Investigation of the Total Energy Losses for Si and Sic Shottky Diodes

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ABSTRACT

This research serves as basis to investigate the total energy losses in DC-DC converter circuit. The circuit used for the investigation was the inductive load chopper circuit .Two diodes were used one is the Silicon PiN diode (8A/600V) the other is Silicon Carbide Schottky diode (6A/600V).The waveforms of current and voltage diode under test (DUT) and IGBT are measured respectively and compared them with the simulation results. The gate resistance R_G was also changed to further investigate the effect of di/dt of the DUT current during turn-on of the switch on the total energy losses in the system.

Keywords: Loss model; Schottky diodes; Silicon Carbide; PiN;

تحقيق الخسائر الكلية بالطاقة للسليكون والسليكون كربايد لدايود نوع شوتكي

الخلاصة

هذا البحث يستند لتحقيق اجمالي خسائر الطاقة في دائرة تحويل ,DC-DC; الدائرة كانت تستخدم لتحقيق حمل دائرة الاستقراراني حيث استخدمت دايودين واحد من نوع الصمام الثنائي (8A/600V) والاخر دايود صمام ثنائي السليكون نوع كاربيد شوتكي (8A/600V) الحرارة كانت ثابتة مع متغيرات اخرى مثل المدخل وفولتية الحمل والتردد وعامل الجودة .

تم اخذ شكل موجة التياروالفولتيات DUT,IGBT التي قاسوها وقارنوها مع نتائج المحاكاة. كما تم تغيير المقاومة RG لتحقيق تاثير تغير التيار من خلال تحويل تيار DUTوخسائر اجمالي الطاقة في النظام .

INTRODUCTION

The development of DC-DC convert in daily high power application has led to the study in the diode characteristics and behavior. The use of silicon carbide (SiC) Schottky diode reduces the total energy losses compared to silicon Pin (Si PiN) diode. Having a lower diode reverse recovery current, hence low stored charged (Qrr) during turn – on of the switch, makes the system less stress.

Two stages were taken in completing this research, first, pspice simulation was use to investigate theoretically the amount of energy losses from each diode and

IGBT during turn-on period of the switch and hence the total energy losses. Once the simulation results were taken then second stage proceeded. The second stage was to work on the actual experiment using the inductive load chopper circuit's .The waveforms of current and voltages of respective diode and IGBT are saved and saved and measured as the basis to do the comparison (simulation and experiment).

The investigation continues with difference in gate resistance R_G, which changes the current drive to the IGBT. The purpose is to investigate the effect on the di/dt of the diode current on the total energy losses in the system. For consistency all parameters are set fixed (input and load voltages, temperature, frequency, duty ratio) whilst the diodes are only changed to ease the comparison.

Switching Characteristics

Transient performance of the diode includes the switching performance under a variety of circuit conditions. The test circuit used to accurately measure and characterize the ramp reverse recovery of rectifiers is shown in Figure (1). Reverse recovery occurs when a forward conducting diode is turned off rapidly, and the internally stored charges cause transient reverse current to flow at high reverse voltage [1,2]

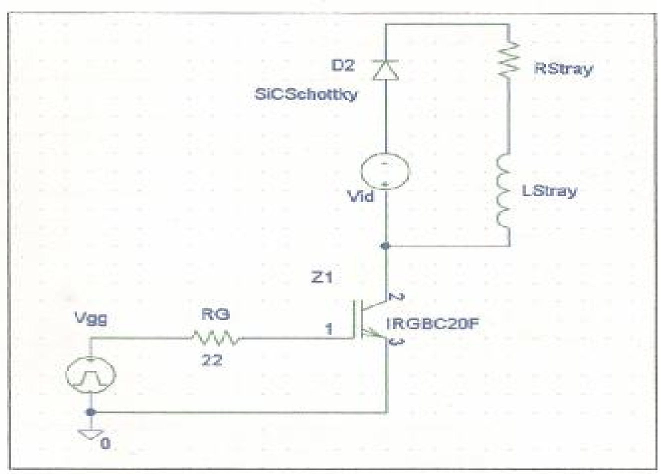


Figure (1) Reverse recovery test circuit.

Initially, a pulse switches the IGBT on, to establish the current through the inductor. When IGBT is switched off, the inductor current freewheel through the diode. The diode is reverse biased and undergoes reverse recovery when IGBT is switched on for the second time. By changing turn-on speed of IGBT, the rate of change of current through diode is adjusted [3].

The IGBT gate drives impedance and gate drive voltage level were fixed to allow a specific reverse di/dt (480 A/μs) to be applied to DUT. The test is current generated by the IGBT is 28A with dc rail voltage of 400V [4]. The DUT involved were Si PiN and SiC Schottky diodes. From Figure (2) and Figure (3), they clearly show that SiC Schottky diode has superior reverse recovery characteristics, such as

lower reverse recovery current, having lower recovered charge and switching loss compare to Si PiN [5]. In comparing the IGBT turn-on losses, it revealed that the employment of SiC Schottky diode has significantly reduced the peak switching power and cumulative loss. The area under the zero
line (Q rr) is a measure of the amount of switching losses of the diodes [6].

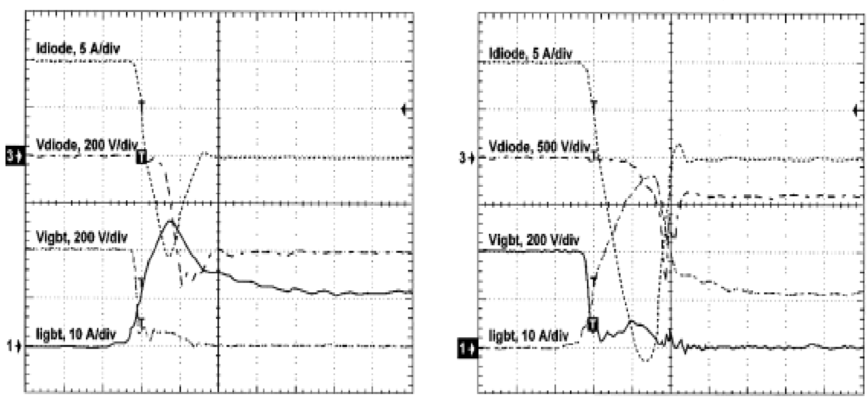


Figure (2) Voltage and current waveforms at 25^o C and 150^{o}C when Ultra-Fast PiN diode is used as DUT 50 ns/div ,di/dt=480A/us.

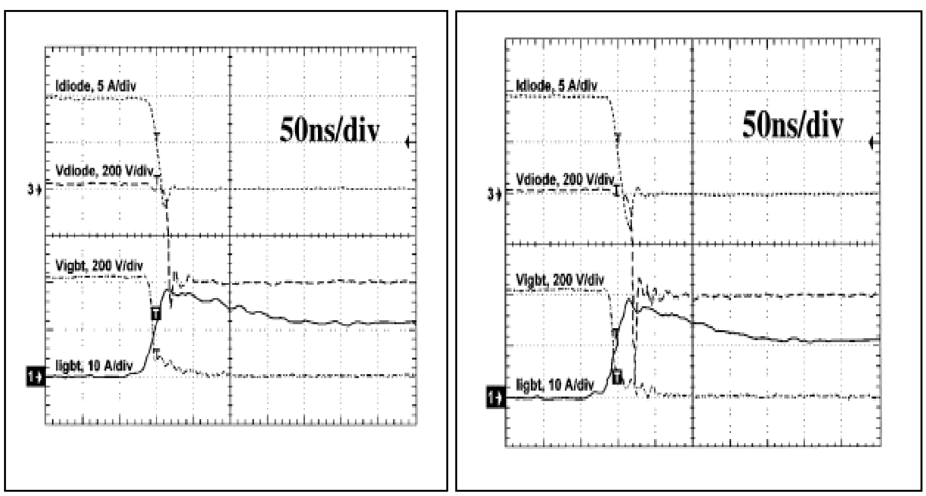


Figure (3) Voltage and current waveforms at 25^o C and 150^{o}C when SiC Schottky diode is used as DUT 50 ns/div, di/dt=480A/us.

The notable current spike in silicon diode is the reverse recovery current, which also gives rise to current spike in the IGBT. The reverse current is created when diode is subjected to reverse voltage. This reverse recovery current eventually affects the switching performance of the DUT and IGBT. Below is the summary of the diode and IGBT loss obtained from the switching measurement Table (1).

Table (1) Summary of Diode and IGBT Losses [3].

	DUT Tj=25℃		DUT Tj=150℃	
	Ultra Fast Si PiN Diode	SiC Schottky Diode	Ultra Fast Si PiN Diode	SiC Schottky Diode
Diode Losses	86μJ	8 μJ	268 μJ	26 μJ
IGBT Losses	88 μJ	56 μJ	172 μJ	56 μJ
Total Losses	174 μJ	64 μJ	440 μJ	92 μJ

Mathematical Explanation of Reverse Recover Current, Charge and Energy Losses.

As shown in Figure (4) the time interval $t_{rr}=t_1+t_3$ is termed as the reverse recover time. The "snappiness" factor S is the fraction of t_3 and t_1, which is said the lower value indicates the effectiveness of the reverse recovery of the diode [7].Assuming the area under negative portion of diode current waveform curve is triangular,

$$Q_{rr}=1/2(t_{rr}I_{rr}) \quad \text{... (1)}$$

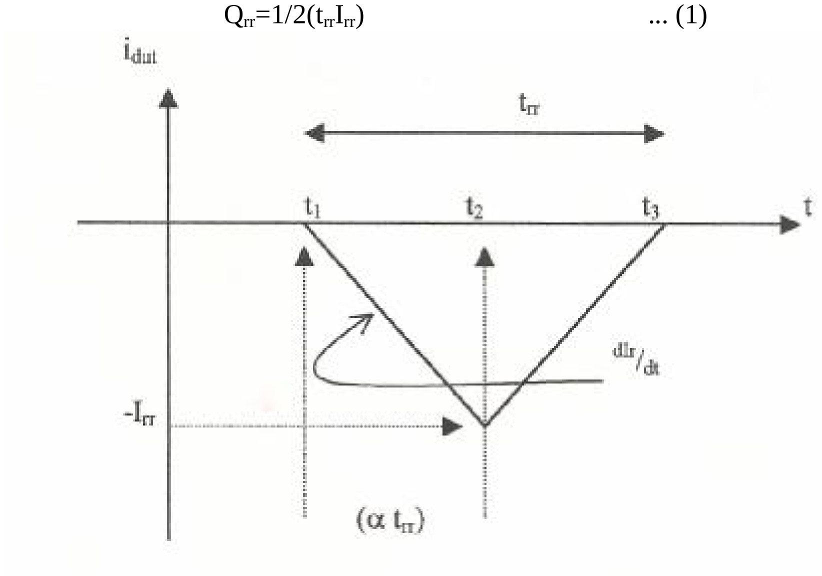


Figure (4) the area between t_1 and t_3 of reverse recovery current.

$$\text{Let } t_2-t_1=\alpha\ t_{rr} \quad \text{...(2)}$$

$$\text{So , } I_{rr}=(t_2-t_1)\ dI_r/dt$$

$$I = \alpha\ t_{rr}\ dI_r/dt \quad \text{... (3)}$$

This then make Qrr $=1/2\ t_{rr}\ (\alpha\ t_{rr}\ dI_r/dt\ )$

$$=1/2\ \alpha\ (t_{rr})^2\ \ dI_r/dt \quad \text{…(4)}$$

Both Q_{rr} and I_{rr} are the function of dI_r/dt. The higher the value of dI_r/dt the higher Q_{rr} and I_{rr} will be. The energy loses in diode can be formulated over t_2 to t_3, voltage across diode is approximately equal to negative dc voltage, by assumption to ignore overshoot. From this, the reverse recovery energy loss from the specified interval will be.

$$E_{rr} = \int_{t_2}^{t_3} (-V_{dc})(I_d)\,dt \qquad ...(5)$$

$$E_{rr} = -V_{dc} \int_{t_2}^{t_3} (I_d)\,dt\ , \qquad ...(6)$$

Where $\int (I_d)dt$ is the recovered charge, then we can conclude that the reverse recovery energy loss is as follow:

$$E_{rr} = (1-a)V_{dc}Q_{rr} \qquad ...(7)$$

Total Power Loss

Overall performance of the Si PiN Schottky diode can be determined by the total power loss versus switching frequency .The approach used to evaluate the devices is based upon the total losses namely the turn-on and turn-off losses in the IGBT and the reverse recovery loss in each diode(8)Figure (5) shows the total power loss density versus switching frequency of the system measured at lower and higher temperature. It can be noted that at lower temperature SiC Schottky diode performances is far superior to that Si PiN diode however, at higher temperature the forward voltage drop of the SiC Schottky diode increases resulting in higher losses as compared to the Si diode at switching frequency below 6KHz It is apparent to observe that SiC Schottky diode becomes obvious to have advantages at higher switching frequencies.

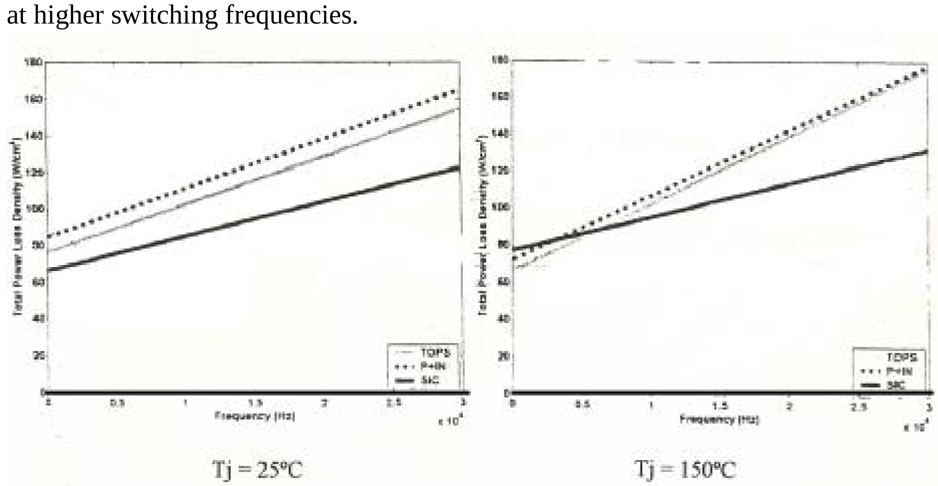


Figure (5) Total power loss density versus switching frequency for Tj=25^{o}C and Tj=150^{o}C.

The overall power loss of the Si PiN and SiC diodes would only be comparable at a switching frequency of 250 KHz [9]. At a switching frequency of 6-7 KHz the

SiC diode has an order of magnitude loss than the Si diode. This strongly indicates that SiC diodes have superior performance over Si diode in high voltage applications with high-switching frequency. In addition, SiC diode can operate at higher temperature than is possible with Si devices.

Turn off Loss

There is no turn off loss occurred. If so, the energy loss is at the minimal value, which can be ignored. During turn off of the switch, the current in the diode is conducting whilst the voltage applied across it decaying to zero. This means that in theory, the energy loss will be zero. That is why the energy loss during this period is not included.

Varying Gate Resistant (RG)

Gate resistance plays an important role in generating di/dt through the diode during turn on of the switch. By having the higher R_G, the di/dt of the current will eventually reduce. This results to lower energy loss in the diode. However, the energy loss in the IGBT increases and hence the total energy loss. In conclusion, optimizing the correct value of RG is essential in determining the lowest possible total energy loss in the system.

METHODOLOGY

This paper involves two stages. First is the simulation using Pspice software. Next is stage is the actual experimentation. All of these stages require precise work and set up especially during the experiment, where by it needs some extra components and adjustment to make the circuit work. Two boards are fabricated in this research. One for the use of Si PiN diode and the other is the SiC schottky diode. Both are the DUTs. Since the initial plan of the work was to use the high voltage (350V) input, due to the safety requirements, this value has been set lower to only 50V.However, the result patterns are still visible and considerable.

Step One-Pspice simulation

The initial stage was to find the suitable circuit to test for the diode. The circuit was found to be the Inductive Load Chopper circuit. It can be used to investigate the amount of energy trapped in the inductive load that is released through the freewheeling DUT during the turn-off period of the IGBT, hence the total energy losses. The circuits diagram that used for simulation is shown in Figure (6) and Figure (7) for Si PiN and SiC Schottky diode respectively.

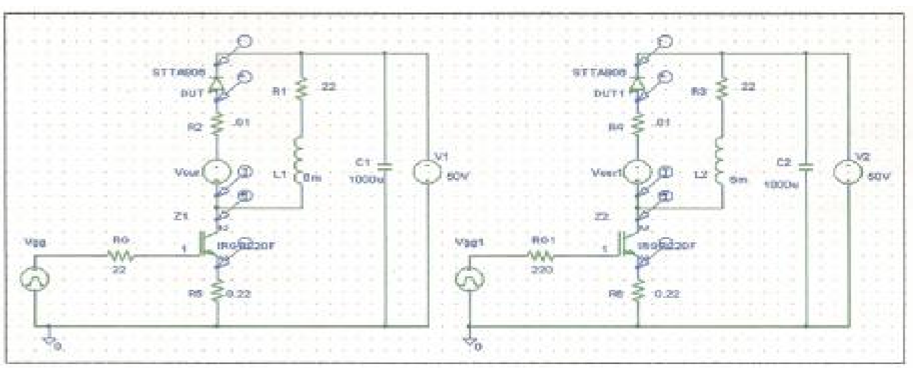


Figure (6) Pspice simulation circuit diagram for silicon PiN diode at R_G=22 ohms and R_G=220 ohms at 25°C.

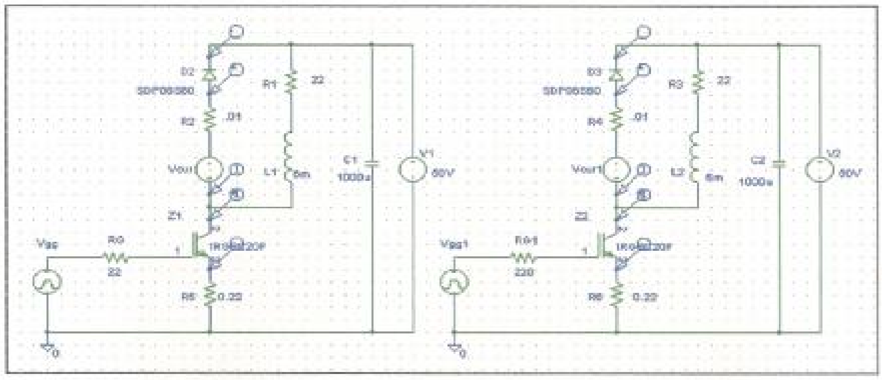


Figure (7) Pspice simulation circuit diagram for SiC Schottky diode at R_G=22 ohms and R_G=220 ohms at 25^{o}C.

Both circuits are simulated separately. Results are taken in terms of current and voltage waveform produced in the DUT and IGBT during turn-on of the switch, all of which are during steady state condition. The relevant results are shown in the ''Result and Discussion ''section.

The Experimental Steps

There were several steps have been done in the experiments and described as follows:

a) Input voltage of 15 volts was applied to the input of the circuit and 50V to the load.

b) Oscilloscope probe was connected to the output of the PWM to ensure the consistency of oscillation throughout the experiment.

c) The current probe was connected to the wire loop to measure of the DUT.

d) The voltage deferential probe was connected to the voltage terminal of the DUT.

e) Steps c) and d) were repeated for the IGBT.

f) The current and voltage were measured during turn-on time.

g) The gate resistance (R_G) was changed from 22 ohm to 220 ohm to investigate the effect on di/dt of the DUT current during turn-on of the switch.

h) The waveforms of current and voltage for each DUT and ICBT were taken and saved respectively.

i) Experimental result was then compared with the simulation results and conclusions will be drawn.

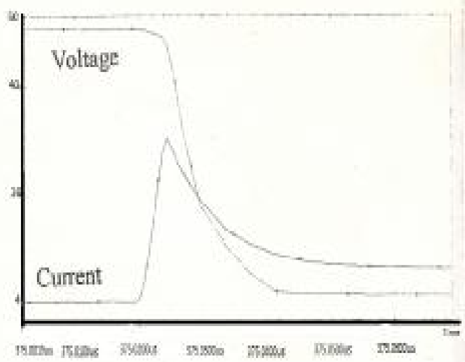
RESULTS AND DISCUSSIONS

The results show that there is significant difference in the waveforms of the current and voltage of both DUT and IGBT during turn-on. Form this information, the energy losses from each component are manually calculated. This is the area of product of current and voltage during the specific interval of ON time.

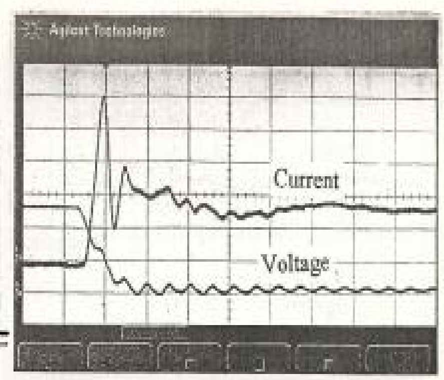
The Operation of Inductive Load Chopper Circuit

During IGBT turn-off, load current will be flowing through the freewheeling diode. When the IGBT turn-on again, the diode is forced to reverse recovery which is represented as an overshoot in the IGBT current waveform as shown in Figure (8) the diode used was the Silicon PiN diode rated 8A/600V (STTA806D). The identical concept applies for the Silicon Carbide Schottky diode rated 6A/800V (SDT06S60).

The IGBT current can be represented as the actual diode current which flows through the sense resistor (R_{sense}). The commutating di/dt of inductor (L) is mainly dependent on the applied reverse voltage and circuit inductance. Different in inductance value can result in different of di/dt effect on the diode current. However, this value used was fixed (6mH/3.5A). For low values of L, the di/dt is influenced by the IGBT turn-on. The voltage across the IGBT (Vcc) during the commutating phase is dependent on the rise time of the drain current [10]. This can easily be controlled by adjusting the gate resistance R_G. The voltage starts to establish across the diode during the reverse recovery stage and hence the Vcc will drop rapidly. This process continues in the next cycle of the switching.



(a)



(b)

Figure(8)IGBT [Si PiN] current and voltage during turn-on with R_G=22 Ohms .a)Simulation .b)Experiment .

Energy Losses using R_G = 22 ohms

There are two values of gate resistance used in this paper. The reason is to investigate the effect of the di/dt in the diode on the energy loss. This difference in R_G makes the current, which drive the IGBT lower or higher in value. The effect on this current at turn-on is an increase in turn-on losses. The simulation and experimental results are compared.

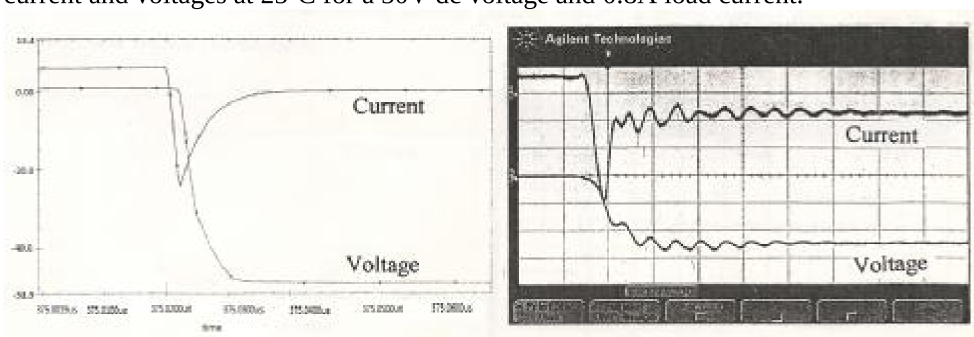
Silicon PiN Diode

For Silicon PiN diode, the reverse recovery current is about 1.6A with a di/dt of 167A/µs and the reverse recovery time (Trr) is 50ns, which makes Qrr equals to 40 nC. As in Table (2) the reverse recovery current contributes about 1680 nJ out of the total 2340 nJ IGBT turn-on losses. This result gives a measurement difference of 6.7% decrease compared to the simulation (1800 n/2400 nJ). Whilst, the diode recovery losses are only 660 nJ Appendix (C). All measured values are close enough to the simulation results. The total energy losses difference between experiment and simulation is 2.5% lower.

Table (2) Silicon PiN Diode and IGBT Energy Losses Summary for RG=22ohms.

Silicon PiN Diode	Eoff(diode)	Eon(IGBT)	Eon(Total)
Simulation	600 nJ	1800 nJ	2400 nJ
Experiment	660 nJ	1680 nJ	2300 nJ

The Figure (8) and Figure (9) below show the silicon PiN diode and IGBT current and voltages at 25^{o}C for a 50V dc voltage and 0.8A load current.

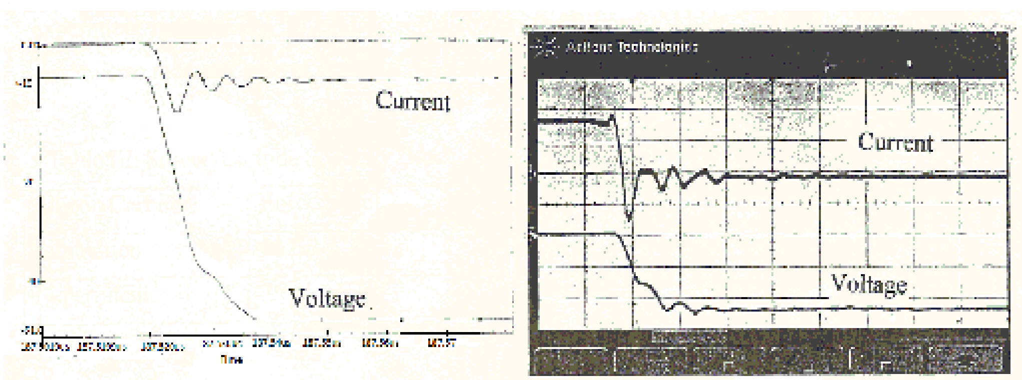


(a) (b)

Figure (9) Silicon PiN diode current and voltage during turn-on with R_G=22 Ohms a) Simulation. B) Experiment.

Silicon Carbide Schottky Diode

The Silicon Carbide Schottky Diode was then tested using the same procedures and parameters values. The waveforms of current and voltages of diode and IGBT are shown in Figure (10) and Figure (11). The comparison can easily be made by looking at the amount of current overshoot of the diode during turn-on period. Having a lower current dip makes the energy loss reduce substantially.



(a) (b)

Figure (10) Silicon Carbide Schottky current and voltage during turn-on with R_G=22 ohms a) Simulation. b) Experiment (0.5A/div, 20v/div, 50ns/div).

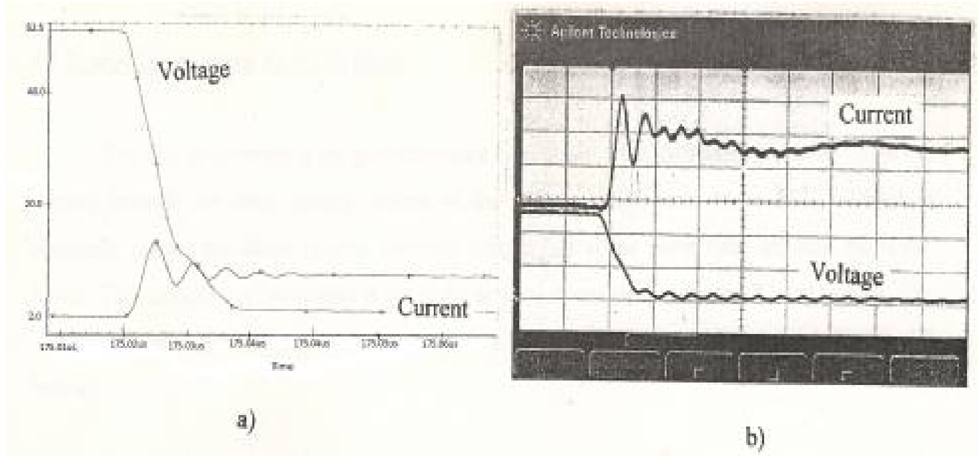


Figure (11) IGBT (SiC Schottky) current and voltage during turn-on with R_G=22 ohms a) Simulation. b) Experiment (0.5A/div,20v/div,50ns/div).

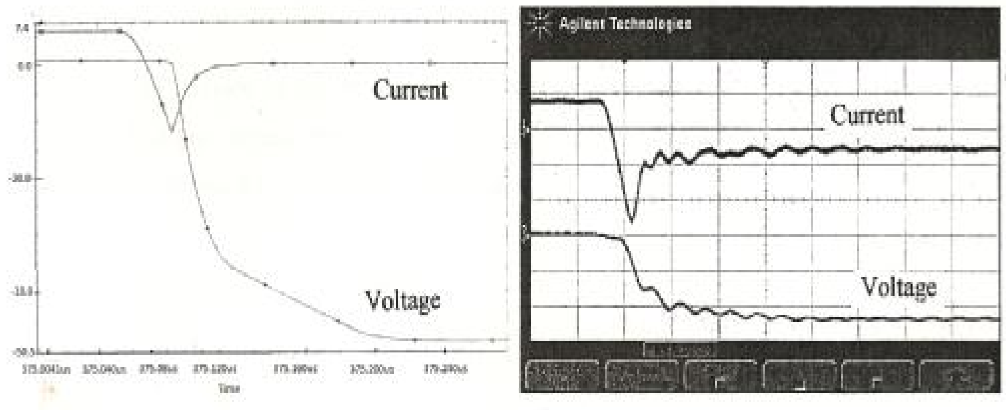
At room temperature, there are only small reverse recovery current (Irr=0.7A) of the Silicon Carbide Schottky diode giving Qrr to be only 17.5nC, which is about 2/5 of stored changed value in the Si PiN diode. This gives a less effect on the IGBT turn-on losses. There is only about 18.1% Eon (total) difference in comparing and experiment result Table (3). This can be concluded as the total energy loss in the Silicon Pin diode current is higher compared to the Silicon Carbide Schottky diode by 355 % and 423%in the simulation and experiment respectively. It can be seen also that the Silicon Carbide Schottky diode produces less reverse recovery current during turn on period that makes lower energy loss.

Table (3) Silicon Carbide Schottky Diode and IGBT Energy Loss Summary for R_G=22ohms.

Silicon Carbide	Eoff(diode)	Eon(IGBT)	Eon(Total)
Simulation	50 nJ	478 nJ	528 nJ
Experiment	75 nJ	372 nJ	447 nJ

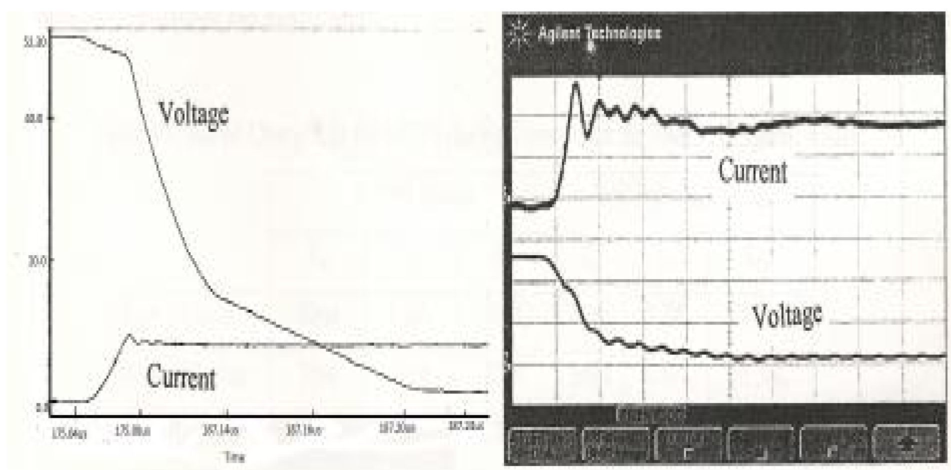
Energy Losses using R_G=220 ohms

The idea of increasing the gate resistance is to observe the decreasing value of di/dt of the current through the diode during turn-on of the switch, which turn to be 85 A/µs. This will obviously reduce the diode reverse recovery current but at the same time increase the IGBT losses. This comparison technique is the same as how it was done with the R_G=22ohms. The simulation and experimental results waveforms are shown in Figure (12) through Figure (13) below.



(a) (a)

Figure (12) Silicon PiN diode current and voltage during turn-on with R_G=220 ohms a) Simulation. b) Experiment (0.5A/div,20v/div,50ns/div).



(a) (b)

Figure (13) IGBT (SiC Schottky) current and voltage during turn-on with R_G=220 ohms a) Simulation. b) Experiment (0.5A/div,20v/div,50ns/div).

Silicon PiN Diode

As shown in Figure (4.5) the diode reverse recovery current is on the order of 0.9A (Qrr=25nC) compared to 1.6A. This is 43% less compared to the tested circuit with RG=22 ohms. The experimental result in diode energy losses is reduced. However, the experimental IGBT energy loss increases about 178%, which makes the total energy losses increases Table (4). More energy is dissipated in the IGBT than in the DUT. The waveforms of current and voltage of I GBT are shown in Figure (14).

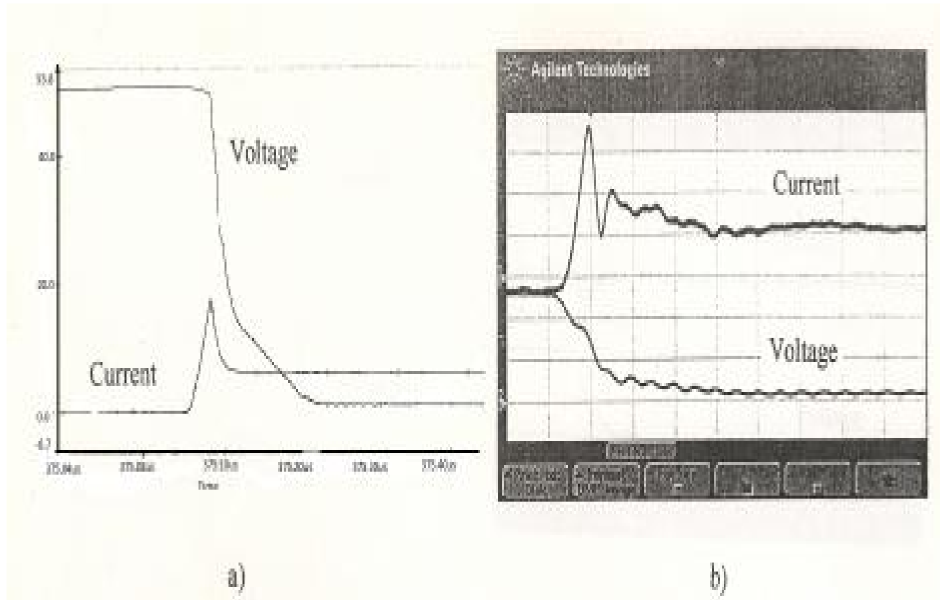


Figure (14) IGBT (Si PiN) current and voltage during turn-on with R_G=220 ohms a) Simulation. b) Experiment (0.5A/div,20v/div,50ns/div).

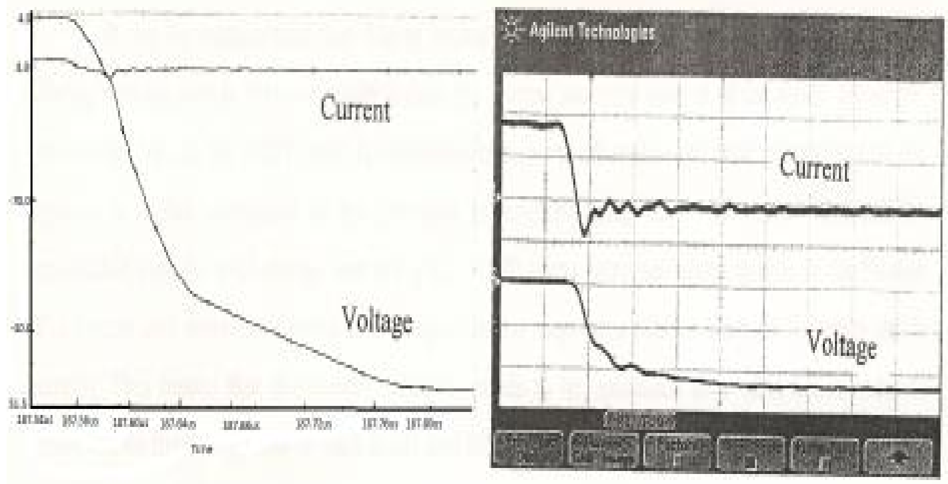
Table (4) Silicon PiN Diode and IGBT Energy Losses Summary for RG=22ohms.

Silicon PiN Diode	Eoff(diode)	Eon(IGBT)	Eon(Total)
Simulation	120 nJ	4800 nJ	4920 nJ
Experiment	142 nJ	4670 nJ	4812 nJ

The increases in the gate resistance value will eventually the turn-on speed (lower di/dt) but increase the total energy losses in the system by 106% (experimental). The switching frequency is maintained to be the same.

Silicon Carbide Schottky Diode

Referring to Table (5), by applying the higher value of gate resistant, the energy loss in the diode (Qrr=10.5nC) is reduced by 68%. The IGBT energy loss however, increases by 767% compared to tested circuit with RG=22 ohms (experimental).Even though the use of Silicon Carbide Schottky diode reduced the energy losses within the component, the total energy loss increases the system stress by 627%. The waveforms of currents and voltage of DUT and IGBT are shown in Figure (13) and Figure (15).



(a) (b)

Figure (15) IGBT [SiC Schottky] current and voltage during turn-on with R_G=220 ohms a)Simulation, b)Experiment.

Table (5) Silicon Carbide Schottky Diode and IGBT Energy Loss Summary for R_G=220 ohms.

Silicon Carbide	Eoff(diode)	Eon(IGBT)	Eon(Total)
Simulation	5 nJ	3750 nJ	3755 nJ
Experiment	24 nJ	3226 nJ	3250 nJ

It can be summarized that due to higher R_G which drives lower di/dt through the diode during turn-on switch, this eventually reduce the reverse recover current of the diode. However, the energy loss in the LGBT itself is substantially high which makes the total energy loss of the system is higher compared to the previous experiment using R_G=22 ohms. This can be concluded that the total energy loss using R_G=220 ohms increases about double in the silicon pin circuit and more than seven times higher in the respective Silicon Carbon Schottky diode circuit .This means that the correct value R_G needs to be optimized as a trade-off in order to compensate the energy loss in each diode and IGBT so that total energy loss in counted to be minimum.

CONCLUSIONS

The switching energy losses for two different diodes Si and SiC are investigated in this paper using DC-DC converter circuit . The use of two types of diodes, the Silicon PiN and Silicon Carbide Schottky diode.In the Inductive Load Chopper circuit, shows the significant difference in the energy loss in the DUT itself and the IGBT. The investigation concentrates on the turn-on time of the switch. From this the waveforms of current and voltage from each DUT and IGBT are obtained and measured. The total energy losses in the entire system justify the stress level of the DC-DC converter. The utilization of Silicon Carbide Schottky diode gives lower total energy losses compared to the Silicon PiN diode by 81 % (Experimental, R_G = 22 ohms).

The increase in the gate resistance (R_G) leads to the increase in the total energy losses. Having a higher R_G value, the current rate of change (di/dt) that flows through the diode during turn-on of the switch will reduce. This causes the energy loss in the diode less. At the same time, however, the energy loss in the IGBT increases substantially. It is concluded that the gate resistance also plays an important role in determining the stress level of the converter. The use of the Silicon Carbide Schottky diode is not only a good solution to produce lower total energy losses, but choice of gate resistance value also needs to be optimized.

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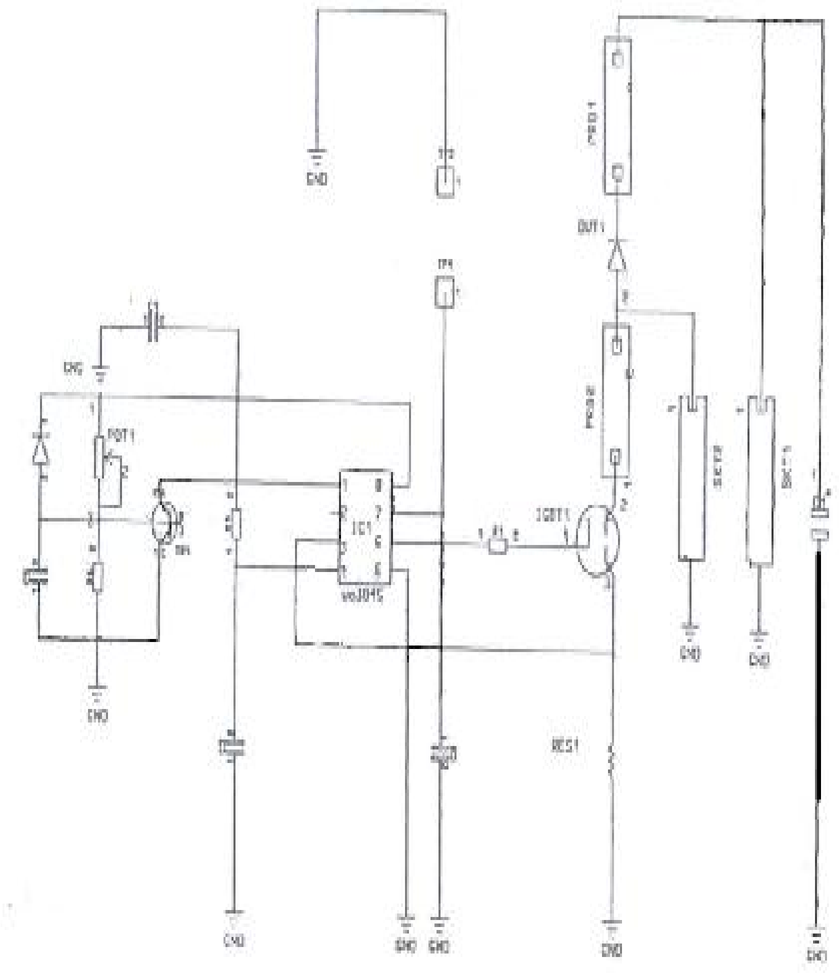
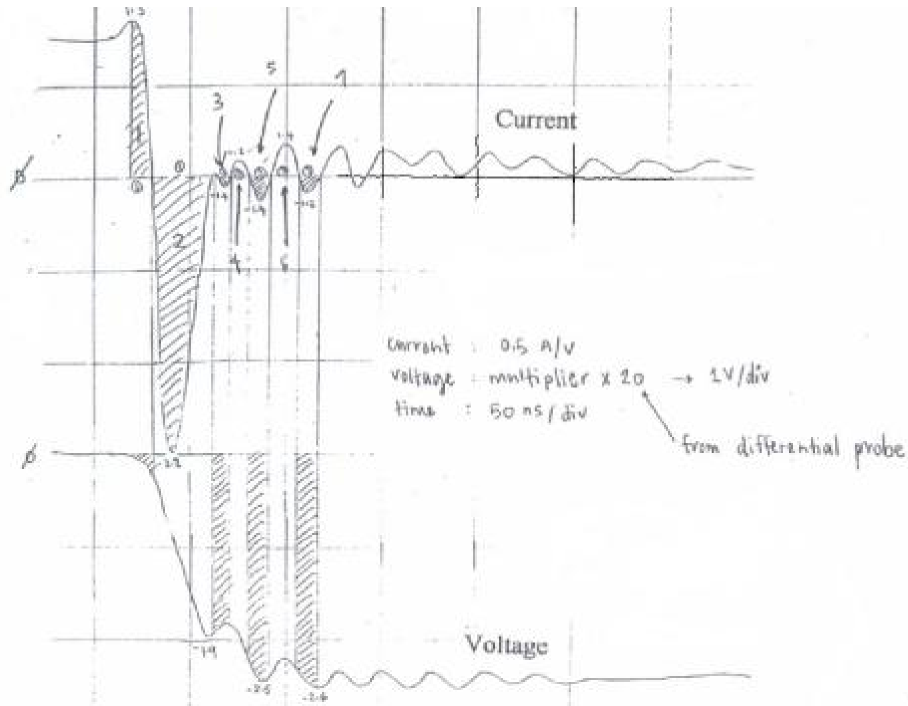
APPENDIX A - List of components used in the experiment.

Item Part No.	Descriptions
UC3845N	High performance Current Mode PWM Controller
STTA806DI	Turbo Switch Ultra fast high voltage diode – PCB 1
SDT06S60	Thin-Q SiC Schottky diode
ALC10C102EL400	Snap-in Capacitor 400V 1000uF
437067	Heatsink 4.7 C/W (3X)
IRG4BC20W	IGBT
HSC 300	High Power Resistor 300W
Capacitors	0.1uF, 1nF, 10nF
Resistors	20Ω, 220Ω , 0.2Ω , 22Ω , 9kΩ , 10kΩ , 4.7kΩ
Diodes	BC179
Trimmer	1kΩ (2X)

APPENDIX-B Schematic diagram



APPENDIX C: Diode Energy Loss Calculation Sample



Area 1: (0.3x50ns) [(1.3x0.5x0.5)x(-0.3x20x0.5)] = -15 nJ

Area 2: (0.7x50ns) [(-3.2x0.5x0.5)x(-1.9x20x0.5)] = 532 nJ

Area 3: (0.2x50ns) [(-1.4x0.5x0.5)x(-1.7x20)] = 119 nJ

Area 4: (0.3x50ns) [(1.2x0.5x0.5)x(-1.9x20)] = -171 nJ

Area 5: (0.3x50ns) [(-1.4x0.5x0.5)x(-2.2x20)] = 231 nJ

Area 6: (0.3x50ns) [(1.4x0.5x0.5)x[(-2.4x20)] = -252 nJ

Area 7: (0.3x50ns) [(-1.2x0.5x0.5)x(-2.4x20)] = 216 nJ

Total Area = 660 nJ