Performance Analysis Of Carbide Element in DC-DC Converter

By

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FINAL PROJECT REPORT

Submitted to the Electrical & Electronics Engineering Programme
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CERTIFICATION OF APPROVAL

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June 2007

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

Fairuz Hanisah Bt Ramle

ABSTRACT

This report study on the performance analysis of carbide element in a DC-DC Converter by having comparisons between Silicon Schottky and Silicon Carbide Schottky Diode in terms of their reverse recovery current, reverse recovery losses and the MOSFET turn-on losses. The results of the analysis had proven how much the carbide element in a Silicon Carbide Schottky Diode effects in the output results. The inductive load chopper circuit was chosen to be used in PSpice simulation to study the characteristics of both Silicon Carbide Schottky and Silicon Schottky diode. The efficiency of Silicon Carbide Schottky diode was proven to be improved by 96.16% compared to Silicon Schottky diode. The Silicon Schottky and Silicon Carbide Schottky diode investigated in this project were both unipolar, therefore the effect of carbide could be distinguished by analyzing the outputs produced by Silicon Carbide Schottky diode.

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CHAPTER 1

INTRODUCTION

1.1 Background of Study

Semiconductors plays an important role in switching for its low power dissipation on the switching device, thus resulting in a very high-efficiency power electronic system. Unlike semiconductor that works in linear mode in power amplifiers and linear regulators, a very 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 forms of heat once the system has a very low efficiency[1].

A Silicon Schottky is a common diode used in power electronics circuits, on the other hand Silicon Carbide Schottky 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 in the 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 recognized as extrinsic material of *n*-type and *p*-type. A predetermined number of impurity atoms will be added into the silicon or germanium base 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 which results to holes.

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[2].

1.2 Problem Statement

Today's technology requires research in order to invent more powerful and portable devices. With that, power losses in device should be put into consideration. An ideal switching device that could decrease the energy losses is what is trying to be investigated in this project.

The Silicon Schottky Diodes is not very suitable for high frequency application due to its small bandgap and slower switching frequency. Silicon Carbide Schottky on the other hand has all the requirement and very suitable to act as a substitute for Schottky Diode especially in High Frequency Application.

The main role of the carbide element in Silicon Carbide Schottky diode is also being investigated in this project in order to see how the carbide element being the most important element in producing such results in application.

1.3 Objectives and Scope of Study

The objective of this project is to come up with a comparison between Silicon Schottky Diode and Silicon Carbide Schottky Diode, to show which diodes shows better performance in terms of energy losses. The Inductive Load Chopper Circuit will be used in the investigation.

From the result, this project will try to reveal the main role of Carbide in the Silicon Carbide device.

The project will be conducted by studying both diodes using simulation and results in PSPICE. Therefore it is needed to study the PSPICE software before the experiment or simulation could be done.

For the first part of the research, this project is focused on research and study of Static and Dynamic characteristic of both diodes; Silicon Schottky and Silicon Carbide Schottky and a simulation of performance for both diodes in PSpice. The second part of the research will emphasize on how much the carbide element effect the Silicon Carbide Schottky Diode's performance according to the simulation results obtained from PSpice.

CHAPTER 2

LITERATURE REVIEW AND THEORY

2.1 The Schottky Diode

The Schottky diode or Schottky Barrier diode is an electronics component that is widely used as a mixer or detector diode. The Schottky diode is also used in power applications as a rectifier, because of its low forward voltage drop leading to lower levels of power loss[3].

Schottky diode is a unipolar device, in which the current transport is mainly due to majority carriers. Characteristics of Schottky diode is that, it does not rely on holes or electrons recombining when they enter the opposite type of region as in the case of a conventional diode and therefore it give better speed. This diode also has low turn on voltage and high frequency capability and low capacitance[4].

2.2 The Silicon Carbide Material

Silicon Carbide (SiC) is a type of Wide-bandgap (WBG) semiconductor with advantages to have fast recovery times. SiC Schottky Diode is seen to have no change (or lesser) on switching loss on increasing of temperature, where else Silicon Schottky Diode's behaviour changes as the increasing of temperature[5]. This device has the potential to operate more efficiently by producing less heat and capable to work at high temperatures compared to Silicon Diodes. The cause of increasing temperature is the increasing of electron's thermal energy which causes reduction of barrier height in the Silicon Schottky Diode. Therefore, the power losses of Silicon Schottky Diode increases because of increasing in its peak reverse recovery current[6].

Silicon Carbide Schottky Diode has higher critical field and higher barrier heights than Silicon Schottky Diode. This two advantages results to reduced on-resistance and lower leakage current of SiC Schottky Diodes [7]. It has been demonstrated that the SiC has the potential to improve power FET performance[8].

The SiC also come in small sizes and lighter weight compared to normal Schottky Diode. The SiC is a semiconductor with bandgap energy at most three times higher than Schottky Diode and due to its wider bandgap, it also gives SiC an electrical breakdown strength about 10 times higher than Schottky Diodes. This means that electronic devices in SiC can operate at voltages 5 to 20 times higher than Schottky Diodes, and current densities 200 to 400 times higher than Schottky Diodes[9].

The normal Schottky diode has a small forward voltage and the reverse breakdown voltage cannot be made too high (currently, approx. 100 to 200 volts). The Schottky diodes for general rectification are used for the rectification of power supplies for low voltages and high currents, or power supply switching for the rectification of high frequencies with its small reverse recovery time.

Silicon Carbide Crystal Structure

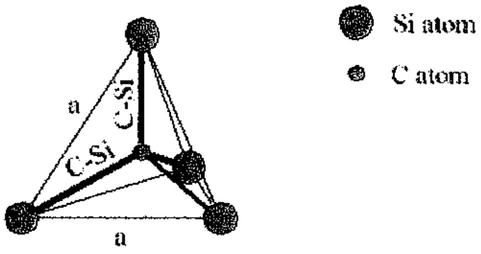


Figure 1: The tetragonal bonding of a carbon atom with the four nearest silicon neighbours[10].

From Figure 1, the four Silicon atoms made a covalent bonding with a single Carbon atom in order to form a Silicon Carbide (SiC). The Carbon atom is located in the middle of the structure, and the distance between all the atoms which marked C-Si are the same.

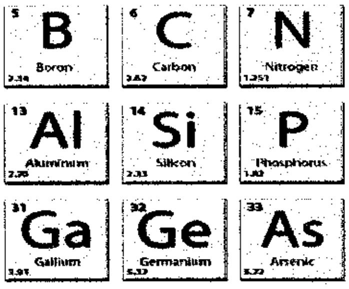


Figure 2: Position of Carbon and Silicon in Periodic Table.

The Silicon Carbide possesses increased tolerance to radiation damage, making it a material desired for defense and aerospace applications. Due to the high tolerance of temperature of Silicon Carbide (up to 650°C) [11], it is used in various industries, such as aircraft, automotive, communications, power, and spacecraft.

Silicon Carbide Schottky as a wide bandgap semiconductor

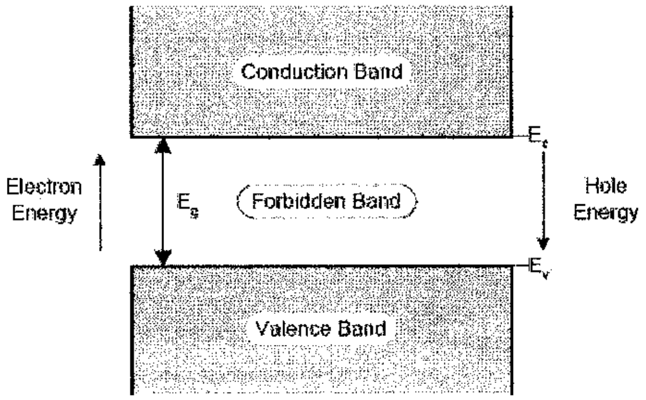


Figure 3: Energy band diagram of a semiconductor[12].

The characteristic of Silicon Carbide Schottky diode as a wide bandgap semiconductor results in more energy to excite the electron from its covalent bonding during turn-off compared to Silicon Schottky diode. Referring to Figure 3, the wide bandgap is measured from the distance between the conduction band and the valence band of the semiconductor. 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 while a conductor would have no forbidden band. From figure 3, the bandgap energy, $E_g = E_c - E_V$. The wider the bandgap of a semiconductor, the more thermal energy is needed to excite the electrons to the valence band, thus a wide bandgap semiconductor could operate at higher temperature without affecting its electrical property.

2.3 Diode Characteristic

Static Characteristic

Components of static characteristic include the I-V characteristics and the reverse characteristics. The Silicon Schottky Diode would have a lower voltage drop than the Silicon Carbide Schottky Diode. This happens when during turn-on, there is a high level injection of carrier for Silicon Schottky diode that leads to a smaller amount of voltage to forward bias the diode. Due to smaller band-gap at Silicon Schottky Diode compared to Silicon Carbide Schottky Diode, higher voltage is required to forward bias the Silicon Carbide Schottky Diode[13].

The Silicon Carbide Schottky Diode can also handle large reverse voltage before having an overshoot of leakage current as compared to Silicon Schottky Diode.

Dynamic Characteristic

Dynamic characteristic are characteristic that changes with time. The studies were performed to study both Silicon Schottky and Silicon Carbide Schottky Diode in terms of forward voltage drop, reverse recovery time and reverse recovery current. The parameters were in **Table 1** in the next page [14]:

Table 1: Dynamic Characteristics Comparison

Characteristics	SiC Schottky (SDP 04S60)	Si Schottky (SB30-03F)
Reverse Recovery Time	Maintain at every case of temperature	Increases as temperature increases
Reverse Recovery Current	Negligible	Increases as temperature increases
Switching Losses	Low	High
Voltage (V) and Current (I) Rating	600V/4A	30V/3A

From Table 1, the dynamic characteristic of Silicon Carbide Schottky diode shows that this diode will have a maintained reverse recovery time independent of temperature, a negligible reverse recovery current and low switching losses compared to Silicon Schottky diode. Silicon Schottky diode shows an increase of reverse recovery time and reverse recovery current as the temperature increases and also shows high switching losses.

2.4 Reverse Recovery

Reverse recovery is one of the properties that can be recognized in a power device such as Silicon Carbide Schottky and Silicon Schottky diode. It is one measurable quantity that can differentiate the efficiency of certain devices.

The reverse recovery in a diode occurred when a semiconductor has been conducting in forward bias long enough for it to establish steady state, there will be charges due to the presence of minority charge carriers. This charge must be removed when the device want to block in reverse direction[15].

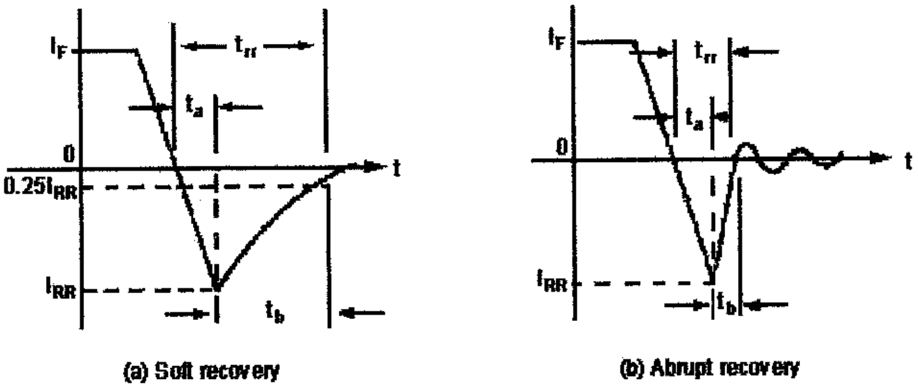


Figure 4: The reverse recovery characteristic.

Figure 4 above shows the characteristic of reverse recovery that is exhibited by a diode. t_{rr} represents the reverse recovery time, I_{RR} is the maximum reverse current, t_a is the time due the charge stored in the depletion region of the junction and is the transition time due to charge stored.

Reverse recovery time, t_{rr} in Figure 4 could be obtained by adding t_a and t_b. While reverse recovery current is the rate of fall of current multiplied with time taken due to charge stored.

The reverse recovery current is directly proportional to di/dt. Below is the formula for reverse recovery current, I_{RR}[16]:

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

From this equation, it can be seen that if the current rate of fall is high, the reverse recovery current would also be high. The diode conducts in reverse direction due to the free carriers in the diode.

CHAPTER 3

METHODOLOGY

3.1 Procedure

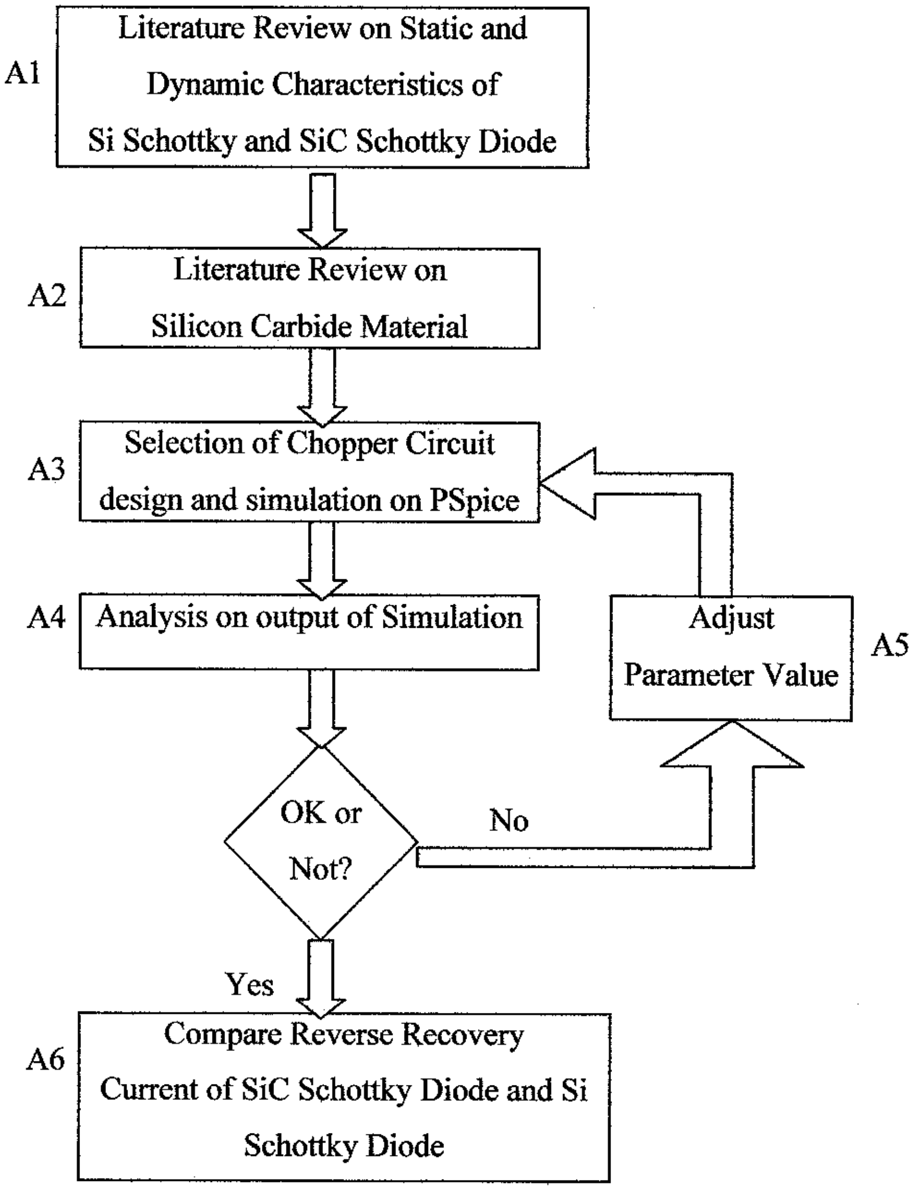


Figure 5: Process Flow of Project Methodology

A1: *Literature Review on Static and Dynamic Characteristics of Si Schottky and SiC Schottky Diode*

The first step in starting the Final Year Project is to do as many literature reviews about the subject that is studied which in this project, the Silicon Schottky Diode and Silicon Carbide Schottky Diode. The journals can be obtained on the web for example the IEEE website because it is the most reliable source as suggested by the supervisor.

A2: *Literature Review on Silicon Carbide Material*

Next, the scope is narrowed down to studying the Silicon Carbide Material, in order to find the answer on the carbide element that is being studied in this project. The sources of the literatures are also searched in the IEEE website and also from the library.

A3: *Selection of Chopper circuit design and simulation on PSpice*

The next step is to select a suitable circuit design for the project, and in this project a DC-DC converter circuit is selected and simulated in PSpice. The PSpice software is also studied in order to have the correct setting and to obtain the desired output waveforms. A detailed explanation on this selecting the circuit design will be discussed later in this report.

A4: *Analyzing Simulation Outputs*

After the simulation is done, the output waveforms are analyzed in order to confirm that the output obtained is as what is expected. In order to prove the output, it is needed to refer back to the journals that are studied and also seek advice from the supervisor.

A5: *Adjusting Parameter Values*

If the output waveform is not as expected, the parameter value and the setting in the PSpice software need to be adjusted. A few trials need to be done in order to get the desired output. Examples of parameters adjusted are the load resistor and load inductor.

A6: *Comparing the results*

Finally, the output waveforms are compared between the two diodes studied in this project, which are Silicon Schottky and Silicon Carbide Schottky Diode. More analysis is done with the results later on in order to achieve the objective of the project.

3.2 Tools/Equipment Required

The tools/equipment required in this project is PSpice.

3.3 Methodology for part A3; the Inductive Load Chopper Circuit

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 Silicon Schottky and Silicon Carbide Schottky diode could be characterized using this circuit. The diode under test (D1_SiC and D2_Si) for this project will be Silicon Schottky Diode and Silicon Carbide Schottky Diode.

Major components used in these circuits are:

M1 and M2: IRF520 – 9.2A/100V MOSFET
DUT (D1_SiC): SDP06S60/INF – 6A/600V Silicon Carbide Schottky Diode
(D2_Si): SB30-03F – 3A/30V Silicon Schottky Diode
$R_{load} = 55\ \Omega$
$I_{load} = 500uH$

The value of R_{g1} and R_{g2} used for the simulation is 21Ω, with temperature at 27 °C and V_{cc} is 25V.

Figure 6 shows an inductive load chopper test circuit.

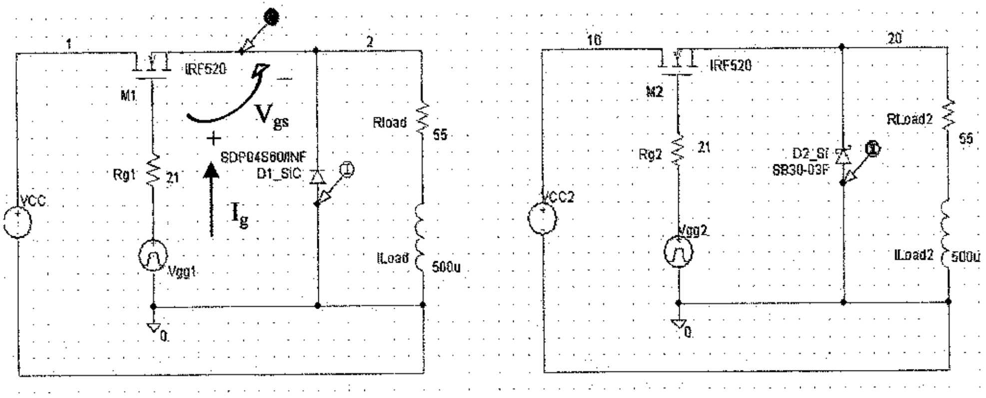


Figure 6: Inductive Load Chopper Circuit

The design of the circuit was made by arranging the load resistor and load inductor in series and the diode under test in parallel to the loads. The pulse voltage (V_{pulse}) is in series to the gate of MOSFET and a limiting resistor were placed in the middle of gate and V_{pulse}, and named R_{g1}.

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}. The operation of the inductive load chopper circuit will be explained in the next part.

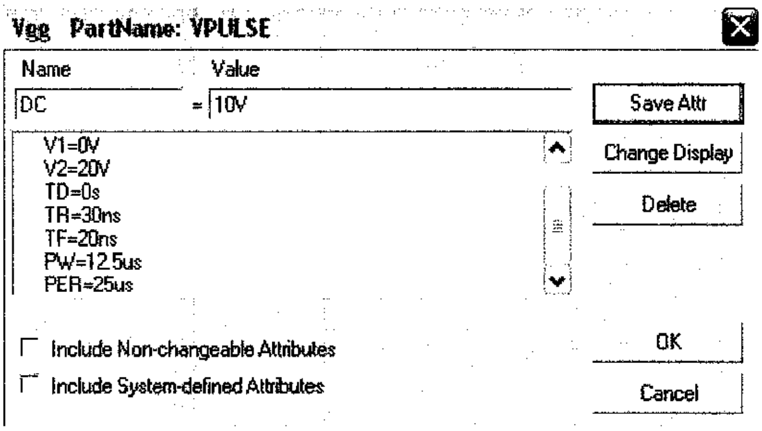
Circuit Operation

This circuit operation will represent one of the circuits above since both circuits are having the same perimeters except for the diode under test. V_{gg1} will provide a pulse signal to the MOSFET (M1) and the signal will appear at V_{gs}. The pulse signal will then forward bias the collector-emitter junction of the MOSFET, using current that passes through R_{g1}, or known as I_g. As a result, the MOSFET is being turned on. The collector current will increase slowly until the pulse signal drops to zero. The current will stop flowing into once I_g drop below the threshold value of the MOSFET due to no current flowing through emitter, the MOSFET is turned off.

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} and inductor, I_{load} and collector of the MOSFET and reached the gate at the emitter of the MOSFET. When the current flow through I_{load}, it charges up the inductor.

D1_SiC is turned on once MOSFET is turned off. This happens when current stored in the I_{load} will start to flow and go through *D1_SiC*. *D1_SiC* will be in forward biased until some period of time that MOSFET get turned on again by V_{gg1} (V_{pulse}) signal. Just a few moment before *D1_SiC* turned off, it will be forced to flow in reverse direction. This is where the reverse recovery current appears and what is tried to be investigated in this project.

The cycle of the signal will repeat again by charging and discharging of I_{load} and turning on and off of MOSFET and *D1_SiC*. The PSpice settings for the circuit above are as follows:



Vgg PartName: VPULSE

Name = Value

DC = 10V

V1=0V
V2=20V
TD=0s
TR=30ns
TF=20ns
PW=12.5us
PER=25us

☐ Include Non-changeable Attributes
☐ Include System-defined Attributes

Figure 7: V_{pulse} Setting

Figure 7 shows the V_{pulse} setting used in this project. The DC voltage provided by the V_{pulse} was set to 20V and the same for V2. V1 is set to 0V. V1 and V2 were set for maximum and minimum voltage of the pulse. The rise and fall time of the pulse was both set to 30ns and 20ns respectively. The frequency of the pulse was set to 40 kHz with 50% duty ratio. Therefore the period (PER) was set to 25μs and the pulse width (PW) was set to 12.5μs, representing the 50% duty ratio. The dc current supplied to the circuit was set to 25V.

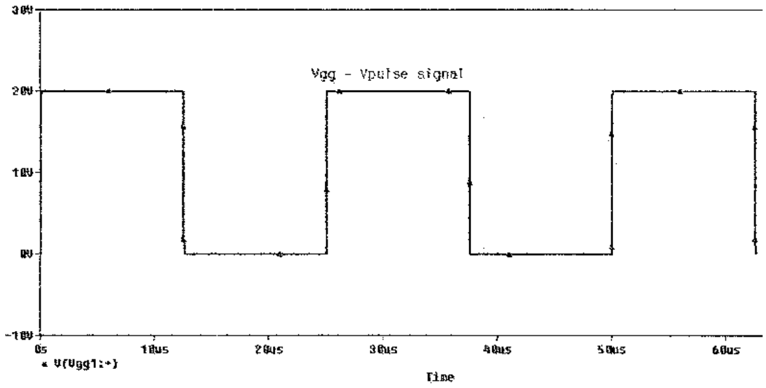


Figure 8: V_{gg1} (V_{pulse}) Signal

Figure 8 shows the signal waveform from the V_{pulse}. The signal was the same for both circuits since the parameters used in both circuits are the same. Therefore, V_{pulse} for Silicon Carbide Schottky diode circuit is shown to represent V_{pulse} from both circuits. The correct signal shows square wave with pulse period at 25μs and the maximum voltage is at 20V while the minimum is at 0V. As the duty ratio is 50%, half of period was seen at 12.5μs.

Part I: Finding V_{gs} and V_{ds}

To find the voltage across gate (g) and source (s) of the MOSFET is by using the voltage-differential marker. The marker will be placed at the gate and source according to its polarity and current flow. The illustration is as follows:

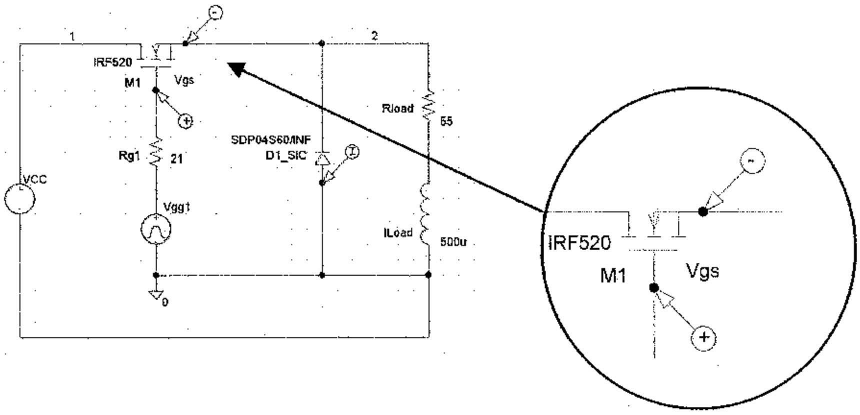


Figure 9: Finding V_{gs} of Silicon Schottky and Silicon Carbide Schottky diode using voltage differential probe.

While to find the voltage across drain (d) and source (s) of the MOSFET is also by using the voltage-differential marker. The marker will be placed at the drain and source according to its polarity and current flow. The illustration is as follows:

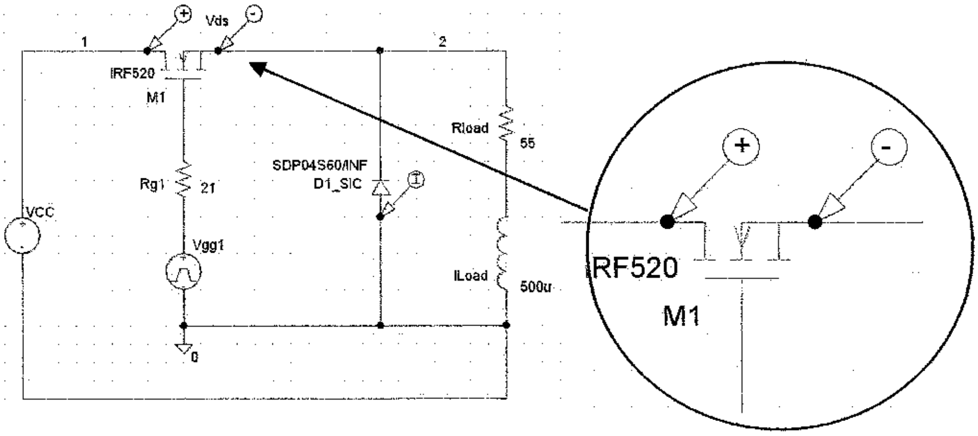


Figure 10: Finding V_{ds} of Silicon Schottky and Silicon Carbide Schottky diode using voltage differential probe.

The simulation was done 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 saved.

Part II: Finding the reverse recovery current (I_{rr})

The next process in the simulation is to find the reverse recovery current produced by Silicon Carbide Schottky and Silicon Schottky diode. The current marker will be placed at the diode and then the simulation began.

Figure 11 below shows the V_{gs} output waveform of measured in both Silicon Carbide Schottky and Silicon Schottky diode.

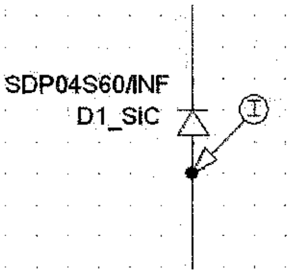


Figure 11: Current probe placed on the diode under test (DUT).

After the setting was done, the simulation will be started. A diode current will be displayed and by using the 'zooming' tool, the reverse recovery current of both diodes could be analyzed.

Part III: Finding diode turn-off power loss and MOSFET turn-on power loss.

The PSpice software is already occupied with a function to find the power loss. The conventional way to find the power loss is by using the equation P = IV, but by using PSpice, after simulation for finding the reverse recovery, the power loss could be found right away. The power loss function is somewhere at the bottom of 'add trace' function and user could select the type of losses they want, for example W(M1) and W(M2) for MOSFET loss in the circuit used in this project.

Part IV: Finding the effect of varying frequency to the reverse recovery loss of the diode.

The frequency of the inductive load chopper circuit used in this project was obtained from the V_{pulse}. Therefore, in order to vary the frequency, the period (PER) inside the V_{pulse} setting will be adjusted according to formula $f=1/T$, where in this case T is the period (PER). It also has to be noted that after the period has been changed, the PW (pulse width) must also be changed to follow the setting of 50% duty ratio.

All of the results will be discussed in the next chapter.

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Simulation Results and Discussion

The inductive load chopper circuit used is constructed using Pspice and the circuit is as follows:

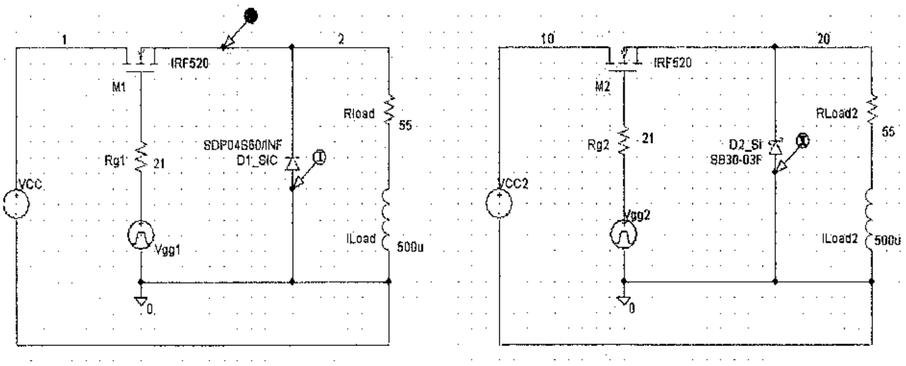


Figure 12: Circuit Diagram for PSpice Simulation of Both Diodes.

Major components used in these circuits are:

M1 and M2: IRF520 – 9.2A/100V MOSFET

DUT (D1_SiC): SDP04S60/INF – 4A/600V Silicon Carbide Schottky Diode

(D2_Si): SB30-03F – 3A/30V Silicon Schottky Diode

$R_{load} = 55\ \Omega$

$I_{load} = 500uH$

The value of R_{g1} and R_{g2} used for the simulation is 21Ω, with temperature at 27 °C and V_{cc} is 25V.

From the steps explained in Chapter 3, the results of the simulation will be shown and explained in this part of the report, according to the sequence from Chapter 3.

Part I: Results of V_{gs} and V_{ds}

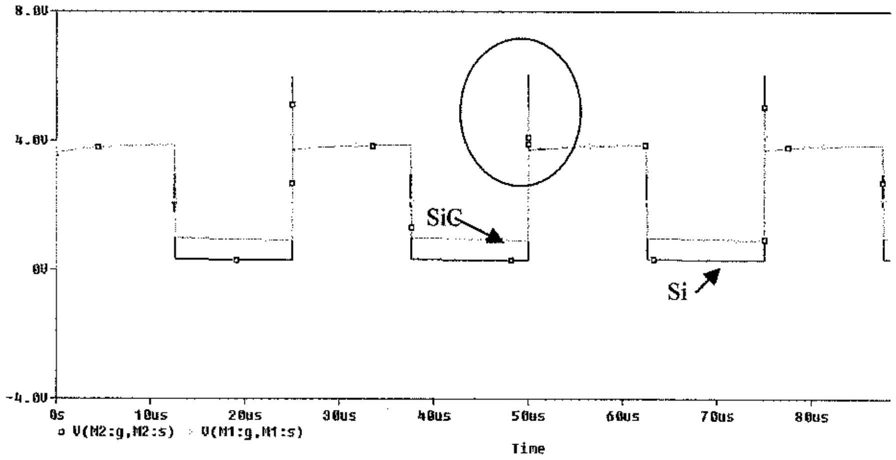


Figure 13: V_{gs} of switch M1 and M2 applied at SiC Schottky Diode and Si Schottky Diode Circuit respectively.

Figure 13 shows the voltage waveform of V_{gs} for Silicon Carbide Schottky and Silicon Schottky diode. There is some voltage overshoot during the turn-on of the MOSFET and in Figure 14, the closer picture of the overshoot is shown.

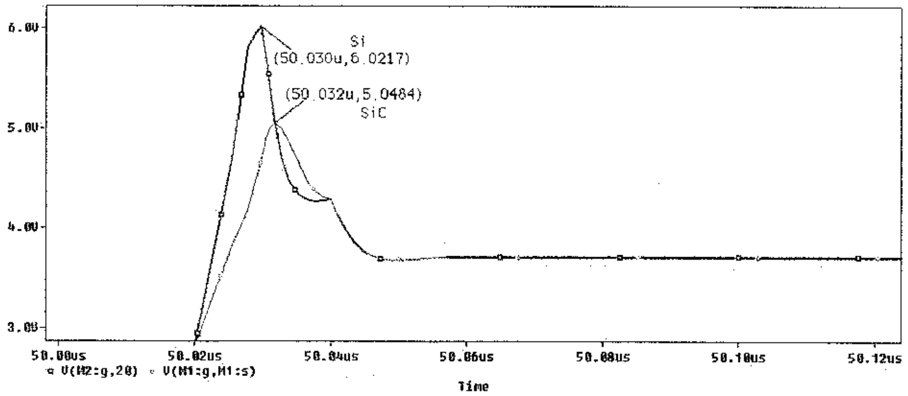


Figure 14: V_{gs} overshoot of forward switch M1 (SiC circuit) and M2 (Si circuit).

As seen in Figure 14, the voltage overshoot of MOSFET using Silicon Schottky diode is higher than using Silicon Carbide Schottky diode with 6.0217V overshoot, compared to MOSFET with Silicon Carbide Schottky diode at 5.0484V.

Schottky diode circuit compared to Silicon Schottky Diode circuit, due to low

Figure 15 below shows the voltage across the drain and source of MOSFET 1, V_{ds}

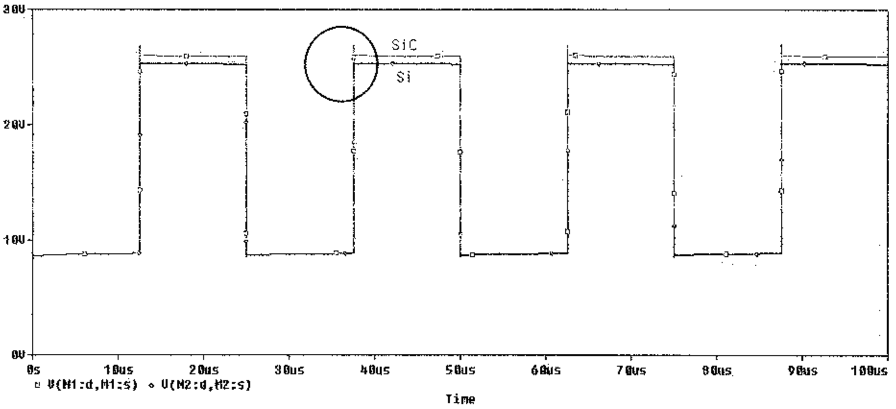


Figure 15: V_{ds} of switch M1 and M2 applied at SiC Schottky Diode and Si Schottky Diode Circuit respectively.

Figure 15 above shows the voltage across drain and source of the MOSFET for both circuits using Silicon Carbide Schottky and Silicon Schottky diode. Figure 16 below shows the overshoot that happened during turn-on, from the part that is circled red in Figure 15.

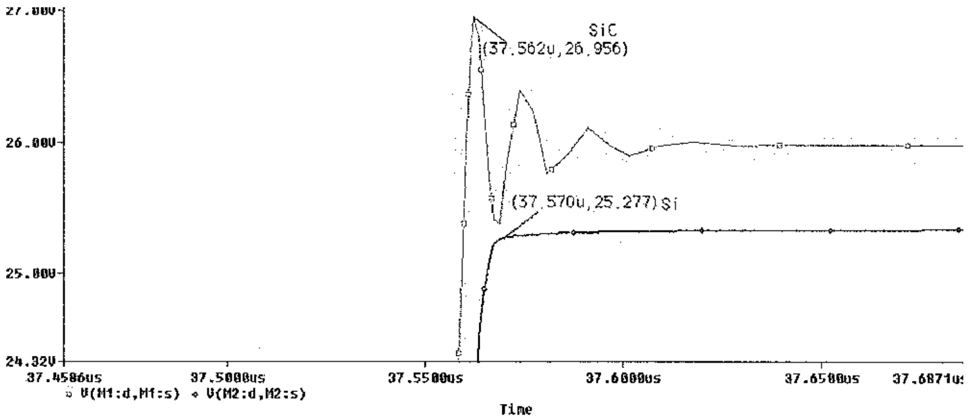
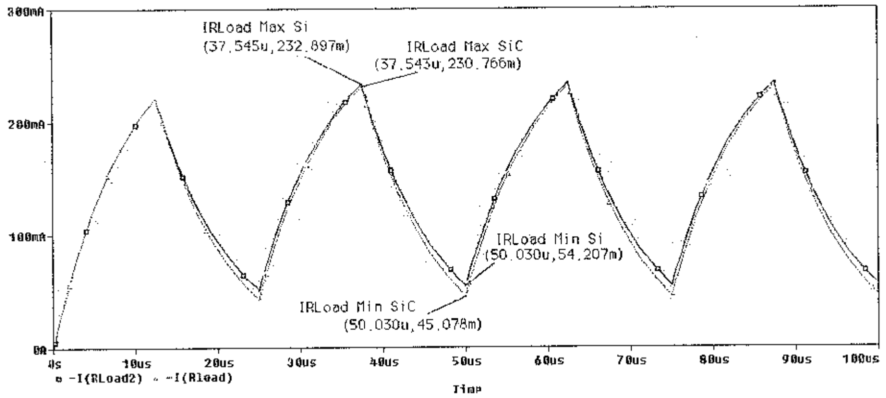


Figure 16: V_{ds} overshoot of forward switch M1 (SiC circuit) and M2 (Si circuit).

As seen in Figure 16, the MOSFET's V_{ds} overshoot or ringing effect were visible in circuit containing Silicon Carbide Schottky diode with value of overshoot of 26.956V. While for MOSFET in circuit containing Silicon Schottky diode, no overshoot was recorded at V_{ds} and it turns on smoothly, but at lower value than Silicon Carbide Schottky diode, which is 25.277V.

Figure 17 shows the load resistor's current, I_{RLoad} for both circuits containing Silicon Carbide Schottky and Silicon Schottky diode.



[illegible] for Silicon Carbide Schottky and Silicon Schottky Diode

Schottky diode is 230.766mA. While minimum I_{RLoad} is 45.078mA. As for I_{RLoad} in

minimum I_{RLoad} is 54.207mA.

of output power of the circuits.

The targeted load power for the circuits are obtained from calculation:

Silicon Carbide Schottky diode circuit:

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

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

$P_{out} = I_{Rload,avg}^2 \times R_{Rload,load}$
$= 92.844mA^2 \times 55\Omega$
$= \underline{474.100mW}$

Silicon Schottky diode circuit:

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

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

$P_{out} = I_{Rload,avg}^2 \times R_{Rload,load}$
$= 89.045mA^2 \times 55\Omega$
$= \underline{436.096mW}$

From the calculation done, the output power given by Silicon Carbide Schottky diode circuit is 474.100mW and Silicon Schottky diode circuit provide an output power of 436.096mW.

The output power from Silicon Carbide Schottky diode was higher than the output power of Silicon Schottky diode by 8.016% improvement. The output power from Silicon Carbide Schottky diode was expected to be higher because it provides higher output current, thus higher efficiency than Silicon Schottky diode with the same parameter.

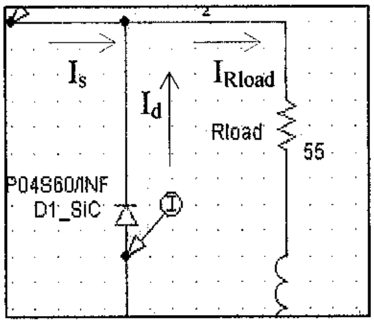


Figure 18: Source current, I_s, Current across diode, I_d and load current, I_{Rload}.

Figure 18 shows the flow of current to the load. This explanation could easily be seen by the formula for diode current, $I_d = I_s - I_{Rload}$.

The output current of Silicon Schottky diode was lower than Silicon Carbide Schottky diode because the current had gone to diode current, I_d of Silicon Schottky diode. The next part will discuss how much is the power loss across the diode, however from simulation, the Silicon Schottky diode was proven to have larger power loss than Silicon Carbide Schottky diode. Thus, current that went through R_{load} was lower in Silicon Schottky diode circuit because more current is needed by Silicon Schottky diode to produce high power loss at the diode.

The carbide element in Silicon Carbide Schottky diode is the element that helps in increasing the output current, thus the output power of the circuit is higher. This is due to the fact that Silicon Carbide has lower reverse recovery current, thus lower power losses at the diode during turn-off. The next part of the results will discuss about the reverse recovery of both diodes.

Part II: Finding the reverse recovery current (I_{rr})

Figure 19 below shows the diode current, I_d of both diodes in one simulation window.

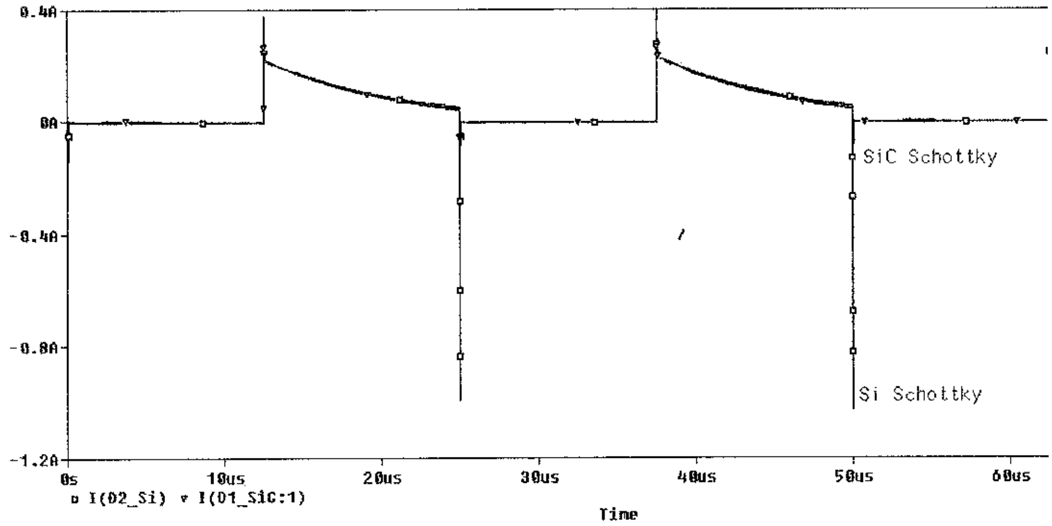


Figure 19: Diode Current, I_d at Silicon Schottky and Silicon Carbide Schottky Diode

From Figure 19, it can be seen that there are some overshoot during the turn-on of the diode, and also a reverse recovery current that goes below 0A. This is the reverse recovery current, I_{rr} that is investigated in this project.

In this simulation, the transient setting was set to 100μs, which explains why the waveform results are below 100μs.

Below are the results for Reverse Recovery Current, I_{rr} during DUT turn-off of Silicon Schottky Diode and Silicon Carbide Schottky Diode.

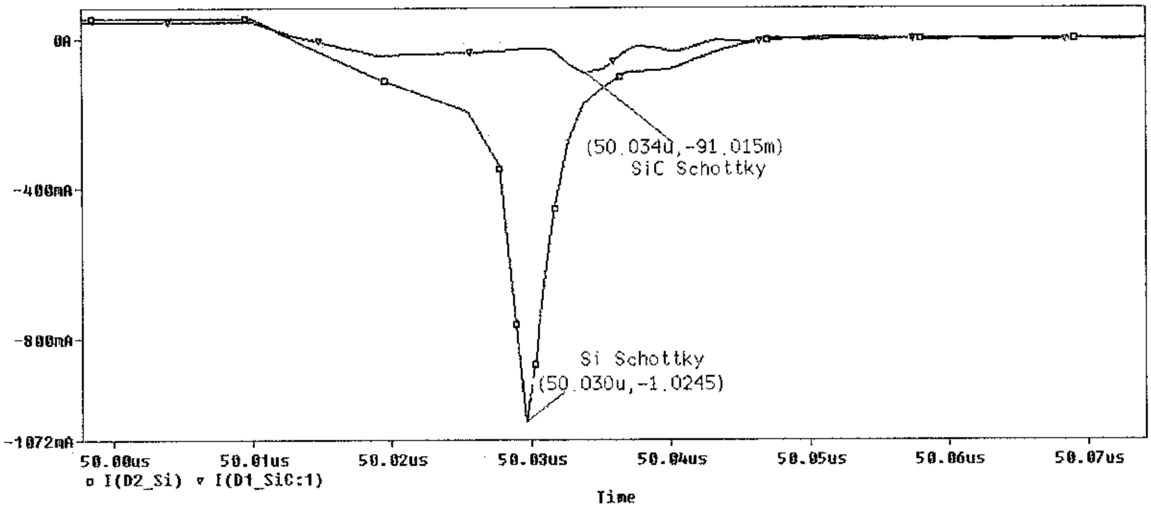


Figure 20: Reverse Recovery Current of Silicon Schottky and Silicon Carbide Schottky Diode

From Figure 20, a significant difference of reverse recovery current between Silicon Carbide Schottky diode and Silicon Schottky diode can be seen. The value of reverse recovery current of Silicon Schottky diode is -1.0245A, while Silicon Carbide Schottky diode produce a reverse recovery current of -91.015mA.

The advantage of carbide is that the leakage current from anode to cathode is lower due to the fact that Silicon Carbide structure of metal-semiconductor barrier is two times higher than Silicon and its smaller intrinsic carrier concentration[17,18]. The reverse recovery current in Silicon Carbide Schottky diode is also smaller than Silicon Schottky Diode as Silicon Carbide has no stored charges and a majority carrier device which could operate without high-level minority carrier injection. Therefore, during the turn-off of the SiC Schottky diode, large reverse recovery currents due to stored charges are removed[19]. The low switching losses of SiC Schottky diode is due to the factor of high breakdown field of SiC Schottky which results in reduced blocking layer thickness, in conjunction to the reduced charges[20].

Figure 21 shows the turn-off loss of both Silicon Carbide Schottky and Silicon Schottky diode, taken at the same moment the reverse recovery current happened.

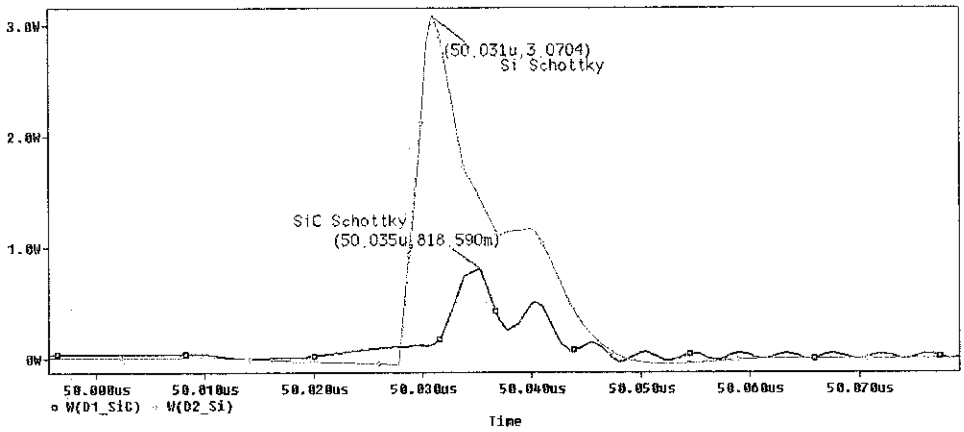


Figure 21: Turn Off Loss of Silicon Schottky and Silicon Carbide Schottky Diode

From Figure 21, it can be seen that Silicon Schottky diode has a turn-off loss of 3.0704W larger than Silicon Carbide Schottky diode, which is 818.590mW. This significant results was expected since the reverse recovery current of Silicon Schottky diode is higher than Silicon Carbide Schottky diode.

With higher reverse recovery current, more power loss will be produced because more power will be needed for the reverse recovery in order to have the diode to be fully turned off.

Figure 22 below shows the MOSFET turn-on power loss during diode turn-off.

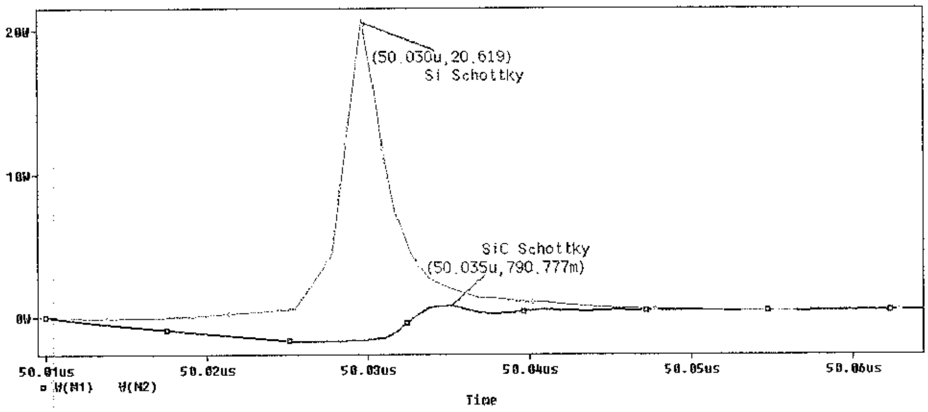


Figure 22: MOSFET turn-On Power Loss during DUT turn-Off

From Figure 22, it can be seen that MOSFET turn-on power loss in Silicon Schottky diode circuit is higher than in Silicon Carbide Schottky diode. The value of Silicon Schottky diode circuit MOSFET turn-on loss is 20.619W while in Silicon Carbide Schottky diode, the MOSFET turn-on loss is 790.777mW.

The higher loss of MOSFET in Silicon Schottky diode during turn-on follows the high power loss produced by the diode during turn-off. The carbide element in Silicon Carbide Schottky diode will be the main factor the Silicon Carbide Schottky diode produced lower power loss both during diode turn-on and MOSFET turn-off.

From results obtained for voltage across gate and source, Vgs of the MOSFET in *Part I*, it can be seen that lower current spike were produced in Silicon Carbide Schottky diode circuit during turn-on. With lower voltage ringing effect in Silicon Carbide Schottky diode, lower power loss will be produced by the MOSFET during turn-on. The carbide element in Silicon Carbide Schottky diode had helped improving the MOSFET's performance in this circuit.

Table 2 shows all the data collected from the simulations done in this project, tabulated into one table.

Table 2: Simulation Results

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%

From Table 2, Silicon Schottky Diode has higher peak Reverse Recovery Current compared to Silicon Carbide Schottky Diode with -1.0245mA for Silicon Schottky and -91.015mA for Silicon Carbide Schottky Diode. Therefore, this is confirmed that theoretically, a Silicon Carbide Schottky Diode will show less Reverse Recovery Current than Silicon Schottky Diode.

As for Turn-OFF Loss of both diodes, it also shows that Silicon Schottky Diode possesses more losses than Silicon Carbide Schottky diode. The MOSFET Turn-ON Loss for Silicon Schottky also shows a very significant difference from Silicon Carbide Schottky with 96.16% improvement.

Part IV: The effect of varying frequency to the reverse recovery loss of the diode under test (DUT).

Figure 23 shows the result of varying frequency in both Silicon Carbide Schottky and Silicon Schottky diode circuit.

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

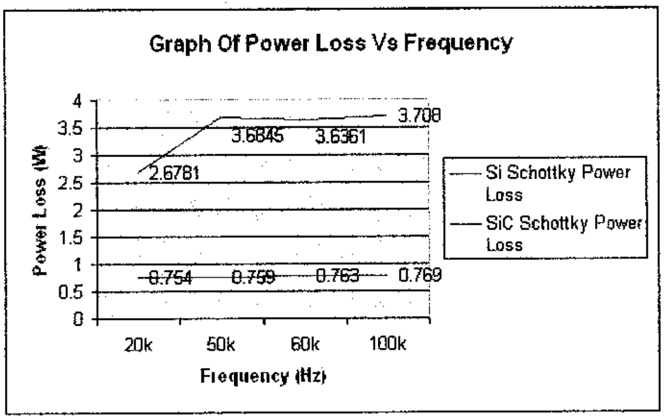


Figure 23: Graph of Power Loss vs Frequency of Silicon Schottky and Silicon Carbide Schottky Diode.

From the graph, it is obvious that SiC Schottky Diode Circuit doesn't have a significant difference once the frequency is increased. While Si Schottky Diode shows an increase in the reverse recovery current with large range of increasing value. SiC Schottky shows independency on the frequency due to its low switching power losses, as proven in simulation results in Table 2.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

As a conclusion, this project had come up with analysis of reverse recovery current for both Silicon Schottky and Silicon Carbide Schottky Diode with the study on effects of the carbide element of the Silicon Carbide Schottky Diode through PSpice simulation. This project had also discussed about reverse recovery current and its importance in power electronics.

An inductive load chopper circuit is used in the simulations and the output of the simulations in terms of reverse recovery, power losses of Silicon Carbide Schottky and Silicon Schottky diode, and losses at the MOSFET was analyzed and studied.

From the simulation results, it is proven that Silicon Schottky Diode would produce more reverse recovery current than Silicon Carbide Schottky diode. Therefore, Silicon Carbide Schottky diode produced less power losses than Silicon Schottky diode with 91.12% improvement.

The results also had proven to improve ringing effect at the main switch (MOSFET) by 16.16%. The carbide element helps in achieving more output power by 8% improvement compared to diode without carbide.

The turn off losses produced at the diodes were improved by 73.34% by using SiC Schottky diode because the carbide element in SiC helps in setting the diode to be fully turned off without taking much power.

The MOSFET turn on power losses is also reduced by 96.16%, following the reduction of reverse recovery current by Silicon Carbide Schottky diode.

The Silicon Carbide Schottky Diode is better because of the stronger covalent bonding by the carbide element. Switching losses at Silicon Carbide Schottky Diode was also proven to be much smaller than of Silicon Schottky Diode. Silicon Carbide Schottky diode would be a preferable choice for high frequency and high power applications.

5.2 Recommendations

This project could be continued in the future by studying the effect of temperature in detail to see the effect of carbide elements in Silicon Carbide Schottky diode.

Another research could be done in terms of Electromagnetic Interference (EMI) effects of Silicon Carbide Schottky diode.

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APPENDICES

Appendix I

Datasheets

FAIRCHILD
SEMICONDUCTOR®

Data Sheet January 2002

9.2A, 100V, 0.270 Ohm, N-Channel Power MOSFET

This N-Channel enhancement mode silicon gate power field effect transistor is an advanced power MOSFET designed, tested, and guaranteed to withstand a specified level of energy in the breakdown avalanche mode of operation. All of these power MOSFETs are designed for applications such as switching regulators, switching convertors, motor drivers, relay drivers, and drivers for high power bipolar switching transistors requiring high speed and low gate drive power. These types can be operated directly from integrated circuits.

Formerly developmental type TA09594.

Ordering Information

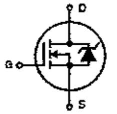
PART NUMBER	PACKAGE	BRAND
IRF520	TO-220AB	IRF520

NOTE: When ordering, use the entire part number.

Features

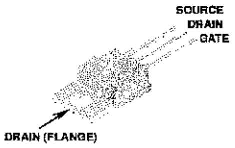
- 9.2A, 100V
- $r_{DS(ON)} = 0.270\Omega$
- SOA is Power Dissipation Limited
- Single Pulse Avalanche Energy Rated
- Nanosecond Switching Speeds
- Linear Transfer Characteristics
- High Input Impedance
- Related Literature
  - TB334 "Guidelines for Soldering Surface Mount Components to PC Boards"

Symbol



Packaging

JEDEC TO-220AB



Absolute Maximum Ratings $T_C = 25^oC$, Unless Otherwise Specified

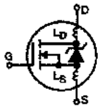
		IRF520	UNITS
Drain to Source Breakdown Voltage (Note 1)	V_{DS}	100	V
Drain to Gate Voltage ($R_{GS} = 20k\Omega$) (Note 1)	V_{DGR}	100	V
Continuous Drain Current	I_D	9.2	A
$T_C = 100^oC$	I_D	6.5	A
Pulsed Drain Current (Note 3)	I_{DM}	37	A
Gate to Source Voltage	V_{GS}	±20	V
Maximum Power Dissipation	P_D	60	W
Dissipation Derating Factor		0.4	W/^{o}C
Single Pulse Avalanche Energy Rating (Note 4)	E_{AS}	36	mJ
Operating and Storage Temperature	T_J, T_{STG}	-55 to 175	^{o}C
Maximum Temperature for Soldering			
Leads at 0.063in (1.6mm) from Case for 10s	T_L	300	^{o}C
Package Body for 10s, See Techbrief 334	T_{pkg}	260	^{o}C

CAUTION: Stresses above those listed in "Absolute Maximum Ratings" may cause permanent damage to the device. This is a stress only rating and operation of the device at these or any other conditions above those indicated in the operational sections of this specification is not implied.

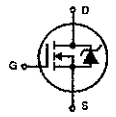
NOTE:

1. $T_J = 25^oC$ to 150^oC.

Electrical Specifications $T_C = 25^oC$, Unless Otherwise Specified

PARAMETER	SYMBOL	TEST CONDITIONS		MIN	TYP	MAX	UNITS
Drain to Source Breakdown Voltage	BV_{DSS}	$I_D = 250\mu A$, $V_{GS} = 0V$ (Figure 10)		100	-	-	V
Gate to Threshold Voltage	$V_{GS(TH)}$	$V_{GS} = V_{DS}$, $I_D = 250\mu A$		2.0	-	4.0	V
Zero Gate Voltage Drain Current	I_{DSS}	$V_{DS} = 95V$, $V_{GS} = 0V$		-	-	250	µA
		$V_{DS} = 0.8 \times$ Rated BV_{DSS}, $V_{GS} = 0V$, $T_J = 150^oC$		-	-	1000	µA
On-State Drain Current (Note 2)	$I_{D(ON)}$	$V_{DS} > I_{D(ON)} \times r_{DS(ON)MAX}$, $V_{GS} = 10V$ (Figure 7)		9.2	-	-	A
Gate to Source Leakage Current	I_{GSS}	$V_{GS} = \pm 20V$		-	-	±100	nA
Drain to Source On Resistance (Note 2)	$r_{DS(ON)}$	$I_D = 5.6A$, $V_{GS} = 10V$ (Figure 8, 9)		-	0.25	0.27	Ω
Forward Transconductance (Note 2)	g_{fs}	$V_{DS} \geq 50V$, $I_D = 5.6A$ (Figure 12)		2.7	4.1	-	S
Turn-On Delay Time	$t_{d(ON)}$	$V_{DD} = 50V$, $I_D = 9.2A$, $R_G = 18\Omega$, $R_L = 5.5\Omega$ MOSFET Switching Times are Essentially Independent of Operating Temperature		-	9	13	ns
Rise Time	t_r			-	30	63	ns
Turn-Off Delay Time	$t_{d(OFF)}$			-	18	70	ns
Fall Time	t_f			-	20	59	ns
Total Gate Charge (Gate to Source + Gate to Drain)	$Q_{g(TOT)}$	$V_{GS} = 10V$, $I_D = 9.2A$, $V_{DS} = 0.8 \times$ Rated BV_{DSS}, $I_{g(REF)} = 1.5mA$ (Figure 14) Gate Charge is Essentially Independent of Operating Temperature		-	10	30	nC
Gate to Source Charge	Q_{gs}			-	2.5	-	nC
Gate to Drain "Miller" Charge	Q_{gd}			-	2.5	-	nC
Input Capacitance	C_{ISS}	$V_{DS} = 25V$, $V_{GS} = 0V$, $f = 1MHz$ (Figure 11)		-	350	-	pF
Output Capacitance	C_{OSS}			-	130	-	pF
Reverse Transfer Capacitance	C_{RSS}			-	25	-	pF
Internal Drain Inductance	L_D	Measured From the Contact Screw On Tab To Center of Die	Modified MOSFET Symbol Showing the Internal Devices Inductances 	-	3.5	-	nH
		Measured From the Drain Lead, 6mm (0.25in) From Package to Center of Die		-	4.5	-	nH
Internal Source Inductance	L_S	Measured From the Source Lead, 6mm (0.25in) From Header to Source Bonding Pad		-	7.5	-	nH
Thermal Resistance Junction to Case	$R_{\theta JC}$			-	-	2.5	^{o}C/W
Thermal Resistance Junction to Ambient	$R_{\theta JA}$	Free Air Operation		-	-	80	^{o}C/W

Source to Drain Diode Specifications

PARAMETER	SYMBOL	TEST CONDITIONS		MIN	TYP	MAX	UNITS
Continuous Source to Drain Current	I_{SD}	Modified MOSFET Symbol Showing the Integral Reverse P-N Junction Diode		-	-	9.2	A
Pulse Source to Drain Current (Note 3)	I_{SDM}			-	-	37	A
Source to Drain Diode Voltage (Note 2)	V_{SD}	$T_J = 25^oC$, $I_{SD} = 9.2A$, $V_{GS} = 0V$ (Figure 13)		-	-	2.5	V
Reverse Recovery Time	t_{rr}	$T_J = 25^oC$, $I_{SD} = 9.2A$, $dI_{SD}/dt = 100A/\mu s$		5.5	100	240	ns
Reverse Recovered Charge	Q_{RR}	$T_J = 25^oC$, $I_{SD} = 9.2A$, $dI_{SD}/dt = 100A/\mu s$		0.17	0.5	1.1	μC

NOTES:

2. Pulse test: pulse width $\leq 300\mu s$, duty cycle $\leq 2\%$.
3. Repetitive rating: pulse width limited by Max junction temperature. See Transient Thermal Impedance curve (Figure 3).
4. $V_{DD} = 25V$, starting $T_J = 25^oC$, $L = 640mH$, $R_G = 25\Omega$, peak $I_{AS} = 9.2A$.

Typical Performance Curves Unless Otherwise Specified

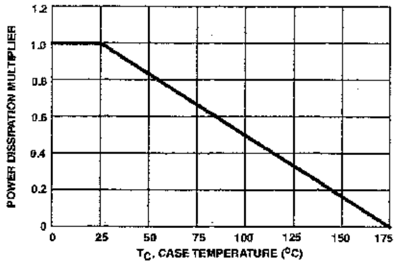


FIGURE 1. NORMALIZED POWER DISSIPATION vs CASE TEMPERATURE

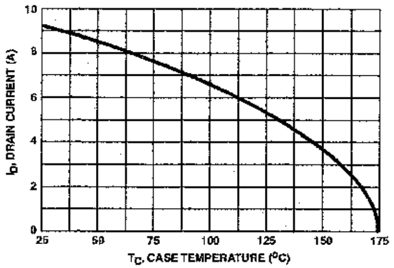


FIGURE 2. MAXIMUM CONTINUOUS DRAIN CURRENT vs CASE TEMPERATURE

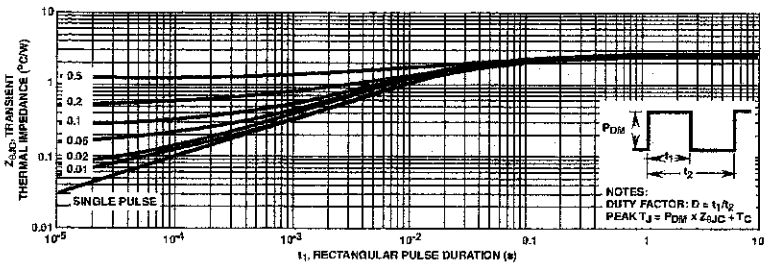


FIGURE 3. MAXIMUM TRANSIENT THERMAL IMPEDANCE

Typical Performance Curves Unless Otherwise Specified (Continued)

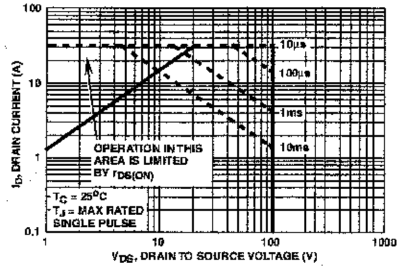


FIGURE 4. FORWARD BIAS SAFE OPERATING AREA

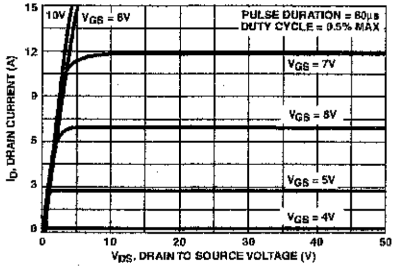


FIGURE 5. OUTPUT CHARACTERISTICS

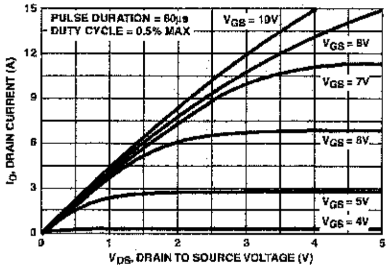


FIGURE 6. SATURATION CHARACTERISTICS

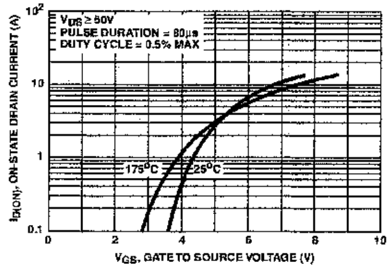


FIGURE 7. TRANSFER CHARACTERISTICS

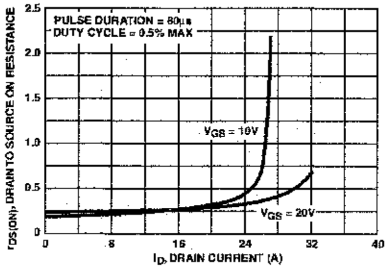


FIGURE 8. DRAIN TO SOURCE ON RESISTANCE vs GATE VOLTAGE AND DRAIN CURRENT

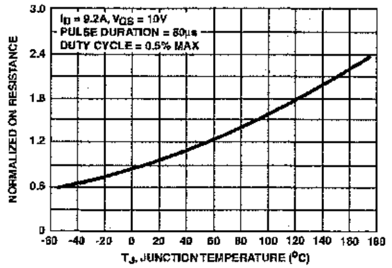


FIGURE 9. NORMALIZED DRAIN TO SOURCE ON RESISTANCE vs JUNCTION TEMPERATURE

Typical Performance Curves Unless Otherwise Specified (Continued)

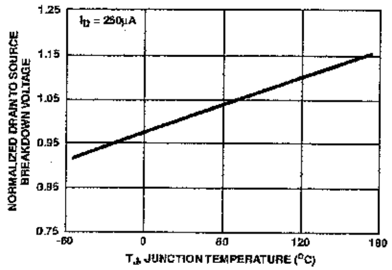


FIGURE 10. NORMALIZED DRAIN TO SOURCE BREAKDOWN VOLTAGE vs JUNCTION TEMPERATURE

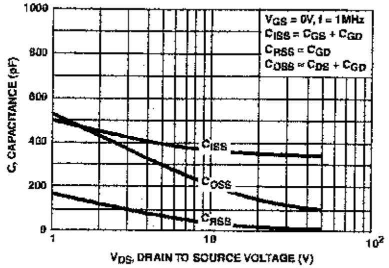


FIGURE 11. CAPACITANCE vs DRAIN TO SOURCE VOLTAGE

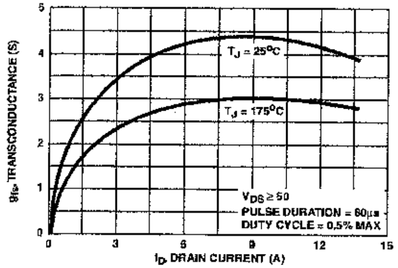


FIGURE 12. TRANSCONDUCTANCE vs DRAIN CURRENT

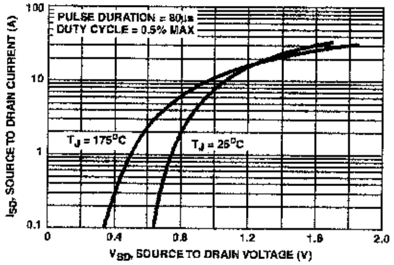


FIGURE 13. SOURCE TO DRAIN DIODE VOLTAGE

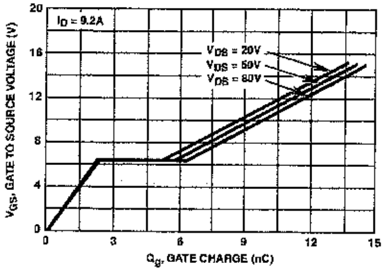


FIGURE 14. GATE TO SOURCE VOLTAGE vs GATE CHARGE

Test Circuits and Waveforms

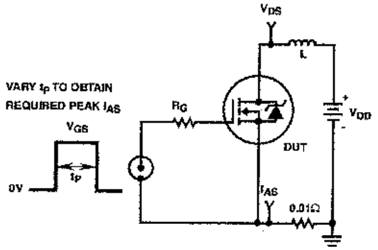


FIGURE 15. UNCLAMPED ENERGY TEST CIRCUIT

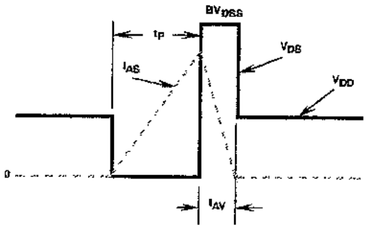


FIGURE 16. UNCLAMPED ENERGY WAVEFORMS

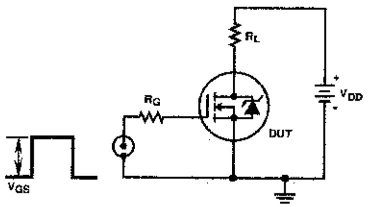


FIGURE 17. SWITCHING TIME TEST CIRCUIT

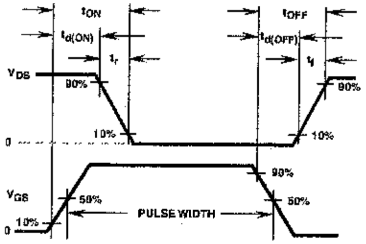


FIGURE 18. RESISTIVE SWITCHING WAVEFORMS

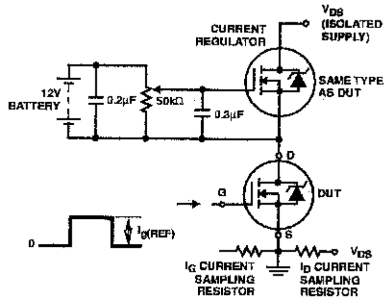


FIGURE 19. GATE CHARGE TEST CIRCUIT

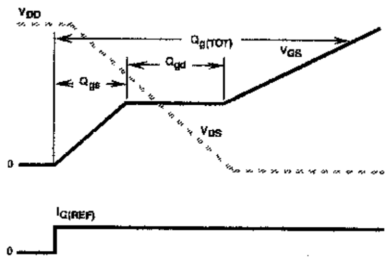


FIGURE 20. GATE CHARGE WAVEFORMS

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GTO™
HiSeC™
ISOPLANAR™
LittleFET™
MicroFET™
MicroPak™
MICROWIRE™
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PACMAN™
POP™
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2. A critical component is any component of a life support device or system whose failure to perform can be reasonably expected to cause the failure of the life support device or system, or to affect its safety or effectiveness.

PRODUCT STATUS DEFINITIONS

Definition of Terms

Datasheet Identification	Product Status	Definition
Advance Information	Formative or In Design	This datasheet contains the design specifications for product development. Specifications may change in any manner without notice.
Preliminary	First Production	This datasheet contains preliminary data, and supplementary data will be published at a later date. Fairchild Semiconductor reserves the right to make changes at any time without notice in order to improve design.
No Identification Needed	Full Production	This datasheet contains final specifications. Fairchild Semiconductor reserves the right to make changes at any time without notice in order to improve design.
Obsolete	Not In Production	This datasheet contains specifications on a product that has been discontinued by Fairchild semiconductor. The datasheet is printed for reference information only.

SB30-03F

Schottky Barrier Diode

30V, 3A Rectifier

Applications

- High frequency rectification (switching regulators, converters, choppers).

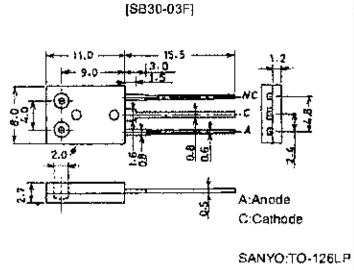
Features

- Low forward voltage (V_F max=0.55V).
- Fast reverse recovery time (trr max=30ns).
- Low switching noise.
- Low leakage current and high reliability due to highly reliable planar structure.

Package Dimensions

unit:mm

1200



Specifications

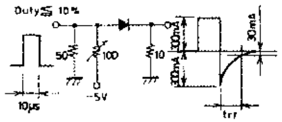
Absolute Maximum Ratings at Ta = 25°C

Parameter	Symbol	Conditions	Ratings	Unit
Repetitive Peak Reverse Voltage	V_{RRM}		30	V
Nonrepetitive Peak Reverse Surge Voltage	V_{RSM}		35	V
Average Output Current	I_O	50Hz, resistive load, Tc=114°C	3	A
Surge Forward Current	I_{FSM}	50Hz sine wave, 1 cycle	30	A
Junction Temperature	Tj		-55 to +125	°C
Storage Temperature	Tstg		-55 to +125	°C

Electrical Characteristics at Ta = 25°C

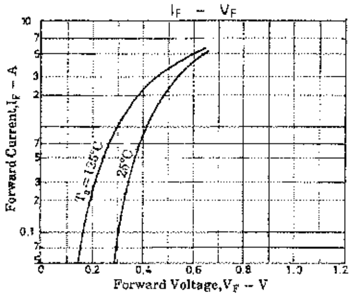
Parameter	Symbol	Conditions	Ratings			Unit
			min	typ	max	
Reverse Voltage	V_R	I_R=2mA	30			V
Forward Voltage	V_F	I_F=3A			0.55	V
Reverse Current	I_R	V_R=15V			700	μA
Interterminal Capacitance	C	V_R=10V, f=1MHz		160		pF
Reverse Recovery Time	trr	I_F=I_R=300mA, See sepcified Test Circuit			30	ns
Thermal Resistance	Rthj-c	Junction-Case,Smoothed DC		4		°C/W

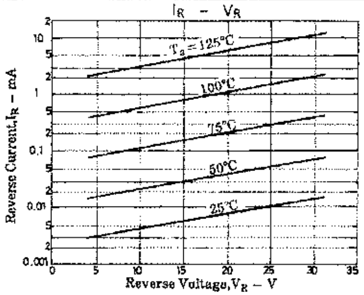
trr Test Circuit

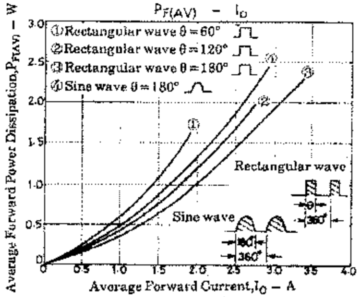


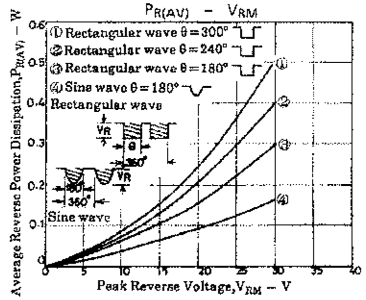
Unit (resistance:Ω)

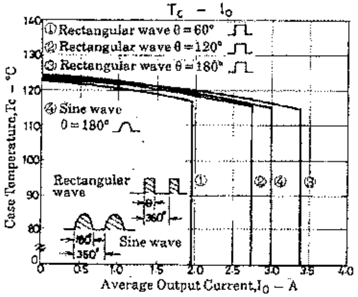
SANYO Electric Co.,Ltd. Semiconductor Bussiness Headquaters
TOKYO OFFICE Tokyo Bldg., 1-10, 1 Chome, Ueno, Taito-ku, TOKYO, 110-8534 JAPAN

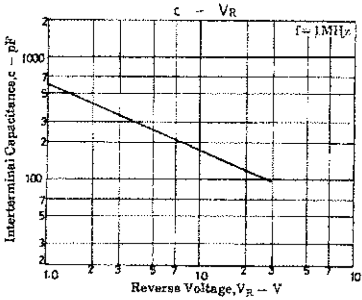


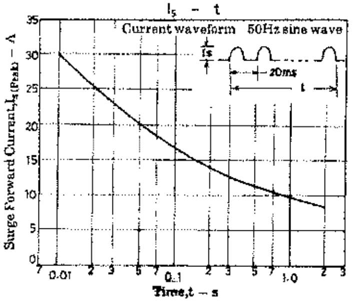












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  ② Not impose any responsibilty for any fault or negligence which may be cited in any such claim or litigation on SANYO ELECTRIC CO., LTD., its affiliates, subsidiaries and distributors or any of their officers and employees jointly or severally.

■ Information (including circuit diagrams and circuit parameters) herein is for example only; it is not guaranteed for volume production. SANYO believes information herein is accurate and reliable, but no guarantees are made or implied regarding its use or any infringements of intellectual property rights or other rights of third parties.

This catalog provides information as of April, 1998. Specifications and information herein are subject to change without notice.

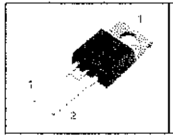
Silicon Carbide Schottky Diode

- Worlds first 600V Schottky diode
- Revolutionary semiconductor material - Silicon Carbide
- Switching behavior benchmark
- No reverse recovery
- No temperature influence on the switching behavior
- Ideal diode for Power Factor Correction up to 800W[1)]
- No forward recovery

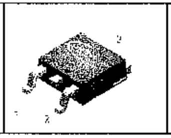
Product Summary

V_{RRM}	600	V
Q_c	13	nC
I_F	4	A

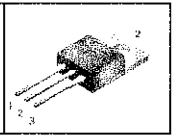
P-TO220-2-2.



P-TO252-3-1.



P-TO220-3-1.



Type	Package	Ordering Code	Marking	Pin 1	PIN 2	PIN 3
SDP04S60	P-TO220-3-1.	Q67040-S4369	D04S60	n.c.	C	A
SDD04S60	P-TO252-3-1.	Q67040-S4368	D04S60	n.c.	A	C
SDT04S60	P-TO220-2-2.	Q67040-S4445	D04S60	C	A	

Maximum Ratings, at T_j = 25 °C, unless otherwise specified

Parameter	Symbol	Value	Unit
Continuous forward current, T_C=100°C	I_F	4	A
RMS forward current, f=50Hz	I_{FRMS}	5.6	
Surge non repetitive forward current, sine halfwave T_C=25°C, t_p=10ms	I_{FSM}	12.5	
Repetitive peak forward current T_j=150°C, T_C=100°C, D=0.1	I_{FRM}	18	
Non repetitive peak forward current t_p=10µs, T_C=25°C	I_{FMAX}	40	
i^2t value, T_C=25°C, t_p=10ms	$\int i^2 dt$	0.78	A²s
Repetitive peak reverse voltage	V_{RRM}	600	V
Surge peak reverse voltage	V_{RSM}	600	
Power dissipation, T_C=25°C	P_{tot}	36.5	W
Operating and storage temperature	T_j , T_{stg}	-55... +175	°C

Thermal Characteristics

Parameter	Symbol	Values			Unit
		min.	typ.	max.	
Characteristics					
Thermal resistance, junction - case	R_{thJC}	-	-	4.1	K/W
Thermal resistance, junction - ambient, leaded	R_{thJA}	-	-	62	
SMD version, device on PCB:	R_{thJA}				
P-TO263-3-2: @ min. footprint		-	-	62	
P-TO263-3-2: @ 6 cm^2 cooling area [2)]		-	35	-	
P-TO252-3-1: @ min. footprint		-	-	75	
P-TO252-3-1: @ 6 cm^2 cooling area [2)]		-	-	50	

Electrical Characteristics, at T_j = 25 °C, unless otherwise specified

Parameter	Symbol	Values			Unit
		min.	typ.	max.	
Static Characteristics					
Diode forward voltage	V_F				V
I_F=4A, T_j=25°C		-	1.7	1.9	
I_F=4A, T_j=150°C		-	2	2.4	
Reverse current	I_R				µA
V_R=600V, T_j=25°C		-	15	200	
V_R=600V, T_j=150°C		-	40	1000	

[1] CCM, V_{IN}= 85VAC, T_j = 150°C, T_C =100°C, η = 93%, ΔI_{IN} = 30%

[2] Device on 40mm*40mm*1.5mm epoxy PCB FR4 with 6cm² (one layer, 70 µm thick) copper area for drain connection. PCB is vertical without blown air.

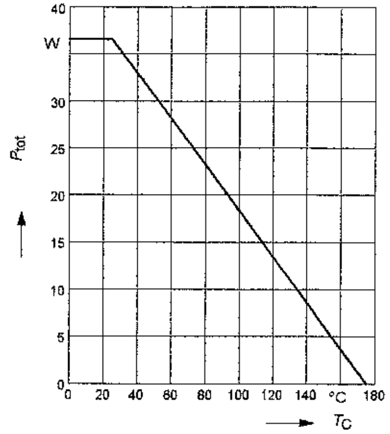
Electrical Characteristics, at T_j = 25 °C, unless otherwise specified

Parameter	Symbol	Values			Unit
		min.	typ.	max.	
AC Characteristics					
Total capacitive charge V_R=400V, I_F=4A, di_F/dt=200A/µs, T_j=150°C	Q_c	-	13	-	nC
Switching time V_R=400V, I_F=4A, di_F/dt=200A/µs, T_j=150°C	t_{rr}	-	n.a.	-	ns
Total capacitance	C				pF
V_R=0V, T_C=25°C, f=1MHz		-	150	-	
V_R=300V, T_C=25°C, f=1MHz		-	10	-	
V_R=600V, T_C=25°C, f=1MHz		-	7	-	

---

1 Power dissipation

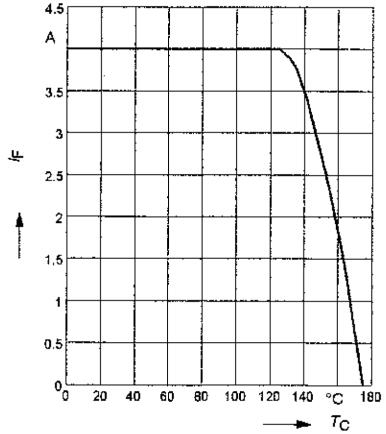
$P_{tot} = f(T_C)$



2 Diode forward current

$I_F = f(T_C)$

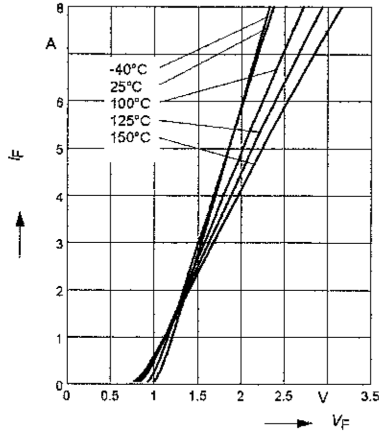
parameter: T_j≤175 °C



3 Typ. forward characteristic

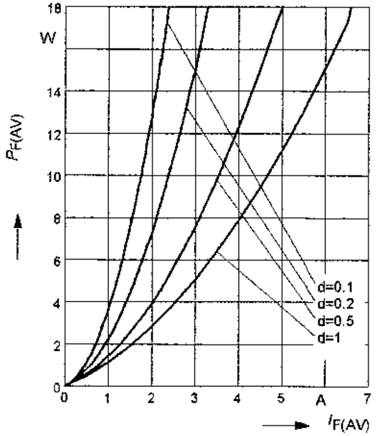
$I_F = f(V_F)$

parameter: T_j , tp = 350 µs



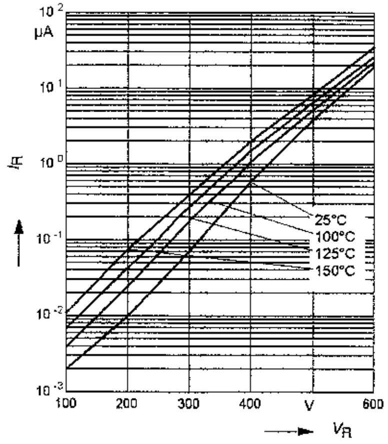
4 Typ. forward power dissipation vs. average forward current

$P_{F(AV)}=f(I_F)$ T_C=100°C, $d = t_p/T$



5 Typ. reverse current vs. reverse voltage

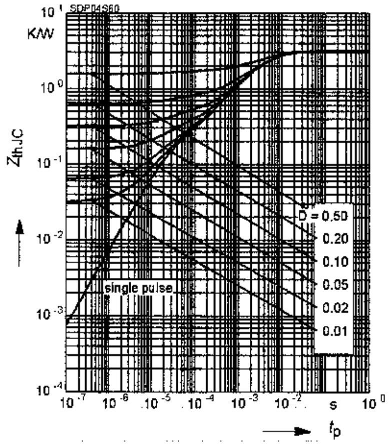
$I_R = f(V_R)$



6 Transient thermal impedance

$Z_{thJC} = f(t_p)$

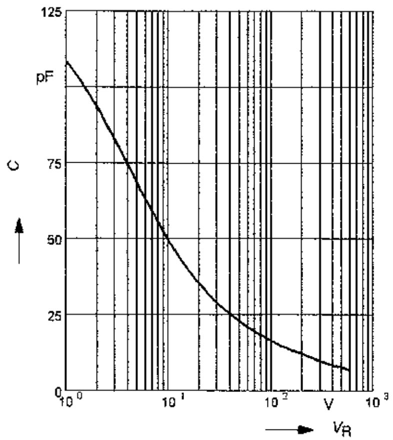
parameter : $D = t_p/T$



7 Typ. capacitance vs. reverse voltage

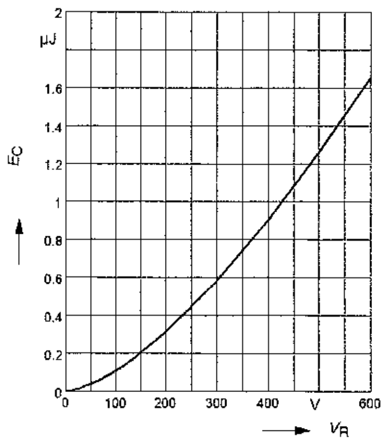
$C = f(V_R)$

parameter: T_C = 25 °C, f = 1 MHz



8 Typ. *C* stored energy

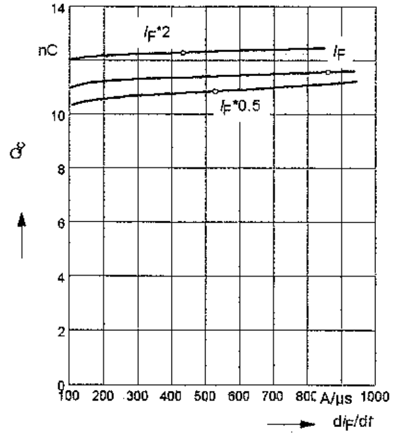
$E_C = f(V_R)$



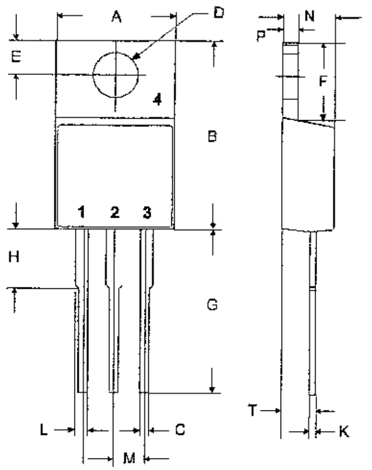
9 Typ. capacitive charge vs. current slope

$Q_c = f(di_F/dt)$

parameter: T_j = 150 °C

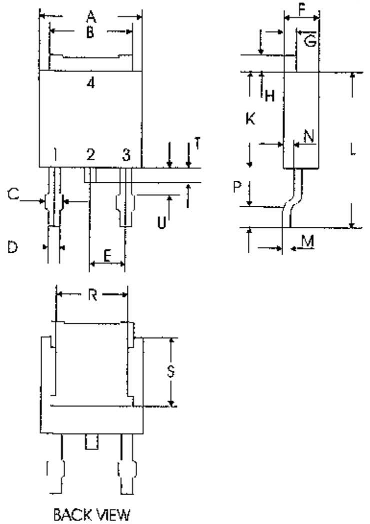


P-TO220-3-1



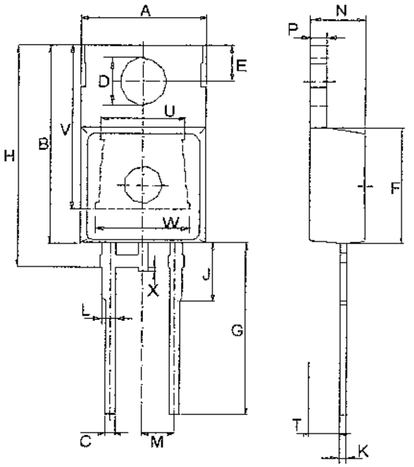
symbol	dimensions			
	[mm]		[inch]	
	min	max	min	max
A	9.70	10.30	0.3819	0.4055
B	14.88	15.96	0.5858	0.6280
C	0.65	0.86	0.0256	0.0339
D	3.55	3.89	0.1398	0.1531
E	2.60	3.00	0.1024	0.1181
F	6.00	6.80	0.2362	0.2677
G	13.00	14.00	0.5118	0.5512
H	4.35	4.75	0.1713	0.1870
K	0.38	0.65	0.0150	0.0256
L	0.95	1.32	0.0374	0.0520
M	2.54 typ.		0.1 typ.	
N	4.30	4.50	0.1693	0.1772
P	1.17	1.40	0.0461	0.0551
T	2.30	2.72	0.0906	0.1071

P-TO252 (D-Pak)



symbol	dimensions			
	[mm]		inch]	
	min	max	min	max
A	6.40	6.73	0.2520	0.2650
B	5.25	5.50	0.2067	0.2165
C	(0.65)	(1.15)	(0.0256)	(0.0453)
D	0.63	0.89	0.0248	0.0350
E	2.28		0.2520	
F	2.19	2.39	0.0862	0.0941
G	0.76	0.98	0.0299	0.0386
H	0.90	1.21	0.0354	0.0476
K	5.97	6.23	0.2350	0.2453
L	9.40	10.40	0.3701	0.4094
M	0.46	0.58	0.0181	0.0228
N	0.87	1.15	0.0343	0.0453
P	0.51	-	0.0201	-
R	5.00	-	0.1969	-
S	4.17	-	0.1642	-
T	0.26	1.02	0.0102	0.0402
U	-	-	-	-

TO-220-2-2



symbol	dimensions			
	[mm]		[inch]	
	min	max	min	max
A	9.70	10.10	0.3819	0.3976
B	15.30	15.90	0.6024	0.6260
C	0.65	0.85	0.0256	0.0335
D	3.55	3.85	0.1398	0.1516
E	2.60	3.00	0.1024	0.1181
F	9.00	9.40	0.3543	0.3701
G	13.00	14.00	0.5118	0.5512
H	17.20	17.80	0.6772	0.7008
J	4.40	4.80	0.1732	0.1890
K	0.40	0.60	0.0157	0.0236
L	1.05 typ.		0.41 typ.	
M	2.54 typ.		0.1 typ.	
N	4.4 typ.		0.173 typ.	
P	1.10	1.40	0.0433	0.0551
T	2.4 typ.		0.095 typ.	
U	6.6 typ.		0.26 typ.	
V	13.0 typ.		0.51 typ.	
W	7.5 typ.		0.295 typ.	
X	0.00	0.40	0.0000	0.0157

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