching cycle.

Fig. 6. Shows the original waveform of the V_{pulse} . It is of the same signal applied for both chopper circuits, having a square wave with pulse period of 25 μ sec and 20-V peak voltage. During turn-off of the MOSFET, current will conduct in the diode, leading to forward bias of the device. Once the switch is turned on again, the diode current, I_d will be forced to discharge rapidly leading to high voltage overshoot in M_1 before it goes back to forward voltage value. In addition, I_d will not decay directly to zero forward current value but to a negative peak instead. This negative or reverse overshoot it is called reverse recovery of diode current. The longer it takes to recover back to zero will indicate a higher switching loss in the device. Due to this, the switching MOSFET will also experience forward overshoot during its turn-on cycle. In this work, the level of switching losses is evaluated to verify the advantages of SiC over Si diode.

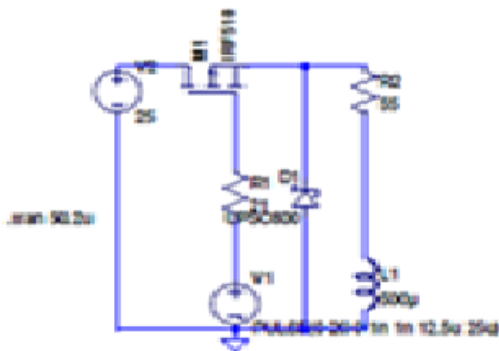


Fig.4. DC- DC converter using Silicon Carbide Schottky diode

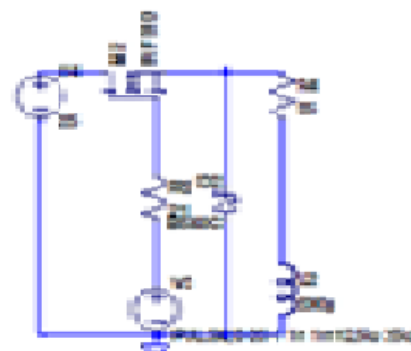


Fig.5. DC-DC converter using Silicon Schottky diode

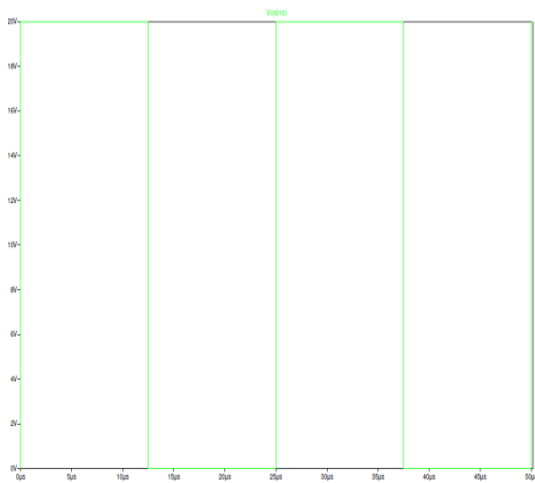
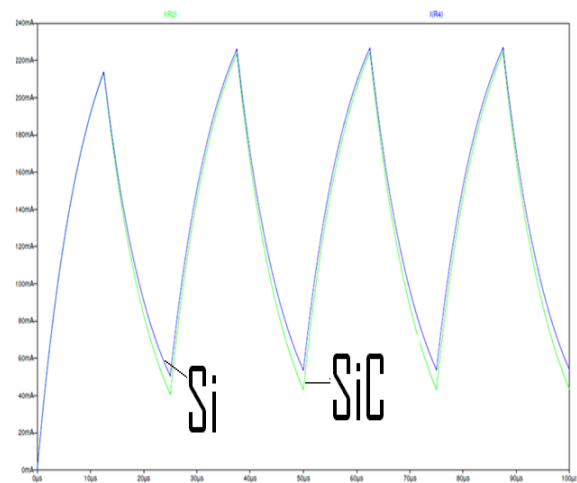


Fig. 6. V_{gg1} (Vpulse) Signal for DC-DC to converter using Si Schottky diode and SiC Schottky diode



I_{Rload} for SiC and Si Circuit.

Fig. 8.

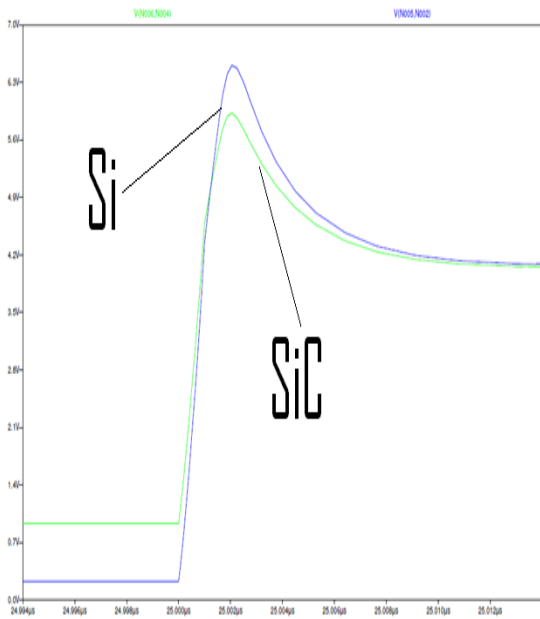


Fig. 7. Overshoot volt

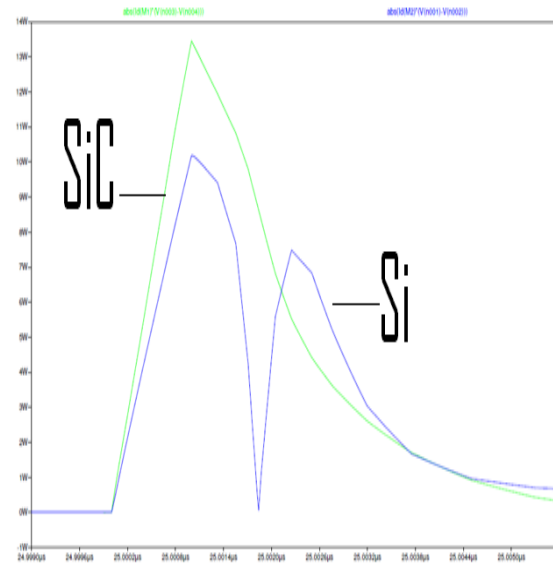


Fig. 9. MOSFET Turn-On Power Loss during DUT Turn-off

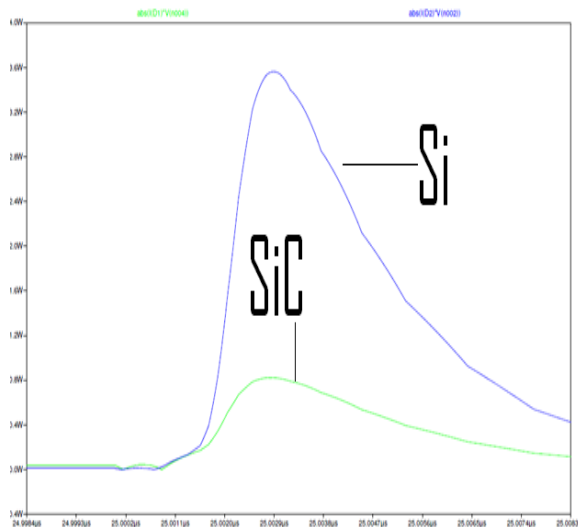


Fig. 10. Shows the turn-off switching losses Si and SiC diodes during MOSFET turn-off

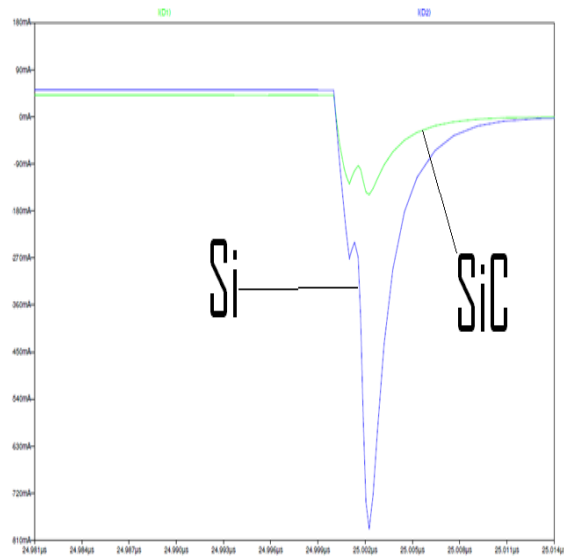


Fig.11. Reverse Recovery Current of Si and SiC Diodes during MOSFET Turn-on

5.2 RESULTS AND DISCUSSIONS

Correct choice of diode is important in understanding its effects on the overall performance in DC-DC converter. One of the effects is the voltage overshoot in the switch. Gate and drain voltages are prone to stress when diode suffers from high reverse recovery and hence may give rise to less switching speed and high dissipation in the circuit. Fig. 7 shows the forward overshoot in V_{gs} of M_1 for SiC and M_2 for Si. It is clearly shown that Si diode imposes a peak overshoot more compared to SiC in the switch. Here, more heat is dissipated in Si, resulting in higher stress to the switch.

Fig. 8 shows the load currents of both diodes in the chopper circuit. The maximum swing of the currents is almost identical in value. However, the minimum peak is slightly greater for the SiC diode by merely 0.91 %. From this result, eventually, the output power can be calculated and compared. The MOSFET's V_{ds} overshoot is higher in SiC diode. This contradictory result makes the only drawback in the device. SiC has an overshoot voltage of 6 V, Which is 6 % higher than Si that only 6.5 V. This is caused by the charge removal response time in SiC where t_d is higher as previously shown in Fig. 3(a). Nevertheless, this results may not affect the improvement in the circuit because the variation in load circuit design may also cause to this drawback.

Even though the MOSFET peak voltage overshoot in SiC chopper circuit is higher, the corresponding output power, P_{out} of the circuit is slightly lower, this is shown in fig. 9. This is due to the smaller peak-to-peak swing at the load current. However, the results are acceptable since the difference is output power and reverse recovery current in the diode.

When MOSFET is turned off, load current will start to discharge through the diode and this overshoots the current further in the negative region before it goes back to zero, this is shown in fig. 10, mainly due to the removal of large amount of charges in the diode. The faster the removal of charge or the smaller of charge appeared in the diode will make the transient response faster. The reverse recovery current of both diodes during MOSFET turn-on is shown in Fig.11.

Table 8.2 Comparison in Current and Output Power

$R_{Load} = 55 \Omega$	Si Schottky	SiC Schottky
$I_{RLoad,min}$	50 mA	38 mA
$I_{RLoad,max}$	222 mA	220 mA
$I_{RLoad,avg}$	136 mA	129 mA

P_{out}	1.017W	0.915W

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