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Comparative Assessment of Si Schottky Diode Family in DC-DC Converter

Nor Zaihar Yahaya
Universiti Teknologi Petronas
Malaysia

1. Introduction

Semiconductors are important as they can serve as switching agents. Unlike semiconductor that work in linear mode such as in power amplifiers and linear regulators, large amount of energy is lost in the power circuit before the processed energy reaches the output. This applies for power conversion from source to load which requires high efficiency. Power will be dissipated in the form of heat once the system has low efficiency (Batarseh, 2004). A Silicon Schottky, (SiS) is a common diode used in power electronics circuits, whereas Silicon Carbide Schottky, (SiCS) is a diode that overall could perform the same operation but at a higher efficiency rate, for example in terms of switching losses.

An ideal semiconductor device would perform within these criteria; possessing large breakdown voltage, low voltage drop during on-state, high switching speed and low power loss. To increase the performance of a semiconductor device, doping process will be experienced by the device, where the characteristic of the device will be altered by adding some impurity atoms to the pure semiconductor material. The material will then be recognized as extrinsic material of *n*-type and *p*-type. A predetermined number of impurity atoms will be added into the silicon or germanium based semiconductor. For silicon, the n-type is created by introducing impurity elements with five valence electrons (*pentavalent*), such as antimony, arsenic and phosphorus. The n-type semiconductor will have electrons as majority carriers due to one extra free electron to move within the newly formed n-type material. On the other hand, p-type material is formed by doping the silicon crystal with impurity atoms having three valence electrons such as boron, gallium and indium. A *p*-type semiconductor will have holes as majority carriers due to insufficient number of electrons to complete the covalent bonds.

A forward bias or "on" condition is established once the positive potential is applied to the *p-type* material and the negative potential to the *n-type* material. The application of forward-bias potential will "pressure" electrons in the *n-type* materials and holes in the *p-type* material to recombine with the ions near the boundary and reduce the width of depletion region. If an external potential of volts is applied across the *p-n* junction such that the positive terminal is connected to the *n-type* material and the negative terminal is connected to the *p-type* material, the number of uncovered positive ions in the depletion region of the n-type material will increase because there are large number of free electrons drawn to the

positive potential of the applied voltage. The number of uncovered negative ions will also increase in the p-type material. Thus, the net effect is a widening of the depletion region and the diode is reverse-biased (Boylestad & Nashelsky, 1999).

2. Silicon Schottky (SiS) diodes

The Schottky diode or Schottky Barrier diode is a semiconductor device that is widely used as a mixer or detector diode. It is also used in power applications as a rectifier, because of its low forward voltage drop leading to lower level of power loss (Malvino, 1980).

Schottky diode is a unipolar device, where the current transport is mainly due to majority carriers. It does not rely on holes or electrons when they enter the opposite type of region as in the case of a conventional diode and therefore it gives better speed. This diode also has low turn-on voltage and high frequency capability with low capacitance (Mohammed et al., 2005).

2.1 Silicon Carbide (SiC) material

Silicon Carbide, (SiC) is a type of wide-bandgap semiconductor having advantages of fast recovery times. SiC diode is seen to have no change (or lesser) on switching loss when temperature increases, whereas SiS diode's behaviour changes in temperature (Ozpincci & Tolbert, 2003). This device has the potential to operate more efficiently by producing less heat and able to work at high temperature compared to Silicon, (Si) diodes. The cause of increasing temperature is the increase in electron's thermal energy which causes reduction of barrier height in the SiS diodes. Therefore, the power losses in SiS diode is due to the increase in its peak reverse recovery current (Chinthavali et al., 2004).

The SiC diode also comes in small size and lighter weight compared to normal schottky diode. It has a bandgap energy at most three times higher and due to this, it also gives better electrical breakdown strength about 10 times higher. This means that electronic devices in SiC can operate at a voltage of 5 to 20 times higher and with current density about 200 to 400 times higher (Wide Bandgap Semiconductor Devices, 2006).

The normal schottky diode has small forward voltage and the reverse breakdown voltage cannot be made too high (currently, approx. 100 to 200 volts). It is normally used for general rectification such as the rectification of power supplies for low voltage and high current application or for high frequency rectification with small reverse recovery time.
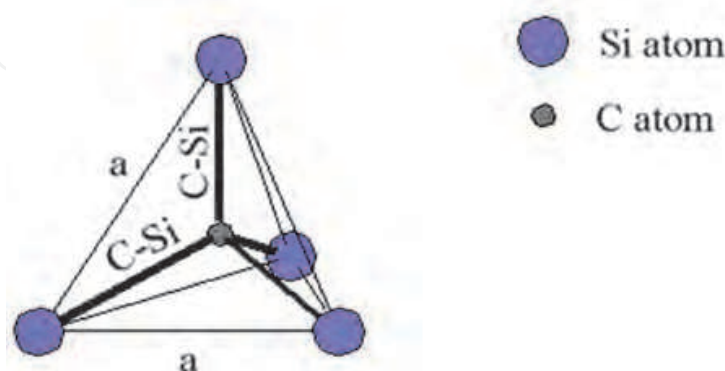

Fig. 1. The tetragonal bonding of a carbon atom with the four nearest silicon neighbours (IFM, 2006).

From Fig. 1, the four Si atoms make a covalent bonding with a single Carbon, (C) atom in order 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 the same. The position of C and Si in periodic table is shown in Fig. 2.

Fig. 2. Position of Carbon and Silicon in Periodic Table

The SiC possesses an increased tolerance to radiation damage, making it a preferred material for defense and aerospace applications. Due to high tolerance of temperature in SiC material (up to 650°C) (Silicon Carbide Electronics, 2006), it is used in various industries, such as aircraft, automotive, communications, power and spacecraft.

In terms of schottky's perspective, SiCS diode has higher critical field and higher barrier height than SiS diode. These two advantages give result in a reduced on-resistance and lower leakage current (Kearney et al., 1990). It has been demonstrated that the SiC material has the potential to improve power FET performance (Balaga, 1989).
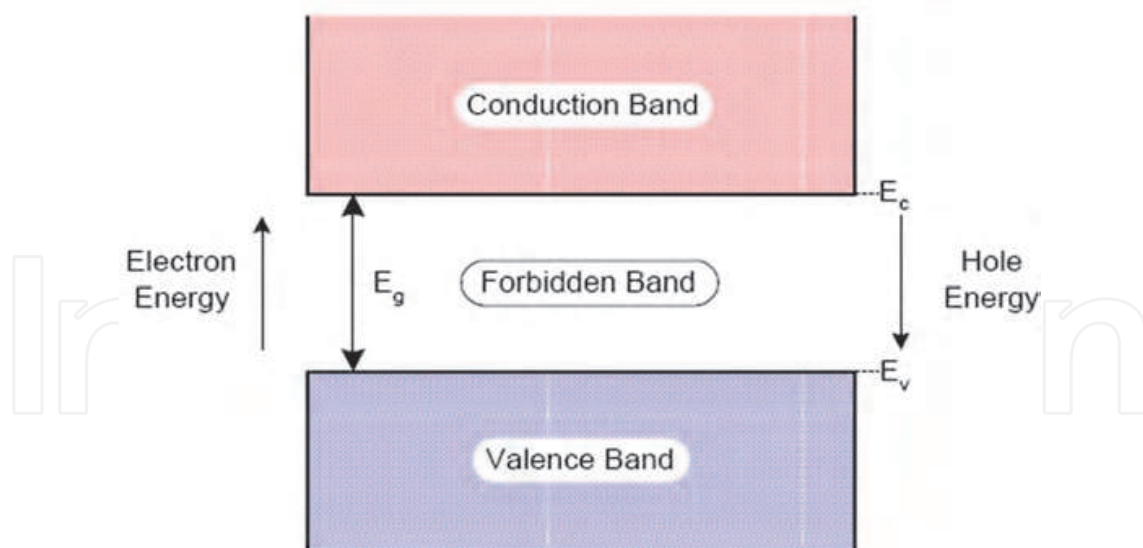

Fig. 3. Energy band diagram of a semiconductor (Ozpincci & Tolbert, 2003)

The characteristic of SiC diode being a wide bandgap semiconductor results in more energy to excite the electron from its covalent bonding during turn-off compared to SiS diode. As shown in Fig. 3, the energy level is measured from the distance between the conduction band and the valence band of the semiconductor that is $E_g = E_c - E_v$. An insulator would have a larger bandgap that it would take a lot of energy for the electrons to move from the

valence band to the conduction band whereas a conductor would have no forbidden band. The wider the bandgap of a semiconductor is, the more thermal energy is needed to excite the electrons to the valence band. Therefore a wide bandgap semiconductor could operate at higher temperature without affecting its electrical property.

3. Diode characteristics

The static property of a diode includes the I-V and reverse characteristics. The SiS diode would have a lower voltage drop than the SiCS diode. During turn-on, there is a high level injection of carrier for SiS diode that leads to a smaller amount of voltage to forward bias the diode. Due to smaller band-gap in SiS diode compared to SiCS, a higher voltage is required to forward bias the SiCS diode (Yahaya & Chew, 2004). However, SiCS can handle large reverse voltage before having an overshoot of leakage current compared to SiS diode.

The study also looks at the dynamic charateristics for both SiS and SiCS diode in terms of forward voltage drop, reverse recovery time and reverse recovery current which is given in Table 1 (Pierobon et al., 2002).

Characteristics	SiC Schottky (SDP 04S60)	Si Schottky (SB30-03F)
Reverse Recovery Time	Does not change much in change of temperature	Temperature dependent
Reverse Recovery Current	Negligible	Temperature dependent
Switching Losses	Low	High
Voltage (V) and Current (I) Rating	600V/4A	30V/3A

Table 1. Dynamic Characteristics Comparison

From Table 1, the dynamic characteristic of SiCS diode shows that the reverse recovery time is independent on temperature, in addition to having negligible reverse recovery current and low switching losses. On the other hand, SiS diode shows an increase in reverse recovery time, t_{rr} and reverse recovery current, I_{RR} as temperature increases as well as high switching losses.

3.1 Reverse recovery

Reverse recovery is one measurable quantity that can be used to indicate the performance and hence the efficiency of the device. The reverse recovery in a diode occurs when a device conducts in forward bias long enough to establish steady state due to the presence of minority charge carriers. These charges must be removed prior to blocking in reverse direction (Ahmed, 1999).

Fig. 4 shows the characteristic of reverse recovery exhibited by a diode. The diode current conducts in reverse direction due to free carriers in the diode. The t_a is the time which is based on the charge stored in the depletion region of the junction. It is seen that the charges are removed faster in abrupt recovery as shown in Fig. 4 (b) compared to soft recovery, Fig. 4 (a).
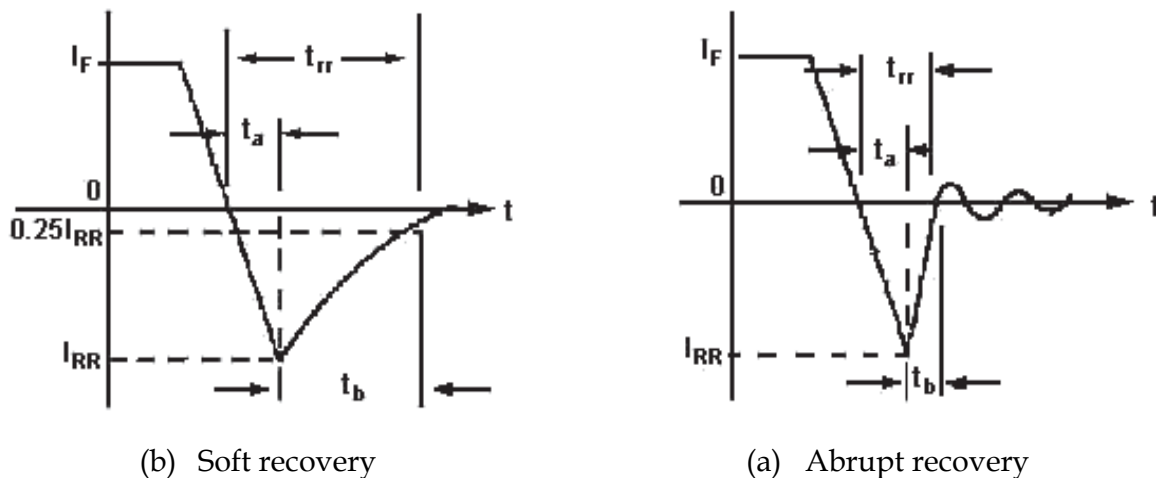
(b)   Soft recovery   (a)   Abrupt recovery

Fig. 4. Diode reverse recovery

The t_{rr} is obtained by adding t_a and t_b. Whilst reverse recovery current is the rate of fall current multiplied with the time taken due to stored charge. The I_{RR} is directly proportional to di/dt. The formula for I_{RR} is given by Eq. (1) (Power Electronic Circuits, 2006).

$$I_{RR} = \sqrt{(2 \times Q_{RR}\, di/dt)} \tag{1}$$

It can be seen that if the rate of fall current is high, the I_{RR} will also be high.

4. Methodology

A chopper circuit, better known as a dc-to-dc converter is used to obtain variable dc voltage from a constant voltage dc source. The SiS and SiCS diodes are characterized using this circuit. The diodes under test (D1_SiC and D2_Si) represent each of the diodes used in the simulation.

Major components used in the simulation are:

     M1 and M2: IRF520 – 9.2A/100V MOSFET

     DUT (D1_SiC): SDP06S60/INF – 6A/600V SiCS diode

        (D2_Si): SB30-03F – 3A/30V SiS diode

     R_{load} = 55 Ω

     I_{load} = 500 uH

The values of R_{g1} and R_{g2} used in the simulation are 21 Ω, with temperature at 27 ˚C and V_{cc} is 25 V.

The circuit shown in Fig. 5 is constructed by arranging the load resistor and load inductor in series whereas the diode under test is in parallel to the loads. The pulse voltage (V_{pulse}) is in series with the gate of MOSFET and a limiting resistor, R_{g1} is placed in between the gate and V_{pulse}.

The DC source current from Vcc will provide current during turn-on of the switch (MOSFET). The turn-on and turn-off of the switch will be determined by V_{pulse}. V_{gg1} will provide pulse signal to the MOSFET (M1) and the signal will appear at V_{gs}. The pulse signal will then forward bias the gate-source junction of the MOSFET, using current that passes through $R_{g1,}$ or known as I_g and eventually the voltage. As a result, the MOSFET is turned on. The drain current will increase slowly until the pulse signal drops to zero. The current

will stop flowing once I_g drops below the threshold value of the MOSFET. Since there is no current flowing through drain, the MOSFET is turned off.
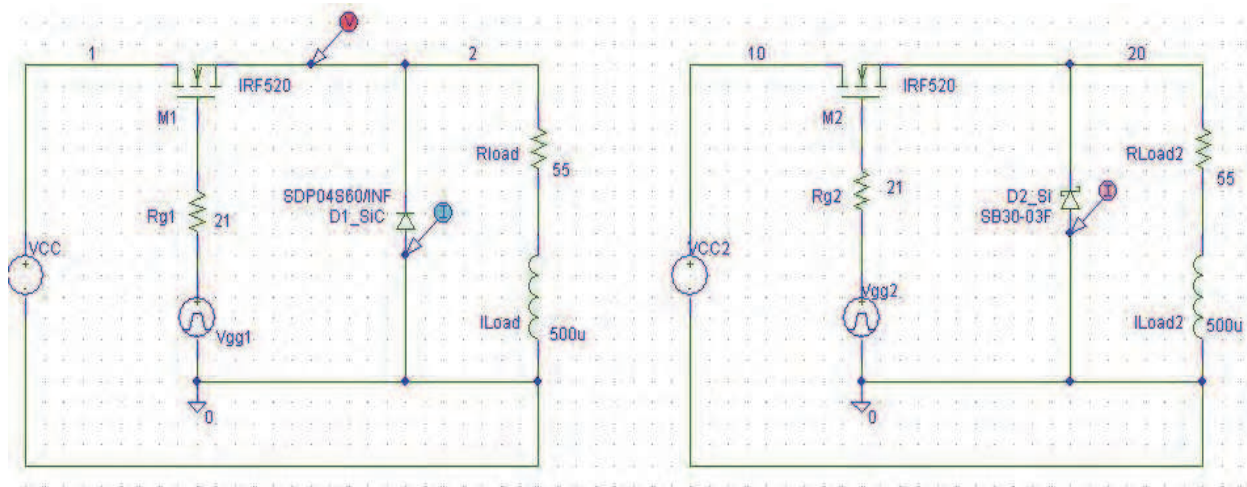

Fig. 5. Inductive Load Chopper Circuit

In the loop containing $D1\_SiC$, R_{load} and I_{load}, during turn-on of MOSFET, $D1\_SiC$ will be turned off due to no current flowing through $D1\_SiC$. The DC current from the DC source will flow through the resistor, R_{load}, inductor, I_{load}, drain of the MOSFET and then to the gate at the source of the MOSFET. When the current flows through I_{load}, it charges up the inductor.

$D1\_SiC$ is turned on once MOSFET is turned off. This occurs when current stored in the I_{load} (inductor) starts to flow and goes through $D1\_SiC$. $D1\_SiC$ will then be in forward biased until MOSFET is turned on again by V_{gg1} (V_{pulse}) signal. Just a few moment before $D1\_SiC$ is turned off, the current will be forced to flow in reverse direction. This is when reverse recovery current appears, which is the interest of this work.

The cycle of the signal will repeat again by charging and discharging I_{load} in inductor to turn on and off of the MOSFET and $D1\_SiC$. The PSpice settings are shown in Fig. 6.
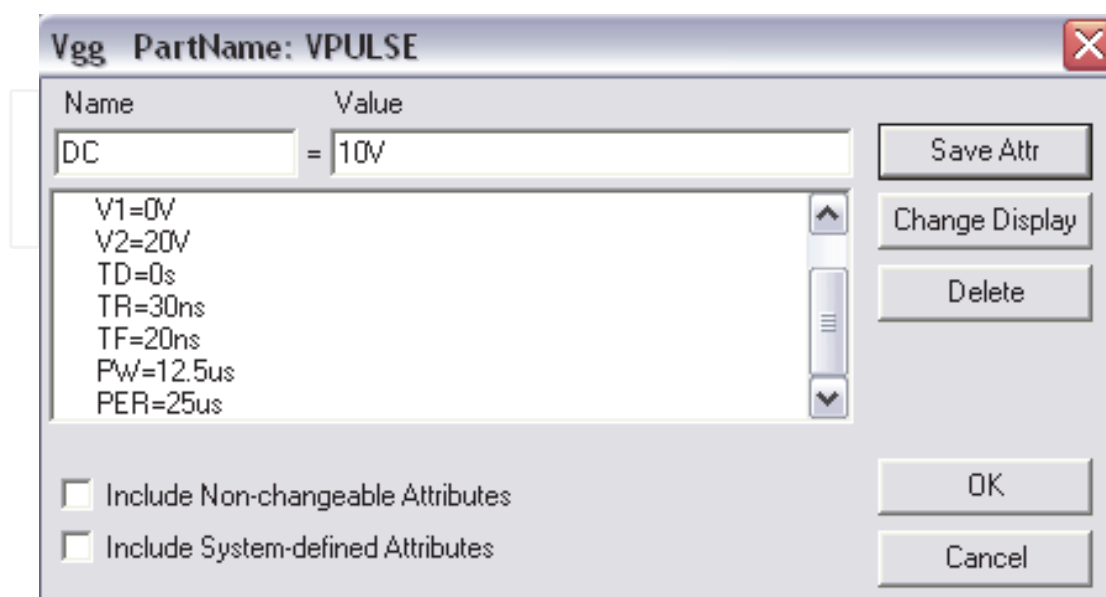

Fig. 6. V_{pulse} Setting

Fig. 6 shows the V_{pulse} setting used in this work. The DC voltage provided by the V_{pulse} is set to 20 V and the same applies to V2. V1 is set to be 0 V. V1 and V2 are for maximum and minimum voltage of the pulse respectively. The rise and fall time of the pulse are both configured to be 30 ns and 20 ns. The frequency of the pulse is 40 kHz with 0.5 duty ratio. Therefore, the period (PER) is 25 μs and the pulse width (PW), 12.5 μs, representing the 0.5 duty ratio.
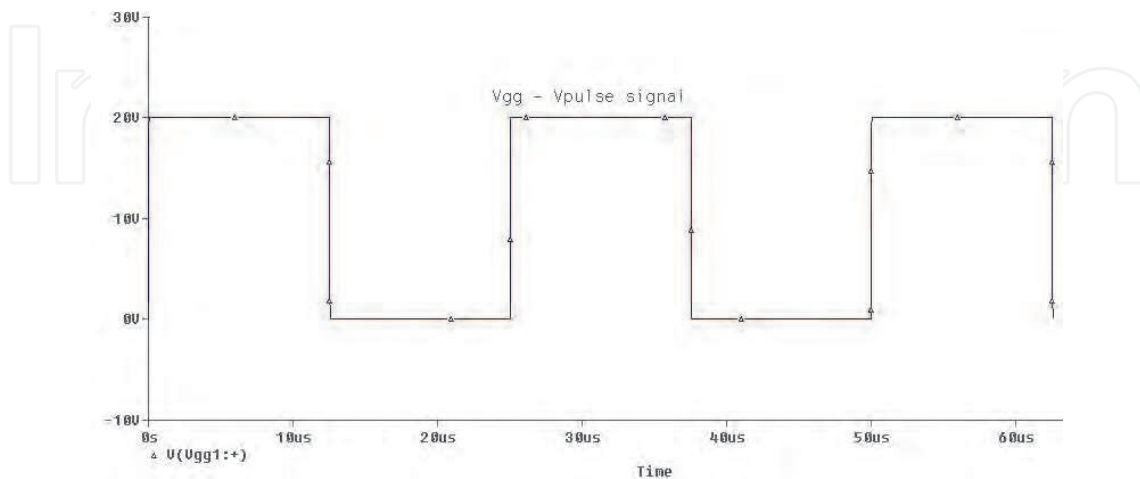

Fig. 7. V_{gg1} (V_{pulse}) Signal

Fig. 7 shows the signal waveform from the V_{pulse}. The signal is the same for both circuits since the parameters used in both circuits are identical. Here, V_{pulse} for SiCS diode circuit is shown to represent V_{pulse} for both circuits. The correct signal shows square wave with pulse period of 25 μs and the maximum voltage is at 20 V whereas the minimum is 0 V. For the duty ratio of 0.5, half period is seen at 12.5 μs.

4.1 Finding V_{gs} and V_{ds}

In order to find the voltage across gate (g) and source (s) of the MOSFET, voltage-differential marker is used. The marker will be placed at the gate and source according to polarity and current flow. The illustration is shown in Fig. 8.
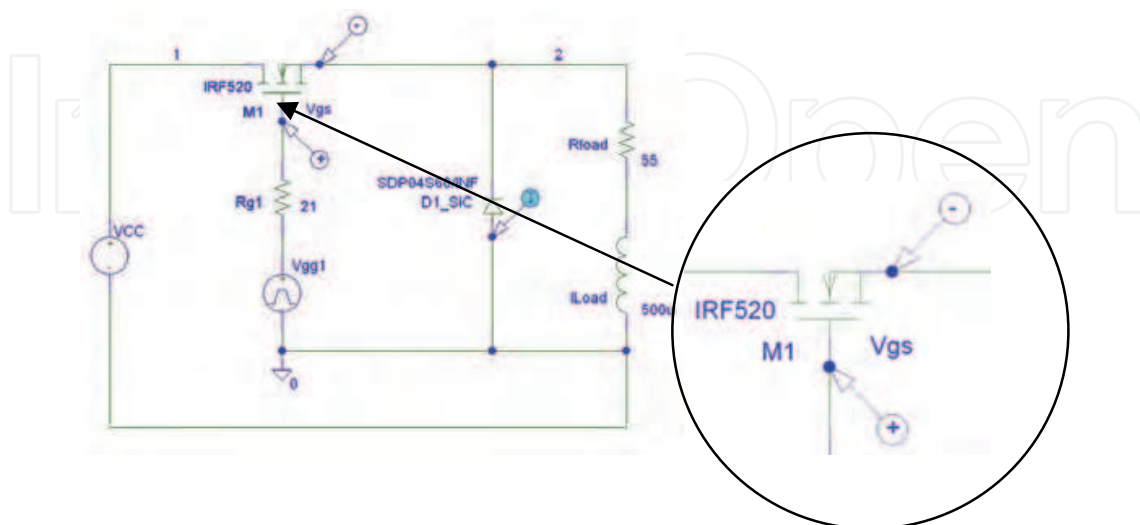

Fig. 8. Finding V_{gs} of Silicon Schottky and Silicon Carbide Schottky diode using voltage differential probe.

Again, similar method is applied to measure V_{ds}. The voltage differential marker is placed at the drain and source of the MOSFET as shown in Fig. 9.
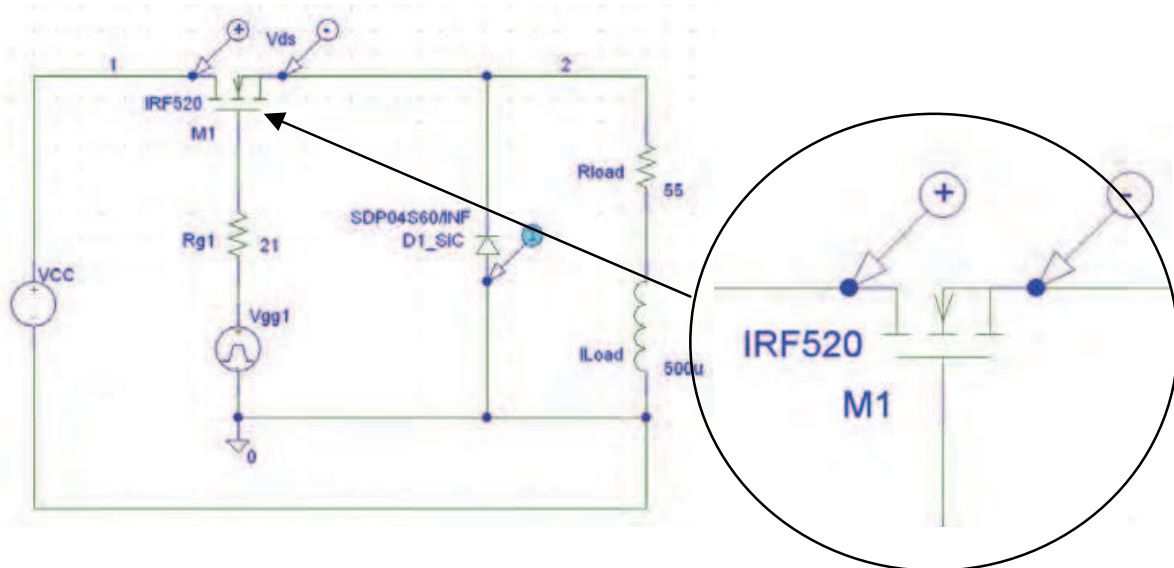

Fig. 9. Finding V_{ds} of Silicon Schottky and Silicon Carbide Schottky diode using voltage differential probe.

The simulation is carried out one at a time starting with finding the voltage across gate and source, and then followed by finding the voltage across the drain and source. Any overshoots or ringing will be noticed and the results are measured.

4.2 Finding reverse recovery current

The next process in the simulation is to capture the reverse recovery current produced by SiCS and SiS diode. The current marker is now placed at the node terminal of the diode and then the circuit is simulated.

Fig. 10 shows the location where current marker/probe is placed on the circuit in order to measure SiCS and SiS currents.
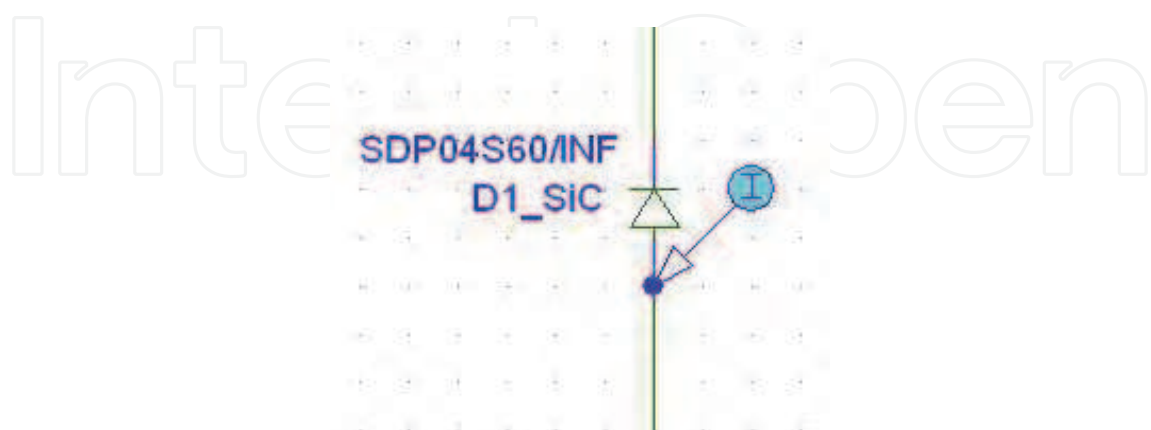

Fig. 10. Current probe placed on the diode under test (DUT)

A diode current will be displayed and by using the 'zooming' tool, the reverse recovery currents of both diodes are measured and analyzed.

4.3 Finding diode turn-off power loss and MOSFET turn-on power loss

The PSpice software is already equipped with a function in calculating power loss. The conventional way is by using the equation P = IV, but by using PSpice, the power loss can be measured straightforward. The power loss function is within the 'add trace' function for example W(M1) and W(M2).

4.4 Finding the effect of varying frequency to the reverse recovery loss in the diode

The frequency of the inductive load chopper circuit used in this project is obtained from the V_{pulse}. Therefore, in order to vary the frequency, the period (PER) within the V_{pulse} setting will be adjusted according to formula *f=1/T*, where in this case T is the period (PER). It is also noted that after the period has been changed, the PW (pulse width) is changed to configure 0.5 duty ratio setting.

5. Results and discussion

The overshoot gate and drain voltages of MOSFET during turn-on in both circuits are measured based on SICS and SiS diodes as well as the load current. In addition, the respective turn-off reverse recovery overshoot current is also determined to observe the influence of carbide material property in the diode.

5.1 Results of V_{gs} and V_{ds}

Fig. 11 shows the voltage waveform of V_{gs} for SiCS and SiS diode. There is voltage overshoot seen during the turn-on of the MOSFET and in Fig. 12, the overshoot portion (circle) is enlarged.
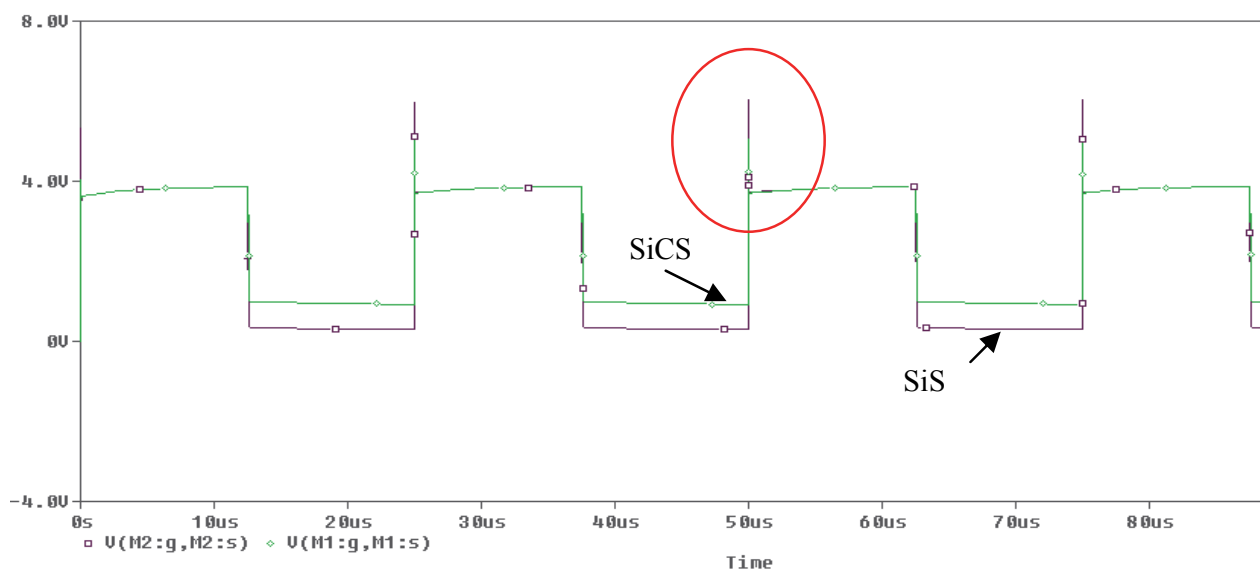

Fig. 11. V_{gs} of switch M1 and M2 applied at SiC Schottky Diode and Si Schottky Diode Circuit respectively.

As seen in Fig. 12, the overshoot voltage of MOSFET using SiS diode is higher than using SiCS diode with 6.0217 V, compared to MOSFET with SiCS of only 5.0484 V.

From this result, MOSFET turn-on power loss is also smaller in SiCS diode circuit compared to SiS circuit, due to low voltage ringing during turn-on, which will be later discussed in this chapter.

Fig. 13 shows the voltage across drain and source of the MOSFET for both circuits using SiCS and SiS diode. On the other hand, Fig. 14 shows the overshoot during turn-on as referred to the circle shown in Fig. 11.
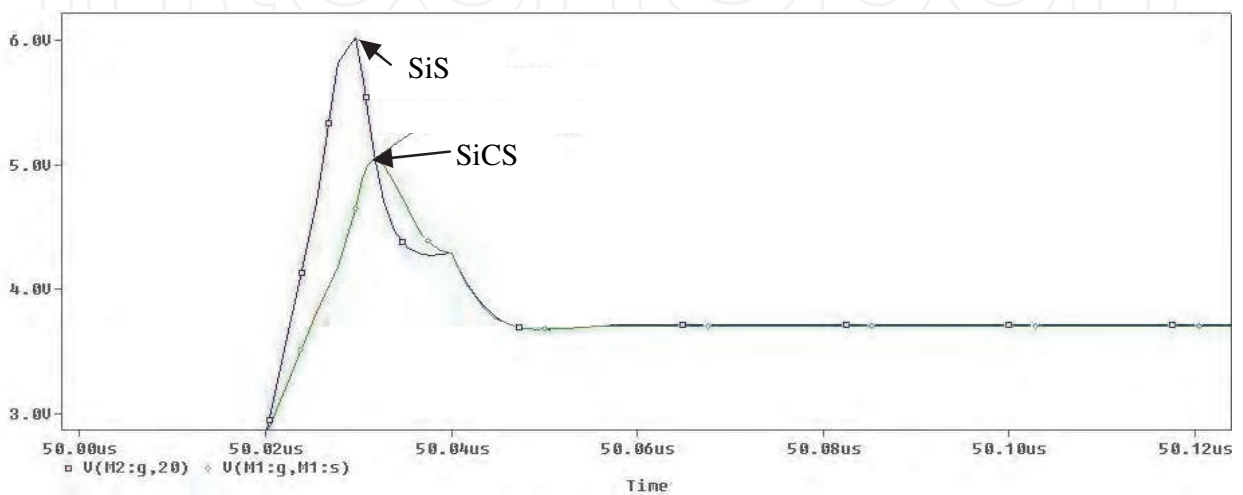
Fig. 12. V_{gs} overshoot of M1 (SiCS circuit) and M2 (SiS circuit)
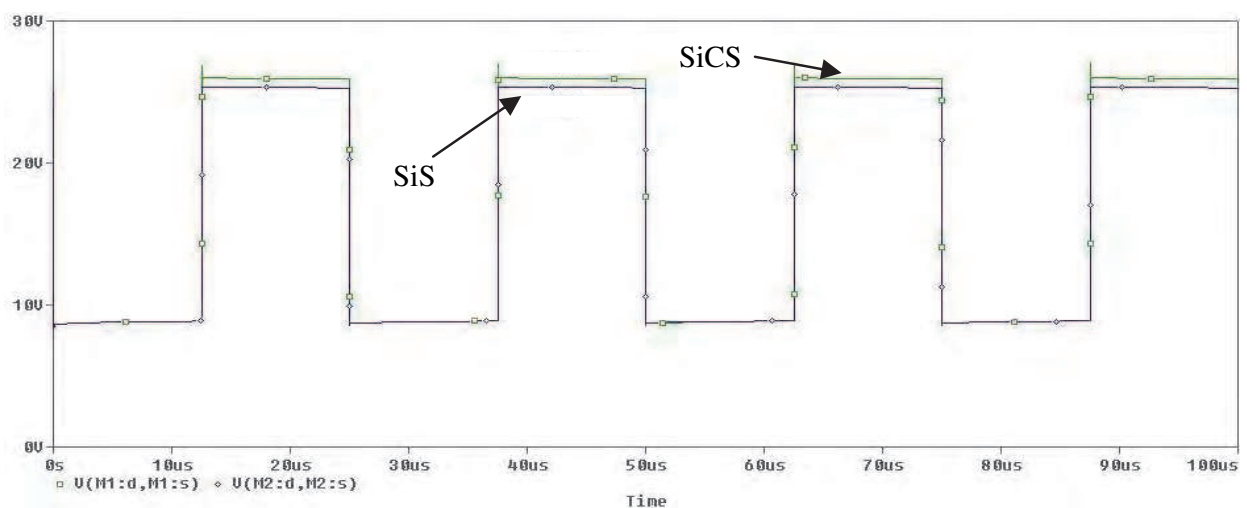

Fig. 13. V_{ds} of switch M1 and M2 applied at SiC Schottky Diode and Si Schottky Diode Circuit respectively

From Fig. 14, it is noticed that the MOSFET's V_{ds} overshoot is visible in SiCS diode circuit having value of 26.956 V. Whilst for SiS diode circuit, no overshoot is recorded at V_{ds}. However, the peak V_{ds} value is 25.277 V for SiS better than SiCS. This is the drawback found in the findings.

Fig. 15 indicates the load resistor's current, I_{Rload} for both circuits. From the figure, the maximum value of I_{Rload} in SiCS diode circuit is 230.766 mA, with a minimum of 45.078 mA. As for I_{Rload} in SiS diode circuit, the maximum is 232.897 mA and minimum of 54.207mA. The values obtained from Fig. 15 above will be used to calculate load output power of the circuits.
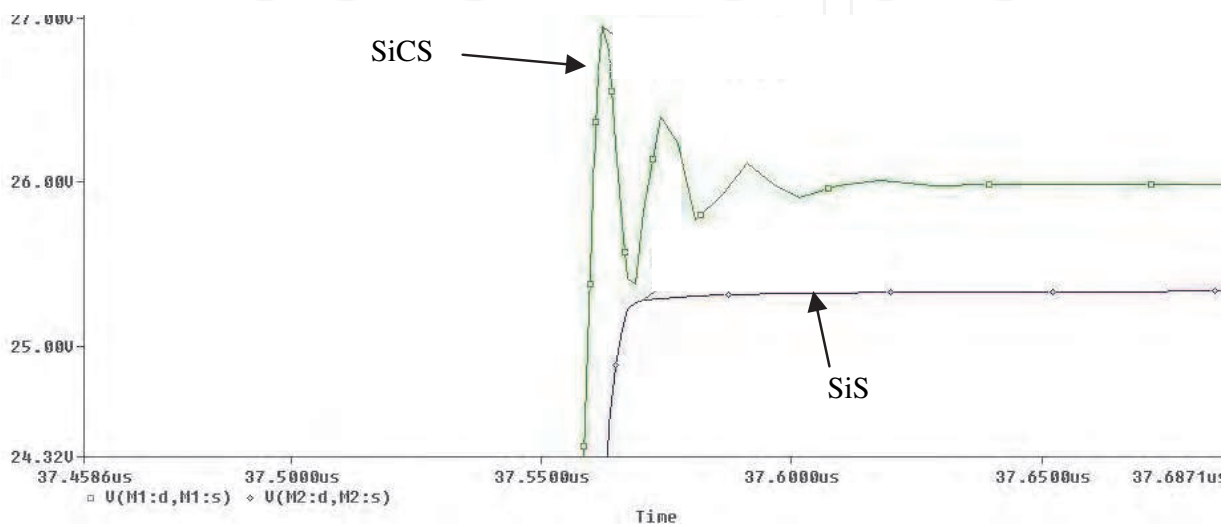

Fig. 14. V_{ds} overshoot of forward switch M1 (SiC circuit) and M2 (Si circuit)
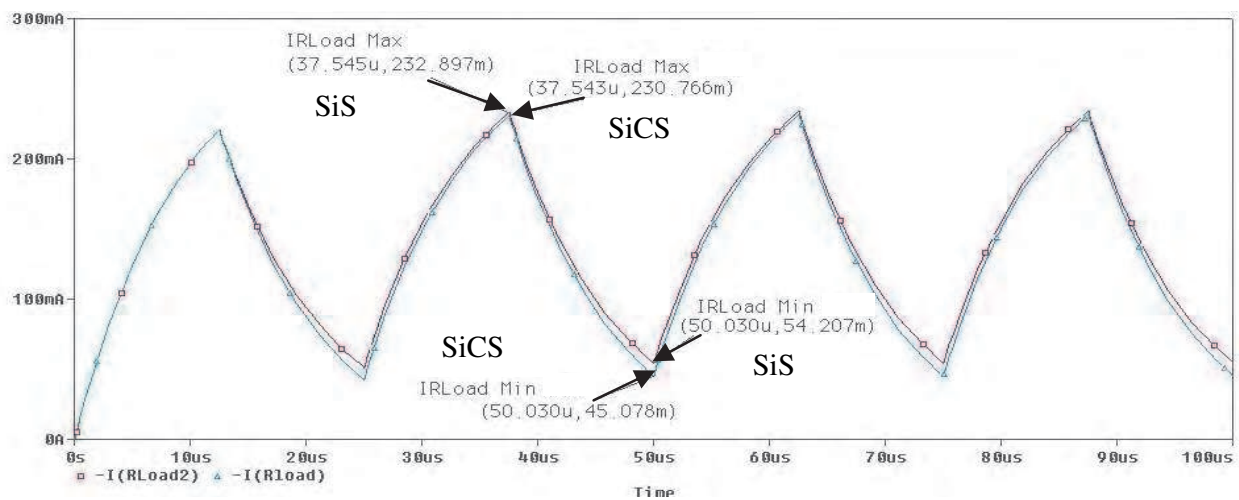

Fig. 15. I_{Rload} for Silicon Carbide Schottky and Silicon Schottky Circuit

The load power for the circuits are obtained from calculation:
a.   Silicon Carbide Schottky diode circuit:

$I_{Rload,avg}$ = ($I_{Rload,max}$ - $I_{Rload,min}$) / 2
          = (230.766 mA – 45.078 mA) / 2
          = 92.844 mA

With R_{load} value of 55 Ω, the output power (P_{out}) is obtained:

P_{out} = $I_{Rload,avg}^2$ x $R_{Rload,load}$
      = (92.844 mA)^2 x 55 Ω
      = 474.100 mW

b.   Silicon Schottky diode circuit:

$I_{Rload,avg}$ = ($I_{Rload,max}$ - $I_{Rload,min}$) / 2
          = (232.297 mA – 54.207 mA) / 2
          = 89.045 mA

With R_{load} value of 55 Ω, the output power (P_{out}) is obtained:

P_{out} = $I_{Rload,avg}^2$ x $R_{Rload,load}$
      = (89.045 mA)^2 x 55 Ω
      = 436.096 mW

From the calculation, the output power, P_{out} generated by SiCS diode circuit is 474.100 mW and 436.096 mW for SiS diode circuit. The Pout of SiCS diode is higher by 8.016 %. This is because SiCS diode provides higher output current, thus higher efficiency.
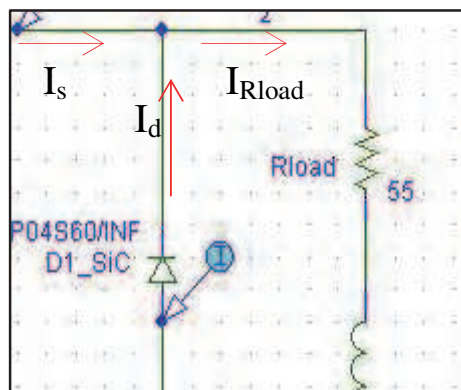

Fig. 16. Source current, I_s, Current across diode, I_d and load current, I_{Rload}

Fig. 16 shows the flow of current to the load. This explanation is referred to current divider for diode current, $I_d = I_s - I_{Rload}$. The I_{Rload} of SiCS diode is obviously lower than SiCS due to lower I_{Rload}. Therefore, the SiS diode is proven to have larger power loss.

The carbide element in SiCS diode helps in increasing the output current and hence the output power of the circuit. This is due to the fact that SiC has lower reverse recovery current, I_{RR} thus lower power losses at the diode during turn-off.

5.2 Results of reverse recovery current

From Fig. 17, it can be seen that there are negative overshoot during turn-off of the diode having I_{RR} below 0A. In this simulation, the transient setting is set to be 100 µs.

Fig. 18 shows a significant difference of I_{RR} overshoot between SiCS diode and SiS diode. It is observed that the I_{RR} of SiS diode is -1.0245 A, whereas -91.015 mA for SiS diode. The

advantage of carbide is that the leakage current from anode to cathode is lower due to the fact that SiC structure of metal-semiconductor barrier is two times higher than Si and its smaller intrinsic carrier concentration (Scheick et al., 2004), (Libby et al., 2006). The I_{RR} in SiCS diode is also smaller than SiS as SiC has no stored charges where a majority carrier device could operate without high-level minority carrier injection. Therefore, during the turn-off of the SiCS diode, most of the stored charges are removed (Bhatnagar & Baliga, 1993). The low switching losses of SiCS diode is due to high breakdown field of SiCS which results in reduced blocking layer thickness, in conjunction to the reduced charges (Chintivali et al., 2005).
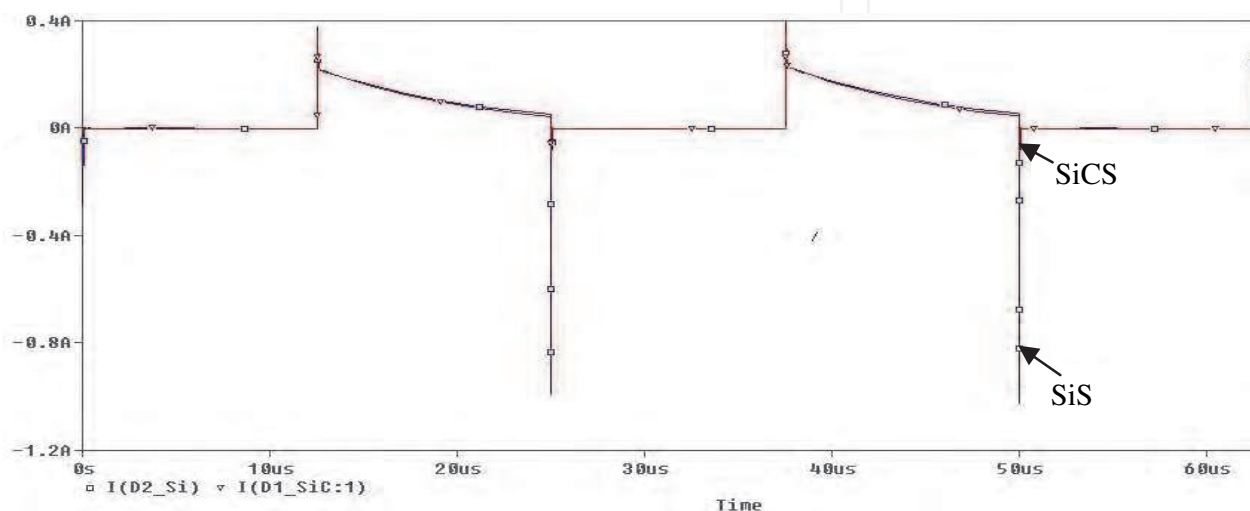

Fig. 17. Diode Current, I_d at Silicon Schottky and Silicon Carbide Schottky Diode
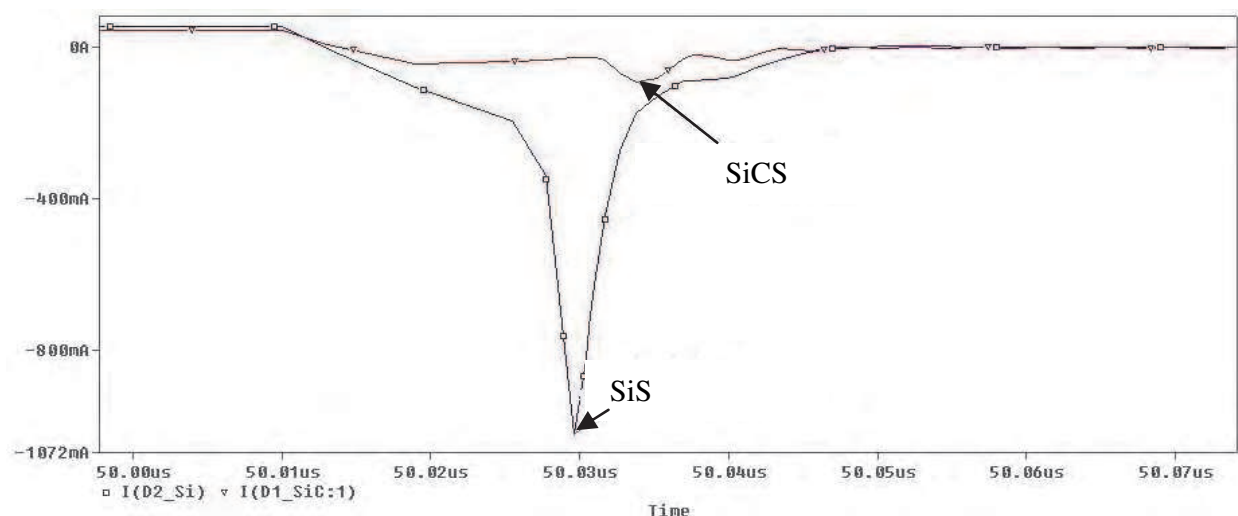

Fig. 18. Reverse Recovery Current of Silicon Schottky and Silicon Carbide Schottky Diode

From Fig. 19, it can be seen that SiS diode has a turn-off loss of 3.0704 W larger than SiCS diode, 818.590 mW. With higher I_{RR}, more power loss will be dissipated because more power is required for the diode to be fully turned off due to a larger stored charge.
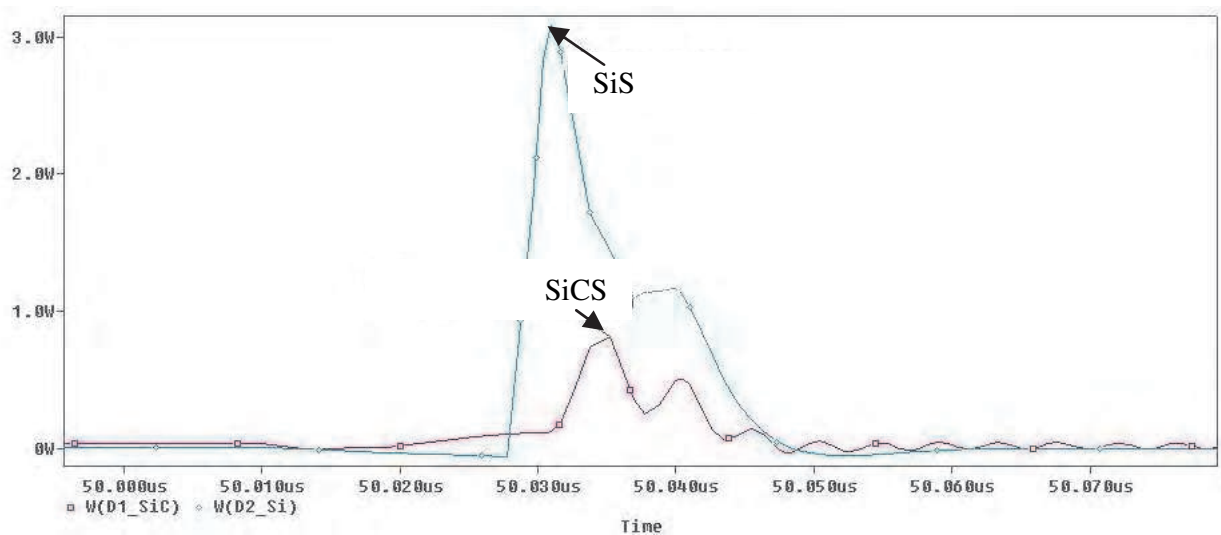

Fig. 19. Turn Off Loss of Silicon Schottky and Silicon Carbide Schottky Diode

Fig. 20 shows that MOSFET turn-on power loss in SiS diode circuit (20.619 W) is higher than in SiCS diode (790.777 mW). The higher power loss of MOSFET SiS diode indicates higher power loss produced by the diode during turn-off. The carbide material in SiCS diode is the main factor why such lower power loss is generated. From the results for Vgs of the MOSFET, it can be seen that lower current spike is observed in SiCS diode circuit during turn-on. With lower voltage ringing effect in SiCS diode, lower power loss will be produced by the MOSFET. It is found that, carbide material in SiCS diode has eventually given some influence in improving the circuit's performance.
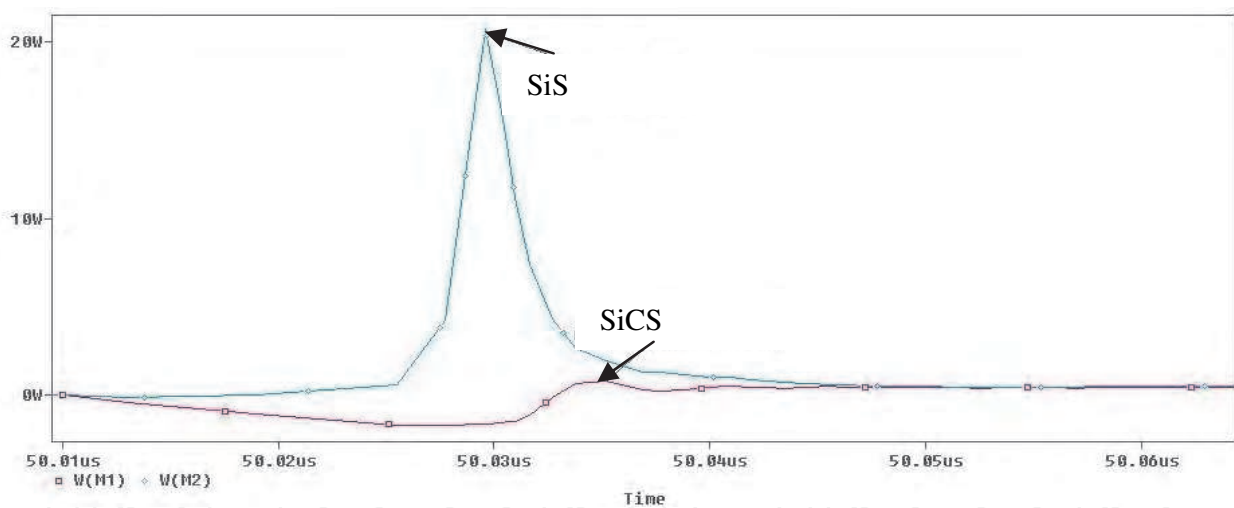

Fig. 20. MOSFET turn-On Power Loss during DUT turn-Off

Characteristics	Si Schottky Diode	SiC Schottky Diode	Percentage Improvement (%)
Output Power, P_{out}	436.096mW	474.100mW	8.016%
Peak Reverse Recovery Current, I_{rr}	-1.0245A	-91.015mA	91.12%
DUT Turn-Off Loss	3.0704W	818.59mW	73.34%
MOSFET Turn-On Loss	20.619W	790.777mW	96.16%

Table 2. Simulation Results

From Table 2, SiS diode has higher peak I_{RR} of -1.0245 A compared to SiCS diode, -91.015mA. As for turn-off loss of both diodes, it also shows that SiS diode generates more losses. This is also applied to MOSFET power loss during turn-on where there shows an improvement of 96.16 % when SiCS diode is used.

5.3 The effect of varying frequency to the reverse recovery loss of the diode under test (DUT)

From Fig. 21, it is obvious that SiCS diode circuit does not experience much difference in frequency variation. As for SiS diode, it shows an increase in power loss. However, it is also noted that once frequency is higher than 50 kHz, the power loss in SiS diode is maintained at around 3.6 W to 3.7 W. Nevertheless, SiCS diode has shown the ability in operating at higher switching frequency with minimal power loss.
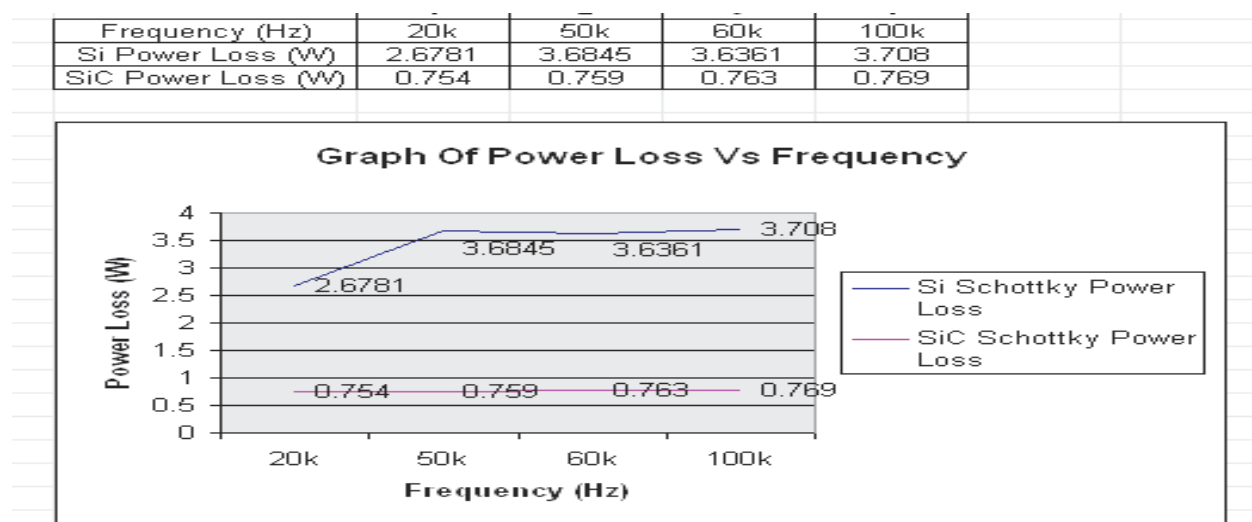
Frequency (Hz)	20k	50k	60k	100k
Si Power Loss (W)	2.6781	3.6845	3.6361	3.708
SiC Power Loss (W)	0.754	0.759	0.763	0.769

Fig. 21. Graph of Power Loss vs Frequency of Silicon Schottky and Silicon Carbide Schottky Diode

6. Conclusion

This work is about the comparative study of silicon schottky and silicon carbide schottky diode using PSpice simulation. An inductive load chopper circuit is used in the simulation and the outputs in terms of reverse recovery, turn-off power losses of both diodes and turn-on losses of the MOSFET are analyzed. It is proven that silicon schottky diode has produced

higher reverse recovery current than silicon carbide schottky diode. Therefore, lesser power losses are generated in silicon carbide schottky diode with 91.12 % improvement. The results also confirmed that the ringing at the switch (MOSFET) has been reduced by 16.16 %. Eventually, the carbide element has helped in achieving higher output power by 8 %. The turn-off losses in diodes have also been reduced by 73.34 % using silicon carbide schottky diode as well as the MOSFET turn-on power losses which is reduced by 96.16 % mainly due to the reduction in reverse recovery current.

7. Acknowledgment

8. References

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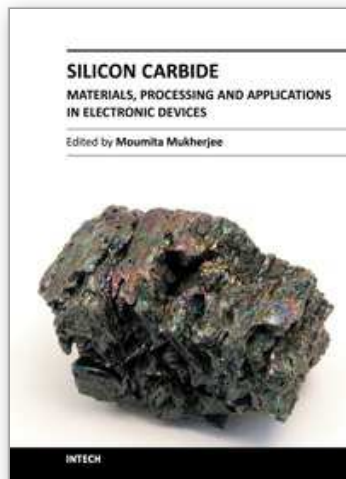
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Silicon Carbide (SiC) and its polytypes, used primarily for grinding and high temperature ceramics, have been a part of human civilization for a long time. The inherent ability of SiC devices to operate with higher efficiency and lower environmental footprint than silicon-based devices at high temperatures and under high voltages pushes SiC on the verge of becoming the material of choice for high power electronics and optoelectronics. What is more important, SiC is emerging to become a template for graphene fabrication, and a material for the next generation of sub-32nm semiconductor devices. It is thus increasingly clear that SiC electronic systems will dominate the new energy and transport technologies of the 21st century. In 21 chapters of the book, special emphasis has been placed on the â€œmaterialsâ€ aspects and developments thereof. To that end, about 70% of the book addresses the theory, crystal growth, defects, surface and interface properties, characterization, and processing issues pertaining to SiC. The remaining 30% of the book covers the electronic device aspects of this material. Overall, this book will be valuable as a reference for SiC researchers for a few years to come. This book prestigiously covers our current understanding of SiC as a semiconductor material in electronics. The primary target for the book includes students, researchers, material and chemical engineers, semiconductor manufacturers and professionals who are interested in silicon carbide and its continuing progression.

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