High Temperature Testing and Noise Integration of a Buck Converter using Silicon and Silicon Carbide Diodes.

by

Murat RAHMANOV

2471

Dissertation submitted in partial fulfillment of

the requirements for the

Bachelor of Engineering (Hons)

(Electrical and Electronics Engineering)

22 November 2004

University Technology PETRONAS

Bandar Seri Iskandar

31750 Tronoh

Perak Darul Ridzuan

CERTIFICATION OF APPROVAL

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A project dissertation submitted to the Electrical and Electronics Department of University Technology PETRONAS in partial fulfillment of the requirements for the Bachelor of Engineering (Hons) (Electrical an Electronics Engineering)

Approved By,

(Mr. Nor Zaihar bin Yahaya)

University Technology PETRONAS

Tronoh, Perak

22 November 2004

CERTIFICATION OF ORIGINALITY

This 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 the original work contained herein have not been undertaken or done by unspecified sources or persons.

Murat RAHMANOV

ACKNOWLEDGEMENTS

First of all, I would like to express my deepest gratitude to my Final Year Project supervisor, Mr. Nor Zaihar bin Yahaya for his continuous support and guidance throughout the duration of the Final Year Project.

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I am also very grateful to UTP technicians; Mr. Musa and Mr. Yasin for their help in obtaining the required library files for PSPICE software and installing the simulation software;

I would like to convey my many thanks to people that directly or indirectly assisted in ensuring the successful completion of the Final Year Project. Lastly, I would like to thank my friends and my family for their love and support throughout this project

ABSTRACT

This project includes comparison of the advantages of enhanced SiC device performance at elevated temperatures over Si devices in a buck type DC/DC converter circuit. Being that elevated temperatures in a circuit have always caused energy losses and deviation in results, the manufacturers of silicon technology came up with a much more sophisticated Silicon Carbide technology which dramatically reduces the above mentioned two factors. The scope is mainly to examine thermal effects at high temperatures on the performance characteristics of the buck converter circuit, diode losses, switching losses and overall system losses. This project also includes effect of noise integrated buck converter circuit. So, comparison is being made between that of noise integrated and noiseless circuit both of which are being varied from a low temperature up to temperature of 300 Celsius. This project mainly utilizes PSPICE software to achieve the above stated results. Reasons and causes as to the increase of losses as the increase of temperature have been discussed in this project. Also the source of noise and practical ways of reducing noises in buck converter circuits is being stated in this project. With proper tabulation and graphs of results this project enables to deeply understand Silicon Carbide technology used in buck converter circuit, which is a subject to elevated temperatures and noise.

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CHAPTER 1

INTRODUCTION

1.1 BACKGROUND OF STUDY

Power electronics and systems applications are mainly dominated by Si based power devices. Being as such the advanced power conversion needs faster devices with high voltage and high switching frequency capability. Mainly military applications require devices that operate at temperatures higher than 150^0 Celsius. These levels of temperatures are mainly caused by high voltages, high switching frequencies and high power densities or vice versa. The high-power-density and high-temperature capability of future SiC devices provide a powerful potential for applications in hostile environments. Such devices are also incredibly effective in situations where a reduction in electronic cooling is desired.

The wide band gap of SiC offer potential improvements in electronic switching. There is a high demand for high frequency switching operation of power converters. This leads to further requirements of faster solid state power devices with reduced switching loss. These devices are also expected to have low conduction power losses. High-power converters most commonly require diodes for rectification (ac–dc converter). The rectifier would need to have low forward conducting voltage drop, minimum reverse leakage current and minimum and soft reverse recovery for useful high frequency switching. The performance of Si diodes is now approaching the theoretical limits, and it is apparent that further advances in silicon technology are very difficult because of material properties [1].

Silicon carbide is one of the most efficient elements for achieving lightweight and high-density power converters for high temperature operation in hostile environments. Devices fabricated using SiC, compared to silicon implementations would offer lower losses at higher switching frequencies permitting smaller transformers and heat sinks, and better radiation tolerance [2].

1.2 PROBLEM STATEMENT

Si-based power semiconductor devices, ranging from diodes, thyristors, gate turn-off thyristors, metal–oxide–semiconductor field-effect transistors, and, more recently, insulated-gate bipolar transistors, integrated gate-commutated thyristors, and metal–oxide–semiconductor turn-off thyristors, are the workhorse of power electronic systems and circuits. Si offers multiple advantages to power circuit designers, but at the same time suffers from limitations that are inherent to Si material properties, such as low band gap energy, low thermal conductivity, and switching frequency limitations. Wide band gap semiconductors, such as SiC and gallium nitride (GaN), provide larger band gaps, higher breakdown electric field, and higher thermal conductivity. Power semiconductor devices made with SiC and GaN are capable of higher blocking voltages, higher switching frequencies, and higher junction temperatures than Si devices. SiC is by far the most advanced material and, hence, is the subject of attention from power electronics and systems designers. This final year project looks at the benefits of using SiC in power electronics applications, reviews the current state of the art, and shows how SiC can be a strong and viable candidate for future power electronics and systems applications.

1.3 OBJECTIVES AND SCOPE OF STUDY

The main objective of the project is to verify that SiC schottky diodes yield lower energy loss than Si schottky diodes at elevated temperatures. The energy losses of both diodes are compared to fulfill another objective of the project, which is to determine the diode with better efficiency. The energy loss of each diode is to be identified and compared with respective temperatures (150 Celsius and above).

Another objective is to compare performance of both the diodes using PSPICE simulation and also actual performance that are given in the specification sheets. Through this project simulation skills in using PSPICE software will be highly developed to analyze circuits.

The scope of the project is divided into three main parts; Buck converter circuit, Si Schottky diode and SiC Schottky diode. Effect of high temperature on the circuit which uses these two types of diodes will be compared. Mainly research will be carried out in PSPICE software and results will be that of a simulation. Being yet inaccessible, the apparatus that can test the circuit under elevated temperatures can not be used to actually verify the theory provided. That counts for a limitation of the project. The efficiency will be compared according to high temperature performance of the overall circuit, duty cycle and power dissipation of both the diodes.

CHAPTER 2

LITERATURE REVIEW AND THEORY

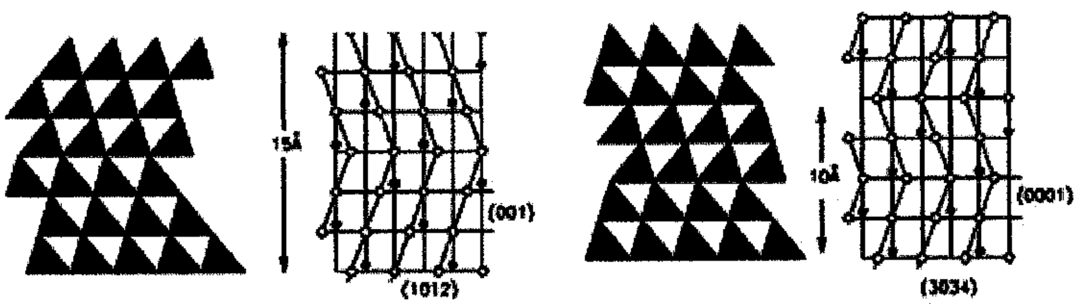
2.0 GENERAL OVERVIEW

Power electronics and systems applications are mainly dominated by Si based power devices. Being such the advanced power conversion needs faster devices with high voltage and high switching frequency capability. Mainly military applications require devices, such as guided missiles (GUSAM), sophisticated military jet planes, military space stations that operate at temperatures higher than 150 Celsius or below than zero degrees. These levels of temperatures are mainly caused by high voltages, high switching frequencies and high power densities or vice versa. The high-power-density and high-temperature capability of future SiC devices provide a powerful potential for applications in hostile environments. Such devices are also incredibly effective in situations where a reduction in electronic cooling is desired. In other words the internal temperature in the functional diode integrated circuits must be kept as low as possible or it must be made sure that the switching and diode losses in the converters do not raise the temperature above a critical level.

The wide band gap of SiC offer potential improvements in electronic switching. There is a high demand for high frequency switching operation of power converters. This leads to further requirements of faster power devices with reduced switching loss. These devices are also expected to have low conduction power losses. High-power converters most commonly require diodes (like Silicon Carbide) for rectification (ac–dc converter). The rectifier would need to have low forward conducting voltage drop, minimum reverse leakage current and minimum and soft reverse recovery for useful high frequency switching. The performance of Si diodes is now approaching the theoretical limits, and it is apparent that further advances in silicon technology are very difficult because of material properties [1]. Silicon carbide is one of the most efficient elements for achieving lightweight and high-density power converters for high temperature operation in hostile environments. Devices fabricated using SiC, compared to silicon implementations would offer lower losses at higher switching frequencies permitting smaller transformers and heat sinks, and better radiation tolerance [2].

2.1 PROPERTIES RELATED TO TEMPERTATURE ON SiC DEVICES

Temperature is highly dependent on the properties of silicon carbide materials. Basically these properties are defined as per polytypes available nowadays. There are mainly two polytypes of SiC devices 6H-SiC and 4H-SiC (refer to figure 1). Despite frequently using 6H-SiC polytype 4H-SiC has been performing much better in terms of high power and high temperature applications due to its higher electron mobility. Conduction parallel to the crystallographic c-axis in 6H-SiC favors the use of 4H-SiC for vertical power applications. It is important that, semiconductors used in high power, high speed and high temperature applications, have a wide energy band gaps. SiC and diamond would be a perfect example to such devices.



6 H silicon carbide structure **4H silicon carbide structure**

Fgiure 1 : Silicon Carbide Structures. [3]

Rapid progress has been made toward the development of improved high-voltage SiC devices despite the limitations that were being imposed by structural defects on the electrical performance of these devices [4]. 4H–SiC diode rectifiers with reverse breakdown voltage up to 5.5kV have been reported [5]. Si diodes fabricated on 4H–SiC have a high built-in forward drop because of the wide band gap (3.26 eV) of the material (refer to figure 2). High-voltage Si diodes have a significant voltage drop across the thicker drift region. This characteristic of SiC leads to a forward voltage drop comparable to similarly rated SiC diodes. If as stated by theory the switching performance of SiC diodes is proven to be far better than Si diodes, the effectiveness of SiC technology for high-voltage power applications would be justified.

Physical properties of wide gap semiconductors

Material	Diamond	GaN	[illegible]	6H-SiC	3C-SiC	GaAs	Si
Band Gap (eV)	5.47	3.39	3.26	2.93	2.23	1.43	1.12
Electron Mobility μ_e	2200	900	1000/850	[illegible]	800	8500	1400
Hole Mobility μ_h	1600	150	115	90	40	400	600
Max. Electric Field E_c	1×10^7	[illegible]	2.5×10^6	[illegible]	1.2×10^6	4.0×10^5	3.0×10^5
Thermal Conductivity • •	20	2.0	4.9	4.9	4.9	0.5	1.5
Saturation Velocity v_{sat}	2.7×10^7	2.7×10^7	2.2×10^7	1.9×10^7	2.0×10^7	2.0×10^7	1.0×10^7
Dielectric Constant • •	5.5	9.0	9.7	9.7	9.7	12.8	11.8
Bulk Growth			• • • • •	• • • • •		• • •	• •
Epitaxial Growth			• • • • •	• • • • •		• • •	• •
BM (vs. Si)	27128	653	340	191	30	16	1
BHFM (vs. Si)	1746	78	50	25	9	11	1
Expected Devices	μ-emitter Power	Blue LD High Freq. Lateral Power	High Power	Substrate for GaN	Medium Power	High Freq.	Overall

Figure 2: Bandgap energies of silicon materials over a range of temperatures.[4]

Advanced performance of SiC has long been predicted on the basis of material properties and measured characteristics of prototype devices [6]. However, a realistic technology comparison must be performed under practical switching conditions using an actual power electronic circuit simulator. In the case of this project the simulator is PSPICE which is very limited in terms of access to certain types of SiC diodes. Despite that simulation in this project was carried out based on the most available SiC diodes manufactured by Infeneon.

2.2 SiC TEMPERATURE CHARACTERISTICS

SiC has over 150 polytypes, but only the 6H– and 4H–SiC polytypes are available commercially. Between the two polytypes, 4H–SiC is preferred for power devices because of its high carrier mobility (ability to move easily), particularly in -axis direction and its low dopant ionization energy. These two properties are the main reason for low heat dissipation and for durability under highly elevated temperatures. In addition, the high electric breakdown field of SiC allows for thinner layers to support the high kV in power devices. A 5000-V power device would require only 40–50 m drift layer, as opposed to almost 500 m in the case of Si. This smaller drift layer leads to low drift resistance; hence, low forward drop and conduction losses (refer to the figure 3). SiC thermal conductivity of about 5 W/cm K allows for high junction temperature operation and for efficient thermal management. In this case, SiC clearly excels over Si over all switching frequencies and the power dissipation is clearly smaller in SiC transistors. By contrast, the IGBT, which is the dominant Si power transistor structure, has an odd number of junctions in its structure and its forward drop cannot be reduced to less than a diode drop. Since SiC has a large diode turn-on voltage due to its larger band gap, its conduction loss cannot be less than the Si device at low to medium current density and only yields a lower total power loss when the switching frequency exceeds a certain frequency . This, at which the conduction loss is equal to the switching loss (at 50% duty cycle), has been considered as the bipolar figure of merit and, in the case of a 1000-V IGBT, is about 20 kHz for SiC when compared to Si. [7]

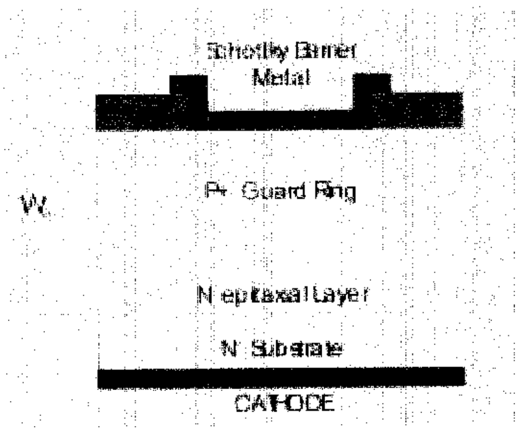


Figure 3: Structure of SiC Schottky diode [5]

2.3 BUCK CONVERTER CIRCUIT

In such circuits main criteria required is to have a regulated stepped down voltage supply. The reason why especially this circuit was chosen is because it is used in wide ranges of circuit models which mainly do require operation under elevated temperatures. This converter circuit has a power stage as in figure below.

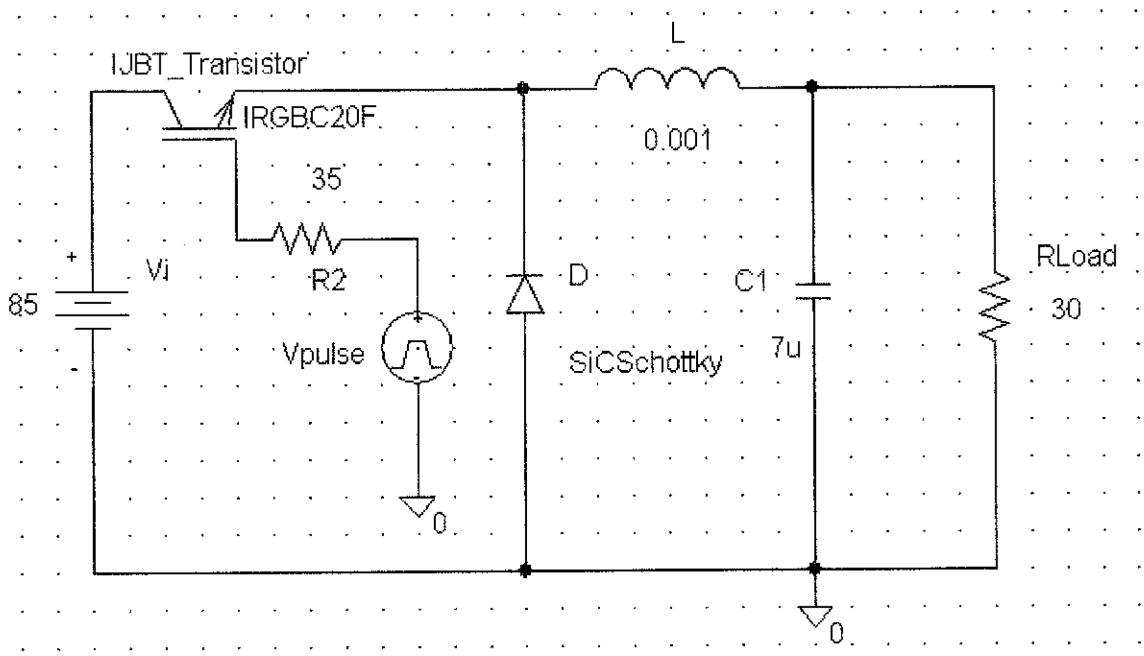


Figure 4: Buck Converter

As seen from the figure it consists of a voltage input, a controlled switch such as a Si MOSFET, a freewheeling diode, an inductor and a capacitor. The power MOSFET is controlled by a PWM controller shown below:

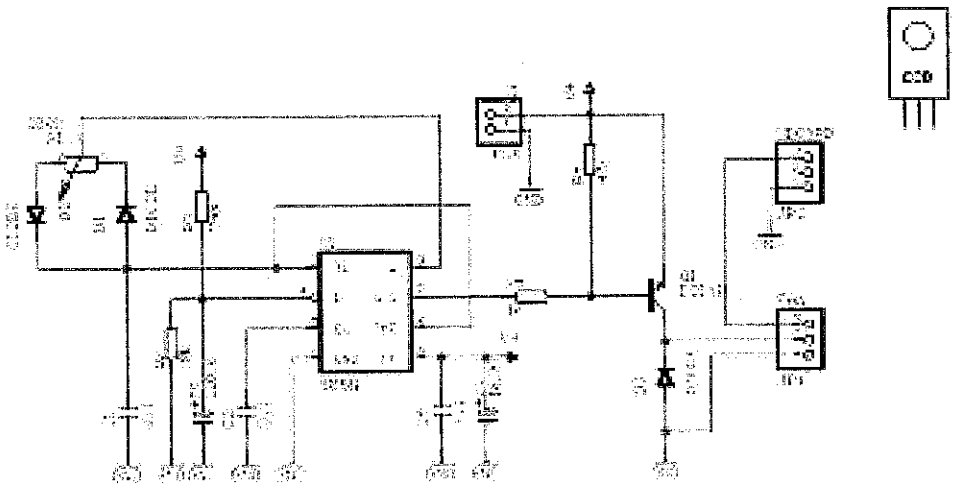


Figure 5: PWM controller 555 [5]

PWM controller switches the MOSFET on for the time DT. (D=duty cycle, T = time period corresponding to switching frequency). To achieve a buck converter performance of which does not get affected by temperature, the main semiconductor components must achieve a significant reduction of switching power losses. For this reason, unipolar semiconductors such as MOSFETs and Schottky barrier diodes are used instead of bipolar devices. The advantage of unipolarity is the absence of stored charge carriers and, therefore, theoretically instantaneous switching transients limited only by small parasitic capacitances.

2.4 INPUT AND OUTPUT NOISES IN BUCK CONVERTERS

Input and output noise in buck converters can be a cause of concern to the system designer. There are individual contributions of conducted noise on the input and output sides of buck converters. Some equations govern the peak-to-peak noise contributions of each noise source. These equations allow the designer of buck converters to pick components that will help them meet their design objectives. However the equations are appropriate for any buck converter, independent of the control scheme, as long as they meet the following limitations:

a) The equations assume continuous conduction above 0A.
b) The load is a constant DC load
c) The converter is 100% efficient

2.4.1 OUTPUT NOISE

Figure 6 shows a typical buck converter, with Figure 7 showing some typical waveforms for that converter. The second graph from the bottom in Figure 7, labeled I(Cout), shows the current flowing into and out of the output capacitor. Note that the net DC current is zero (because it's a capacitor), but there is AC current flowing.

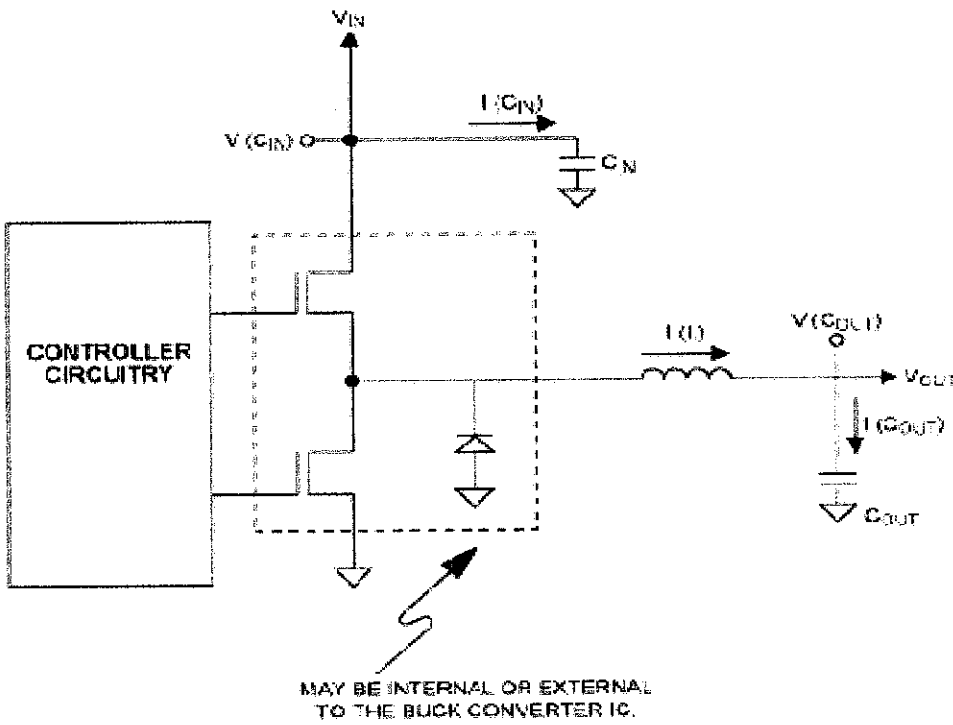


Figure 6: A typical buck converter circuit.[8]

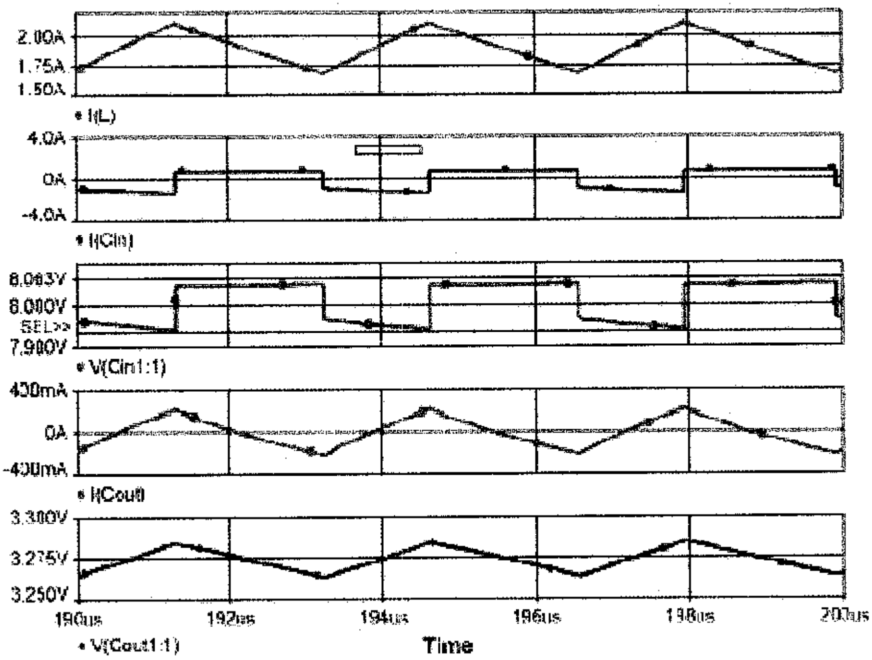


Figure 7: Shown are some typical waveforms for a buck converter.[8]

This AC current working against the output capacitor's finite capacitance and equivalent series resistance (ESR) is what generates the output noise.

2.4.2 INPUT NOISE

Many times engineers calculate the output noise, while ignoring the input noise. Buck converters will also cause conducted noise to be "injected" onto the input supply. For example, in the case of a 5V to 3.3V converter, the buck converter will cause noise on the 5V supply as well as generate noise on the 3.3V supply. If the 5V supply has noise sensitive components powered from it, this injected noise could be important. So there are basically 3 major contributors for this type of noise: finite input capacitance, the input capacitor's ESR, and ringing that is caused by the stray inductance and stray capacitance in the circuit. The current waveform that the input capacitor "sees" is shown in Figure 7, second graph from the top. This AC current works against the input capacitor's finite capacitance to create noise on the input supply. This noise is calculated in the same way as the noise on the output due to finite capacitance.

CHAPTER 3

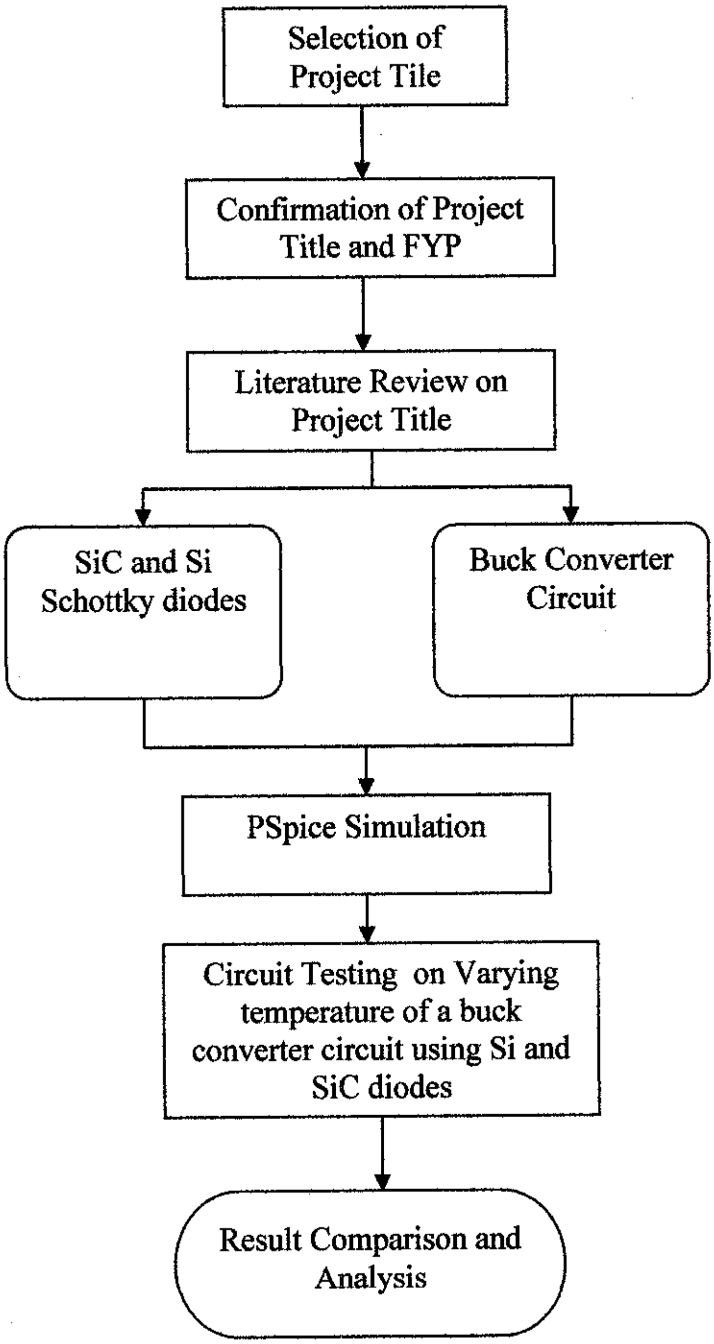
METHODOLOGY

Temperature levels can be increased in various ways in a buck converter circuits. However choosing the most convenient in terms of cost and time is our main objective. There are tools which can increase the overall and diode temperatures separately in a buck converter circuit. Blaze can be used to calculate the forward, reverse, and reverse breakdown losses of a SiC diode at elevated temperatures. Blaze is part of the ATLAS system for 2D device simulation. The other components of the framework can be used to provide added functionality.

The results that obtained using Blaze show that Blaze produces results that are in good agreement with experiment. Blaze can thus provide state-of-the-art SiC device simulation capabilities to the entire SiC device community. Other products of interest to the SiC device community are Giga, MixedMode and PSPICE simulator. Giga works in conjunction with Blaze to account for heat flow, lattice heating, and realistic heat sinks. MixedMode is a SPICE-like circuit simulator that supports the use of numerical physically-based devices simulated using ATLAS as well as compact device models. The combination of Blaze, Giga and MixedMode can predict the performance of circuits that include SiC devices, while taking into account heat flow within the device.

The methodology used in the present work was to first determine overall losses in a buck converter circuit by calculating them using PSPICE software. Diode losses were performed for a range of different temperatures, where the other criteria like duty ratio, frequency bandwidth etc. are kept constant.

3.1 PROCESS FLOW



3.2 TOOLS

During the first semester of the project, the tasks are mainly on research and simulation. Thus, personal computer with access to internet search engines will be primary tool throughout the course of project. Other than that library facilities play an important role in finding information that is not accessible (due to payments needed to be made) via internet research. PSPICE software will be used for simulation purposes.

So, how are the losses actually calculated?

The graphs are obtained prior to any calculation. The PSPICE software has an option where it can calculate the power losses of a graph obtained from its simulation. So there are mainly two types of graphs to be obtained first is forward the second is reverse losses. The number of divisions under each graph represent power loss. It must be marked that it is not energy loss but power loss which will be obtained form the graphs. So, since it is energy that is our main concern the divisions must be converted accordingly. For example if:

1 division of time=2e-10s

1division of power=0.5W

1box=2e-10s X 0.5W =0.1nJ

and if we assume :

Total number of boxes occupied to be = 265 boxes

Hence, Energy loss of the circuit=26.5nJ

CHAPTER 5

RESULTS AND DISCUSSIONS

5.1 FINDINGS

Tasks carried out are: Submission of FYP Project Title Selection was done on 28January2004. Completed the first version of the FYP schedule for reference and proper project and time management. Acquired all the necessary circuit elements of buck converter. Also necessary library files have been obtained from my supervisor. Managed to get into contact with some of IEEE members in order to ask about the importance of buck converter applications in daily life. Several circuit design alternatives have been analyzed and studied. Work is being done on finalizing the actual circuit to be employed. Downloaded some programming tools and methods from the internet. Further investigations on the best tools and programming styles was being carried out. After careful and thorough research has been conducted, the followings are chosen and its design will be implemented into the project:

- PSPICE Circuit Simulator.
- Buck Converter Circuit.
- Silicon Carbide Schottky diode
- Silicon Schottky diode.

Specifications and settings of the following main circuit components were acquired within UTP with the assistance of Mr. Norzaihar.

- DC power supply
- Frequency and Duty cycle.
- Input/Output noise AC voltage
- Library files

Diode, switching and total system losses have been calculated and tabulated accordingly. Circuit is being modified as per requirements of input and output losses to be calculated.

Actual testing and commissioning of the circuit with noise losses have been carried out after semester break due to lack of information on input and output noises. Resistance values for the SiC and Si diodes are missing. Appropriate value for the AC supply and frequency noise value are yet to be obtained. Still having difficulty in accessing flicker noise constant. Also flicker exponential constant is missing.

5.2 SYSTEM CIRCUIT

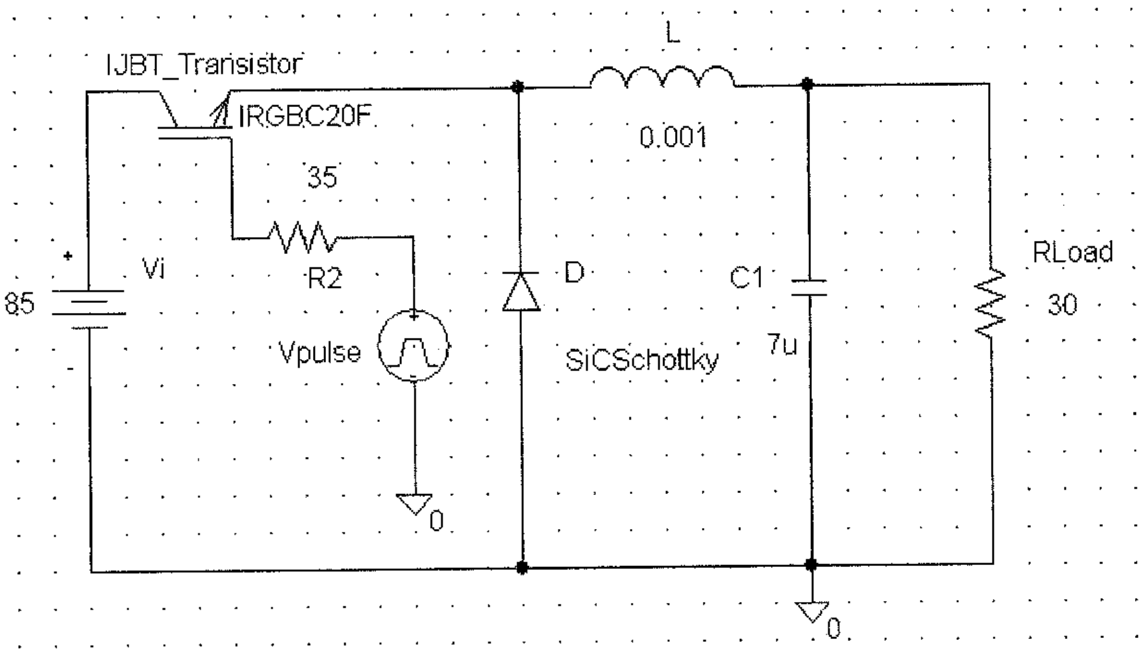


Figure 8: Buck converter circuit which yielded the results in table 1. Achieved by using PSPICE software which utilizes SiC Schottky diode.

	SWITCH LOSSES		
T (C)	ON (µJ)	OFF (µJ)	TOTAL(µJ)
27	1.28	116.5	117.78
100	1.408	127	128.408
200	2.892	178.5	181.392
300	2.916	216	218.916

Table 1: Measured and calculated switch losses on the overall buck converter circuit where only temperature is subject to change. SiC.

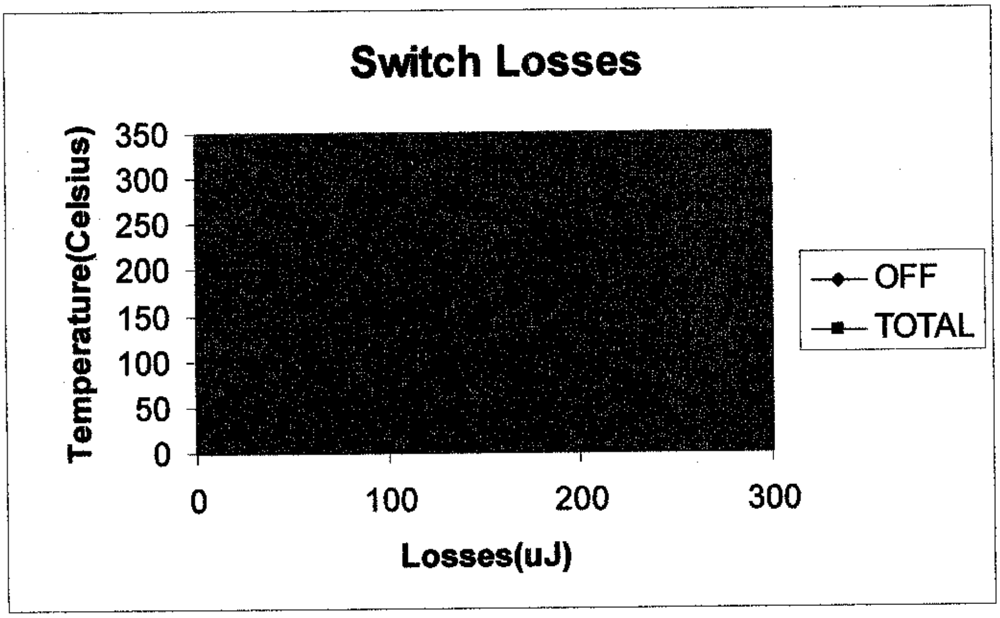


Figure 9: Switch losses against Temperature with ON losses being discarded. (SiC)

	DIODE LOSSES		
T (C)	ON (µJ)	OFF (µJ)	TOTAL(µJ)
27	0.615	1.41	2.025
100	0.768	1.578	2.344
200	0.798	1.713	2.511
300	0.814	1.867	2.681

Table 2: Measured and calculated diode losses on the overall buck converter circuit where only temperature is subject to change. SiC.

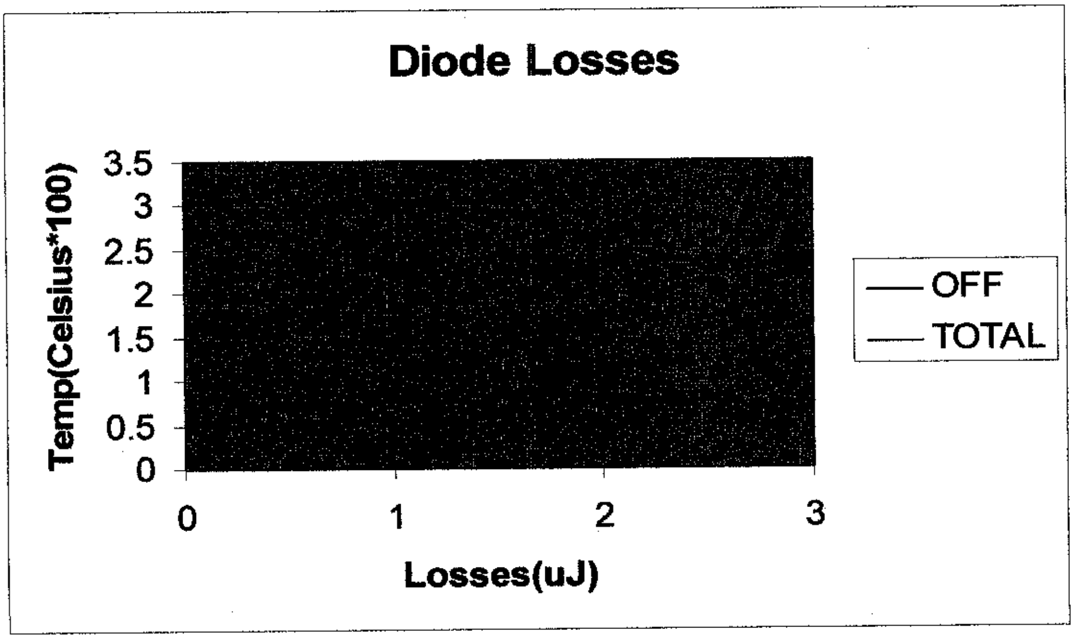


Figure 10: Diode losses against Temperature with ON losses being discarded (SiC)

The table is simulated using SiC and Si diodes. The temperature was varied from 27 Celsius up to 300 Celsius. Each level of temperature yields different rate of conversion and different dead time. In other words as can be seen from above table there is a significant loss of efficiency as temperature is increased in Si diodes. All the conversions begin at different supplication of voltages, which means conversion really takes place after a much later time than when the voltage has began to be supplied, which means that the efficiency of Si and SiC diodes are not the same including the fact that they have different response time. The response time in SiC diodes are same all over any kind of temperature change but simple Si diodes yield inefficient response time. The response time in simple Si diodes worsens as temperature increases (refer to table 2).

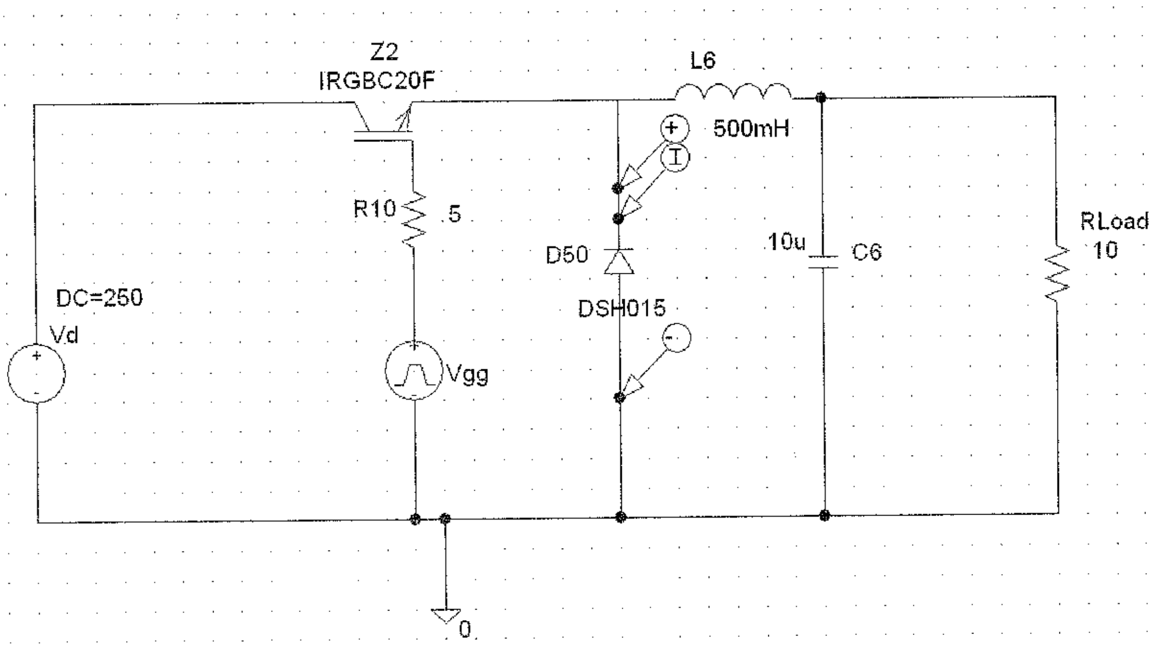


Figure 11: Buck converter circuit which yielded the results in table 2. Achieved by using PSPICE software which utilizes Si Schottky diode.

	SWITCH LOSSES		
T	**ON**	**OFF**	**TOTAL**
27	1.28	163.8	165.08
100	2.658	174.3	176.958
200	4.392	225.8	230.192
250	4.516	278.4	282.916

Table 3: Measured and calculated Switch losses on the overall buck converter circuit where only temperature is subject to change. Si

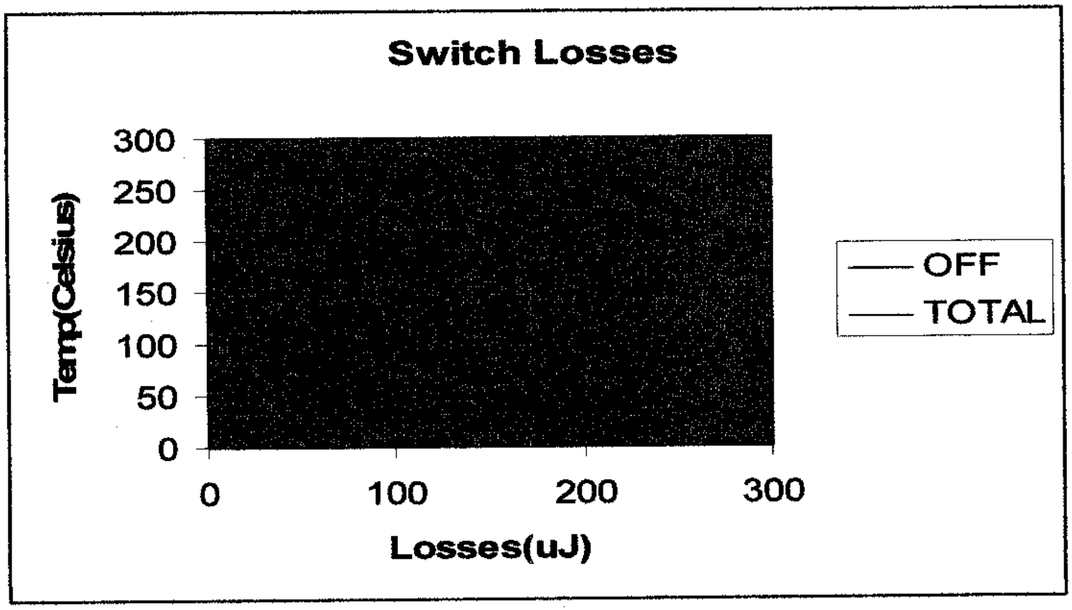


Figure 12: Switch losses against Temperature with ON losses being discarded. (Si)

	DIODE LOSSES		
T (C)	ON(uJ)	OFF(uJ)	TOTAL(uJ)
27	0.595	1.378	1.973
100	1.018	2.828	3.846
200	1.298	3.463	4.761
250	1.564	4.118	5.682

Table 4: Measured and calculated Diode losses on the overall buck converter circuit where only temperature is subject to change. Si.

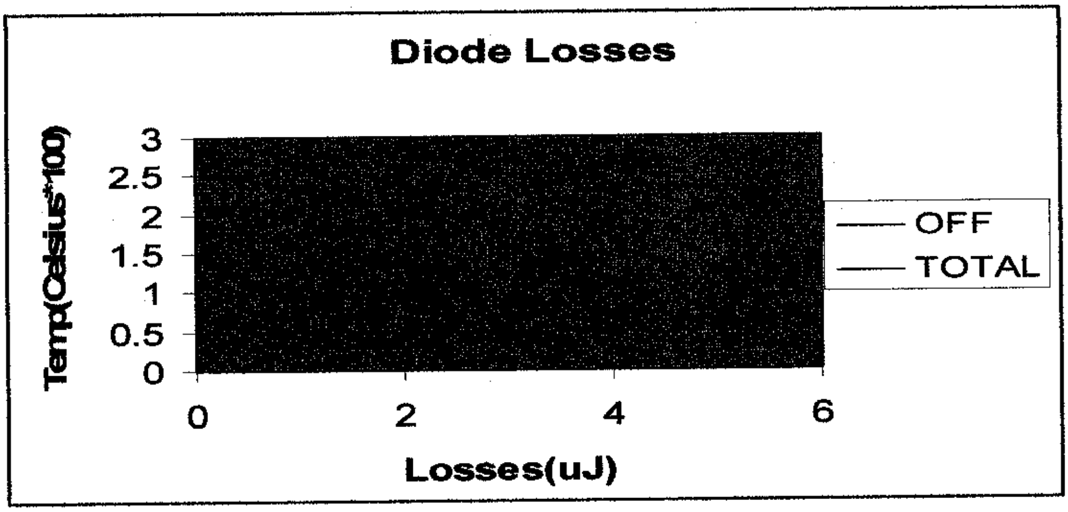


Figure 13: Diode losses against Temperature with ON losses being discarded. (Si)

As put forward by theory the increase in ON-resistance of the IGBT is due to a decrease in the mobility of electrons with increase in temperature, causing local resistance to increase as a function of temperature. Si based materials show a degradation in performance, as seen from the above graphs, with increasing temperature due to an increase in the forward drop, hence dissipation in Si diodes increases with increasing temperature. But SiC diodes show a less degradation than pure Si materials. In fact the performance is kept quite close to nearly constant.

5.3 POWER LOSSES WITH NOISE INTEGRATED CIRCUIT

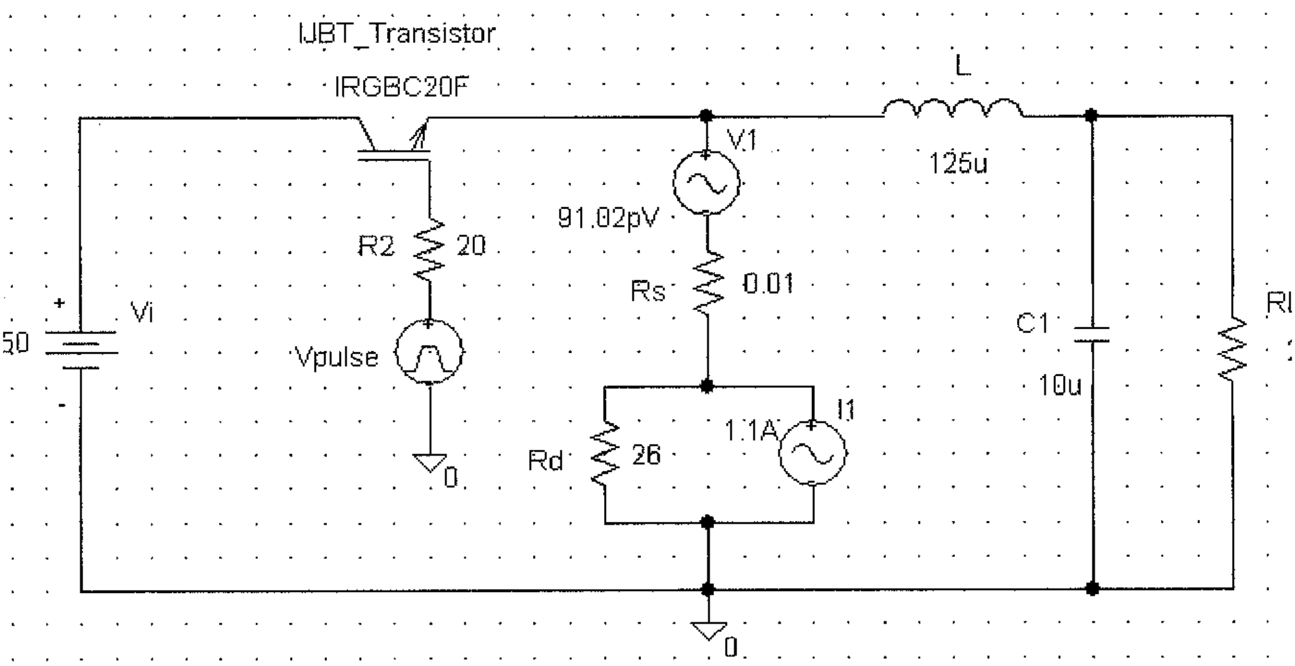


Figure 14: Buck converter circuit where SiC diode is replaced with the above fragment. Achieved by using PSPICE software.

	SWITCH LOSSES		
T (C)	ON (μJ)	OFF (μJ)	TOTAL(μJ)
27	2.356	121.9	124.256
100	2.538	131.65	134.188
200	2.876	182.95	185.826
300	2.993	221.65	224.643

Table 5: Measured and calculated switch losses on the overall buck converter circuit where only temperature is subject to change and the circuit is noise integrated. SiC.

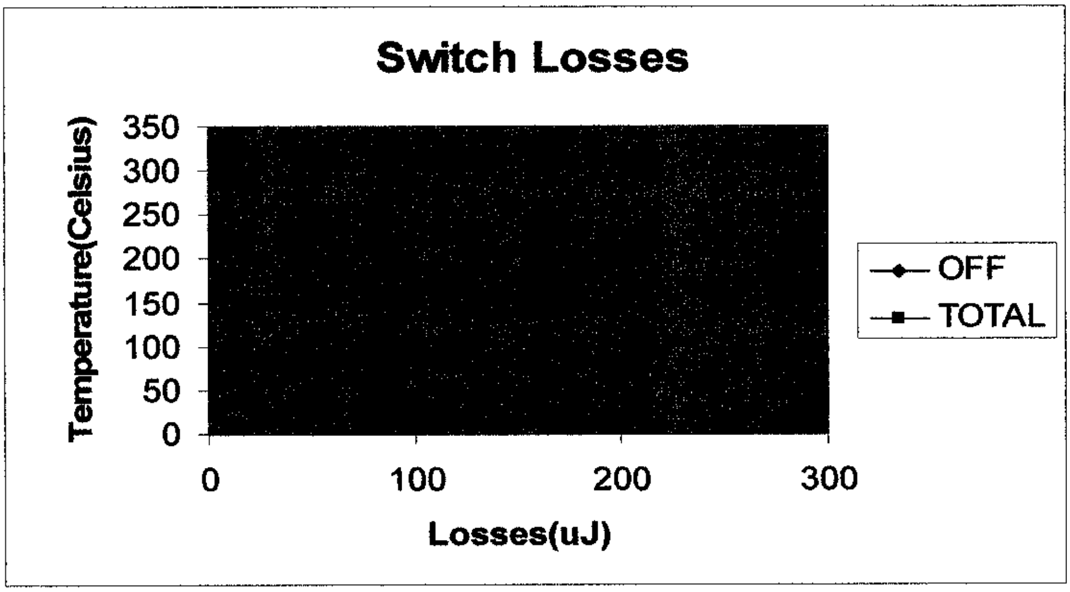


Figure 15: Switch losses against Temperature with ON losses being discarded. Noise integrated circuit. (SiC)

	DIODELOSSES(uJ)		
T (C)	ON (μJ)	OFF (μJ)	TOTAL(μJ)
27	0.343	1.341	1.684
100	0.386	1.487	1.873
200	0.389	1.531	1.92
300	0.394	1.678	2.072

Table 6: Measured and calculated diode losses on the overall buck converter circuit where only temperature is subject to change and the circuit is integrated with noise. SiC.

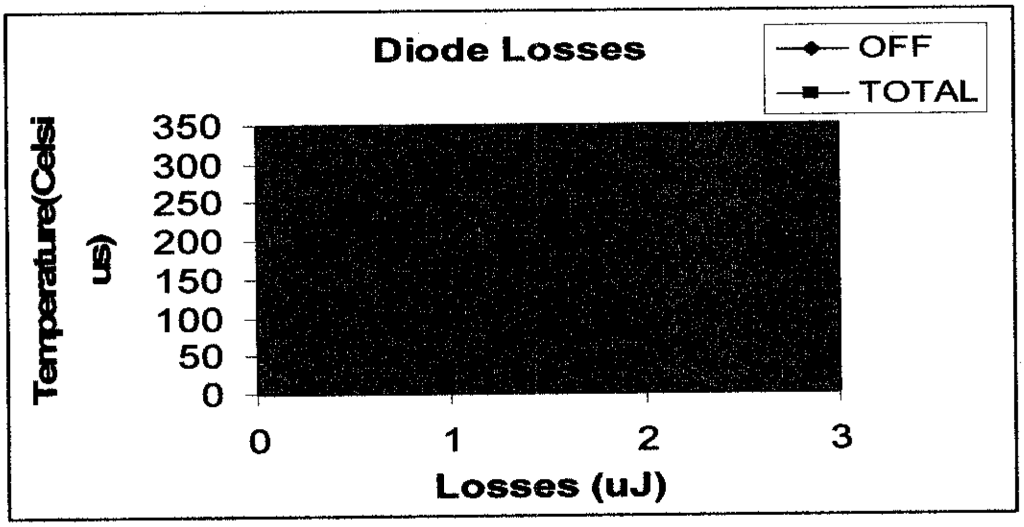


Figure 16: Diode losses against Temperature with ON losses being discarded. Noise integrated circuit. (SiC)

The table is simulated using the appropriate fragments of SiC and Si diodes. In this fragment the resistive values of the diodes are changed to a corresponding ohmic value. The temperature again was varied from 27 Celsius up to 300 Celsius. The losses in diode have changed slightly whereby the switching losses remain almost unchanged. However when the circuit is integrated with noise and temperature is increased above 100 the efficiency still decreases as seen from the graphs above. This shows that noise also adds inaccuracy to the results causing unnecessary energy losses.

	SWITCH LOSSES		
T (C)	ON (μJ)	OFF (μJ)	TOTAL(μJ)
27	2.328	183.567	185.895
100	2.958	197.369	200.327
200	3.293	227.495	230.788
250	3.367	269.413	272.78

Table 7: Measured and calculated Switch losses on the overall buck converter circuit where only temperature is subject to change. Si

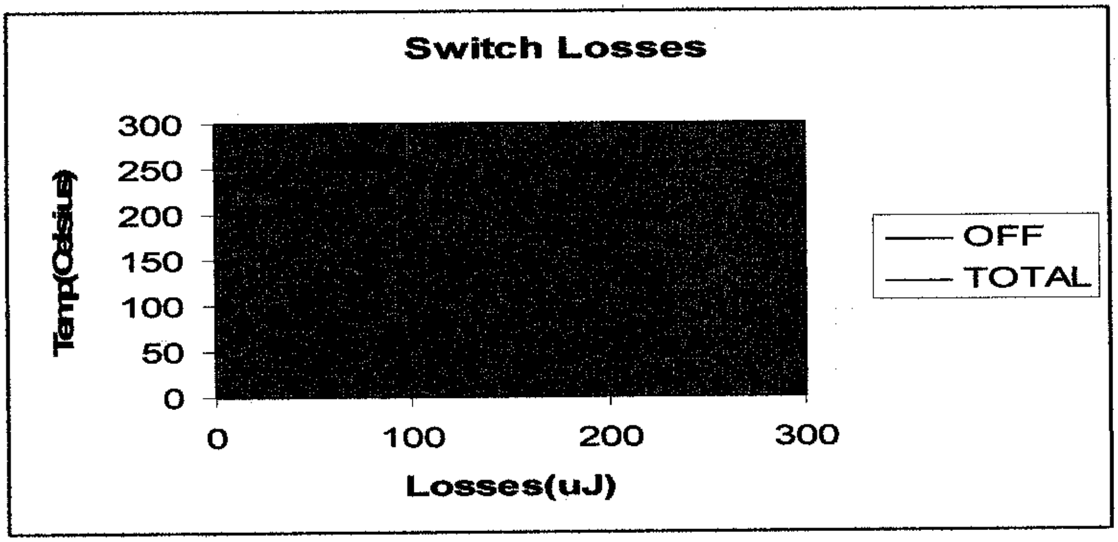


Figure 17: Switch losses against Temperature with ON losses being discarded. Noise integrated circuit. (Si)

	DIODE LOSSES		
T (C)	ON (µJ)	OFF (µJ)	TOTAL(µJ)
27	0.259	1.787	2.046
100	0.518	3.018	3.536
200	0.689	3.736	4.405
250	0.748	4.237	4..985

Table 8: Measured and calculated Diode losses on the overall buck converter circuit where only temperature is subject to change. Si.

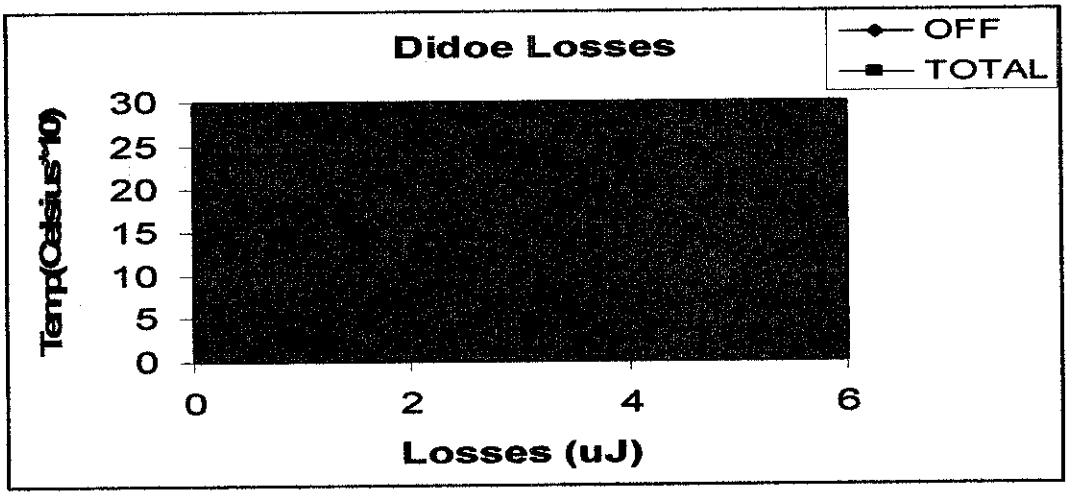


Figure 18: Diode losses against Temperature with ON losses being discarded. Noise integrated circuit. (Si)

As put forward by theory the increase in ON-resistance of the IGBT is due to a decrease in the mobility of electrons with increase in temperature, causing local resistance to increase as a function of temperature. Si based materials show a degradation in performance, as seen from the above graphs, with increasing temperature due to an increase in the forward drop, hence dissipation in Si diodes increases with increasing temperature. But SiC diodes show a less degradation than pure Si materials. In fact the performance is kept quite close to nearly constant.

5.4 CONCLUSION

Fundamental knowledge on SiC and Si Schottky diodes was presented. Buck converter circuit basics were discussed. Also specifications about buck converter and use of SiC Schottky diodes were stated. Also simulations achieved so far are attached. The project is successfully initiated as a final year project. In the course of the implementation of this project, several tasks have been carried out namely:

1) Preliminary Research
2) Literature Studies
3) Problem Statement Definition
4) Scope of Work and Objectives
5) Circuit Design
6) System Losses
7) Noise integration
8) Tabulation of data.

Understanding the many characteristics and features of Buck Converter circuit, mainly the SiC and Si diodes, are crucial in the successful implementation of this project. These two diodes are the main components of this project. Another important aspect is the temperature increase and simulation at different values of temperature. The main objective in simulating a buck converter circuit is to check for the losses as temperature increases. Also, since in actual, daily life circuits noise is inevitable, losses were as well calculated with noise integrated buck converter circuit.

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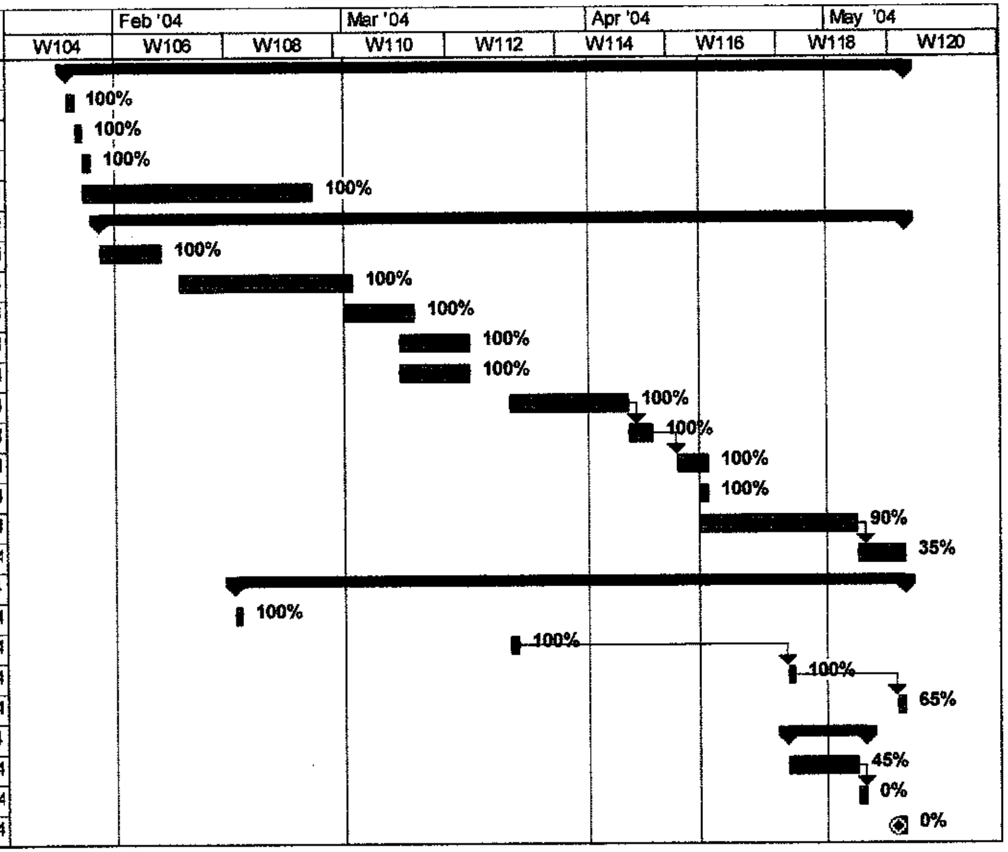
APPENDIX 1

1.0 PROJECT SCHEDULE

Final Year Project II 2004 (FYPII)

Temperature Effect on SiC Diodes

ID		Task Name	Duration	Start
1		**Final Year Project 1 (FYP1)**	**76 days**	**Mon 26/01/04**
2	✓	Briefing	1 day	Mon 26/01/04
3	✓	Meeting with Supervisor	1 day	Tue 27/01/04
4	✓	Title Selection	1 day	Wed 28/01/04
5	✓	Preliminary Research	21 days	Wed 28/01/04
6		**Execution of Project**	**72 days**	**Fri 30/01/04**
7	✓	Design Alternatives	6 days	Fri 30/01/04
8	✓	Design Selection	16 days	Mon 09/02/04
9	✓	Detail Part List	7 days	Mon 01/03/04
10	✓	Cost Analysis	7 days	Mon 08/03/04
11	✓	Procurement	7 days	Mon 08/03/04
12	✓	First prototype	11 days	Mon 22/03/04
13	✓	Test on BreadBoard	3 days	Tue 06/04/04
14	✓	Evaluation	4 days	Mon 12/04/04
15	✓	Final prototype	1 day	Thu 15/04/04
16		Printed Circuit Board Design	14 days	Thu 15/04/04
17		Test and Commissioning	4 days	Wed 05/05/04
18		**Progress Report Submission**	**61 days**	**Mon 16/02/04**
19	✓	Preliminary Report	1 day	Mon 16/02/04
20	✓	Progress Report	1 day	Mon 22/03/04
21	✓	Interim Report Final Draft	1 day	Mon 26/04/04
22		Interim Report	1 day	Mon 10/05/04
23		**Seminar/Presentation**	**8 days**	**Mon 26/04/04**
24		Preparation	7 days	Mon 26/04/04
25		Oral Presentation	1 day	Wed 05/05/04
26		Project Completion	1 day	Mon 10/05/04



Silicon Carbide Schottky: Novel Devices Require Novel Design Rules

I. Zverev* (*contact author), H. Kapels, R. Rupp, M. Herfurth
* Infineon Technologies AG, P.O.Box 801709, D-81617 Munich, Germany,
fax +4989234712476, ilia.zverev@infineon.com

Abstract

The close-to-ideal properties of novel silicon carbide Schottky diodes (thinQ!™), that can reach higher blocking voltages than the actual Silicon Schottky limit of 250V, are well suited for hard switching commutation. In order to maximize the benefit from these characteristics, a different design-in approach compared to conventional diodes is required.

Introduction

Silicon diodes have been used in power electronics for a while. Their properties and characteristics have been studied in very detail. Designing with such diodes has become a routine and as every routine it has established some paradigms. One of them is - for example – the selection of the appropriate current rating of a booster diode in continuous conduction mode PFC.

The introduction of Silicon Carbide high voltage Schottky diodes will shift these paradigms. Due to their superior characteristics, the design guidelines must be rewritten.

Properties of Silicon Carbide

With Silicon Carbide, belonging to the so called *wide bandgap semiconductors,* the voltage range for Schottky diodes now can be extended to more than 3000V. This is possible by the material related benefits of SiC.

Dynamic characteristics of SiC Schottky diodes

The quasi "reverse recovery" charge Q_c and the switching power losses of SiC Schottky diodes are not only ultra low. Compared to Silicon ultra fast diodes, where losses strongly depend on dI/dt, current level and temperature, they are more or less independent on these boundary conditions (Fig. 1). A dependency of Q_c on these parameters can not be seen at the same scale as with a benchmark Si diode approach. This is due to the capacitance like behavior of SiC device in reverse direction

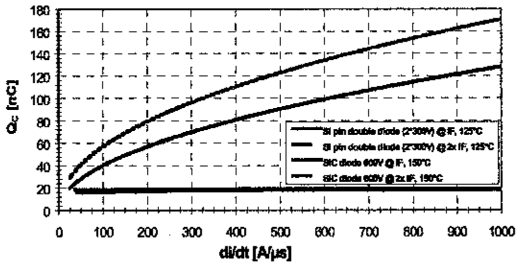


Fig. 1: Comparison of stored charge in SiC (Q_C) and Silicon diodes (Q_{rr}).

Active Power Factor Correction (Boost Converter)

Worldwide requirements for power factor correction are growing strongly driven by legal requirements.

Basics of PFC Boost

Boost converters are usually used to realize active power factor correction (Fig. 2). They can be driven in Discontinuous Conduction Mode (DCM) and Continuous Conduction Mode (CCM).

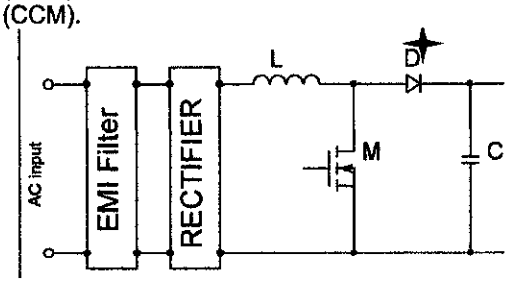


Fig. 2: Schematic circuit of a power factor corrector (PFC) with a boost converter.

How to select the right current rated device

Selecting the current rating for the PFC boost diode is an important design consideration. Differently rated currents mean different die

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sizes, power losses and cost. An optimal solution would be obviously the smallest die size, which can handle defined output power under given thermal considerations.

Inrush current during initial charge of the bulk capacitor

Ultra fast diodes have a limited inrush surge current capability. The initial charge of a relatively large bulk capacitor during the plugging in can exceed the maximum allowed peak current through the booster diode and even through the input rectifier bridge. This can be avoided using a conventional silicon diode initially charging the bulk capacitor from the rectified AC voltage, which avoids high surge currents in the booster diode (Fig. 3).

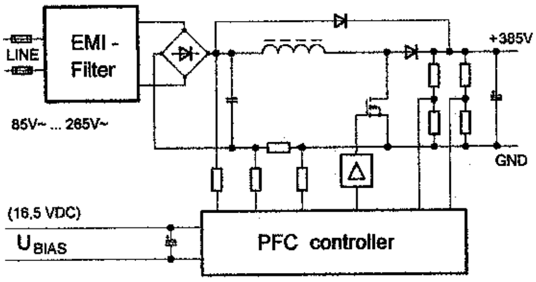

Fig. 3: Bypass diode for inrush current

Another approach is to use a resistor in serial with the bulk capacitor for initial charge.

Pulse current during operation

During the sinus wave of the main line the peak current through the boost diode can reach relatively high values compared to it's average current (Table 1).

P_{OUT}, W	$I_{D\ average}$, A	$I_{D\ rms}$, A	$I_{D\ peak}$, A
75	0.202	0.247	1.509
100	0.271	0.329	2.013
200	0.542	0.659	4.025
300	0.813	0.988	6.038
400	1.084	1.317	8.051
600	1.626	1.976	12.076
800	2.168	2.635	16.101
1000	2.71	3.294	20.126

Table 1: Booster diode stress in CCM PFC (V_{IN}=85Vac, V_{OUT}=400Vdc, efficiency=93%)

It is important not to exceed the maximum pulse current rating of the booster diode in order to maintain reliable operation. It is another selection criteria for the booster diode.

Start up of PFC boost converter

After the bulk capacitor has been charged up through the bypass circuit up to the voltage corresponding to the amplitude of the main line the PFC controller starts up. The bulk capacitor will be charged as shown in Fig. 4.

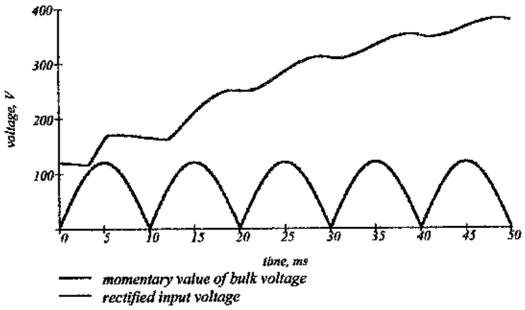

Fig. 4: Bulk cap & main voltages

The Control IC will try to charge the bulk cap with the maximum allowed duty cycle. Some Control IC's have a "soft start" for the duty cycle of the switch (Fig. 5).

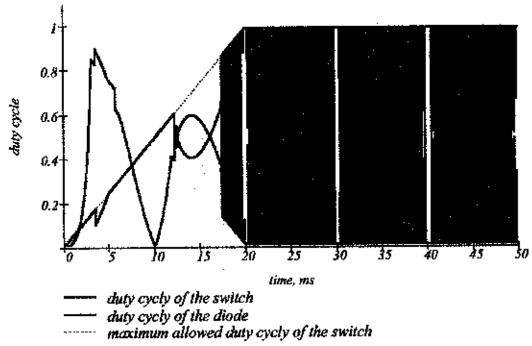

Fig. 5: Duty cycle

Nevertheless, the peak current limiting will be reached already at the first half period (Fig. 6).

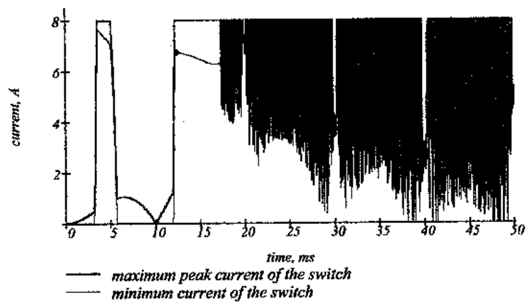

Fig. 6: Maximum & minimum currents

The minimum and maximum current through the diode are equal to current limiting value, e.g. highest possible value (Fig. 6). On the other hand the "soft start" duty cycle limiting for the switch does not help for the diode. The diode conducts the rest of the switching period. This leads to very long duty cycles for the diode (Fig. 5). Combination of high peak current and long duty cycles causes large conduction power losses in the diode (Fig. 7).

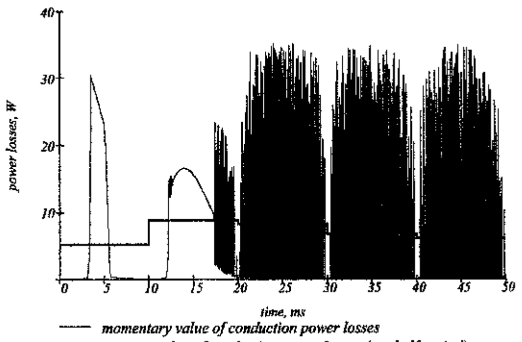

Fig. 7: Conduction power losses in the diode

Increase in power losses leads correspondingly to a rapid junction temperature increase (Fig. 8).

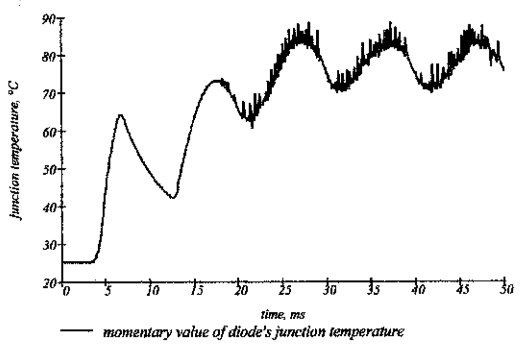

Fig. 8: Junction temperature of the diode (start at 25°C)

As long as junction temperature stays below the maximum specified value it is a safe design. It is important to consider that this first temperature increase can be higher than the junction temperature under full load. In case of "hot" restart (for example after mains drop out) the junction temperature may exceed the specified limit.

The duty cycle limiting for the switch does not protect the diode at all. Safe design should include junction temperature analysis during possible transients.

Current capability of Silicon Carbide diodes in CCM PFC Boost applications

SiC diodes have different features as ultra fast silicon diodes. The most important differences are the missing reverse recovery charge and the positive temperature coefficient of the forward voltage of the SiC diodes. Instead of reverse recovery charge there is only a small capacitive charge of the junction. Due this feature the SiC diode is best suited for continuous conduction mode (CCM) switching applications. The positive temperature coefficient of the forward voltage allows to operate SiC diodes in parallel, but on the other hand we have to design applications of SiC diodes carefully in respect to thermal household. With SiC diodes we have to avoid thermal runaway due to conduction losses, with silicon diodes we have to avoid thermal runaway due to switching losses.

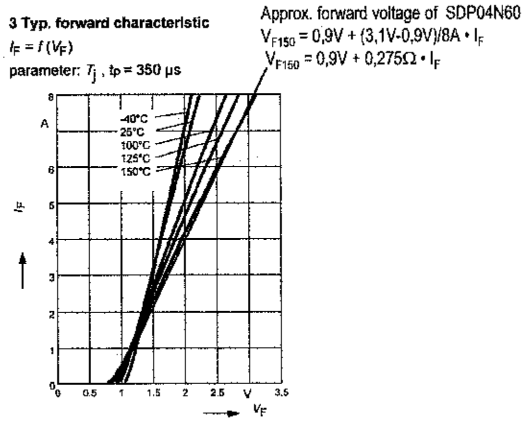

Fig. 9: Forward characteristics of 4A/600V SiC SBD

Fig. 9 shows the typical forward voltage versus forward current of a 4A-SiC diode with the temperature as parameter. We can approximate the forward voltage by a threshold voltage V_{T0} and a differential resistor R_{DIFF}. The worst case conditions according data sheet at a junction temperature of 150°C can be described as follows:

Approximation of forward voltage:

$$V_F = V_{T0} + R_{DIFF} \cdot I_F$$

Worst case conditions:

$$V_F = V_{T0} + R_{DIFFMAX} \cdot I_F$$

SiC diode Type	SDP02S60	SDP04S60	SDP06S60
Voltage/current rating	600V/2A	600V/4A	600V/6A
Package	P-TO220-3-1	P-TO220-3-1	P-TO220-3-1
Alternative package	P-TO-252-3-2	P-TO-252-3-2	P-TO-252-3-2
Thermal resistance J-C	10K/W	4,1K/W	2,6K/W
Power dissipation at T_C = 25°C	15W	36,5W	57,6W
Maximum operating temperature T_J	175°C	175°C	175°C
Total capacitive charge	6nC	13nC	21nC
Typical threshold voltage at T_J=150°C	0,9V	0,9V	0,9V
Differential resistance at T_J=150°C	0,62Ω	0,275Ω	0,135Ω
Max. differential resistance at T_J=150°C	0,82Ω	0,375Ω	0,202Ω
Max. forward voltage $V_{FMAX150}$	0,9V+0,82$\Omega \cdot I_F$	0,9V+0,375$\Omega \cdot I_F$	0,9V+0,202$\Omega \cdot I_F$
Power dissipation at rated forward current	5,08W	9,6W	12,66W
Required heat sink including washer at T_J = 150°C and T_A = 75°C	4,16K/W	3,1K/W	2,7K/W
Output power of CCM PFC boost converter at V_{INMIN} = 90V, V_{OUT} = 400V with same P_D	383W	772W	1184W
Output power of CCM PFC boost converter at V_{INMIN} =180V, V_{OUT} = 400V with same P_D	518W	1042W	1585W

Table 2: Power handling capability of SiC Schottky diodes

In order to get a feeling about the current capability of SiC diodes we calculated the power dissipation P_D based on:

- conduction losses at rated DC current, and
- the required heat sink at T_J = 150°C and T_A = 75°C.

In a second step we calculated the output power of CCM PFC boost converter with an estimated efficiency of 0,9 and a minimum input voltage of 90V and 180V that produces same power dissipation as calculated under DC conditions.

A SiC diode does not produce switching losses in the diode itself (only small capacitive losses in the MOSFET). So the total thermal household can be used for current conduction. A 2A-SiC is able to handle 380W output power in an universal input CCM PFC boost converter in steady state condition.

Secondary Side Rectification for 48 volts output

An output voltage of 48 V is used in a vast number of power supplies for telecommunication equipment and distributed power system servers. This output voltage theoretically allows to use Silicon Schottky diodes, but in practice Gallium Arsenide and Silicon Carbide Schottky diodes are better suited for the secondary side rectification.

Basics

The basic circuit diagram of a typical Zero Voltage Transient (ZVT) phase shifted full bridge converter is shown in Fig. 10. This type of converter is widely used in power supplies for telecommunication equipment.

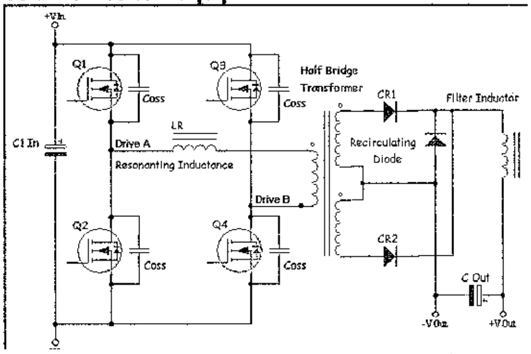

Fig. 10: Circuit diagram of typical telecom AC/DC SMPS

The switching power losses in transistors are very low due to ZVT switching. This enables an increase of the switching frequency without serious efficiency drawback on the primary side. It also means that the diodes on the secondary side have only low switching losses. Here usually Schottky diodes are in use.
The voltage stress across the secondary side diode can be calculated using following equation:

$$V_{CR1}, V_{CR2} = 2 \cdot V_{IN} \cdot \frac{N_2}{N_1}$$

Depending on the transformer design the voltage stress on the secondary diodes is typically in range from 150V to 230V. With some safety margin 180V to 250V rated diodes can be used. Selecting the 300V rated diode will increase the derating and correspondingly the reliability of the system.

Comparison of electrothermal behavior of SiC and GaAs Schottky Diodes:

The total forward voltage drop of a Schottky diode typically consists of 3 major parts:

Voltage drop due to ...	**Variation with temperature increase**
• Schottky barrier	Slightly decreasing
• substrate resistance	Nearly constant
• low doped drift layer	Strongly increasing proportional $T^{1.5 \ldots 2.5}$

In Fig. 11 the relevance and size of these parts is visualized for both a commercial available 250 V GaAs Schottky diode and 300 V SiC Schottky diode (SDP10S30).

SiC Schottky diode (300V /10A), V_F(typ., 25°C)=1.47V (max. 1.7 V according to datasheet)	**GaAs Schottky diode (250V /10A), V_F(typ., 25°C)=1.60V** (max. 2.2 V according to datasheet)

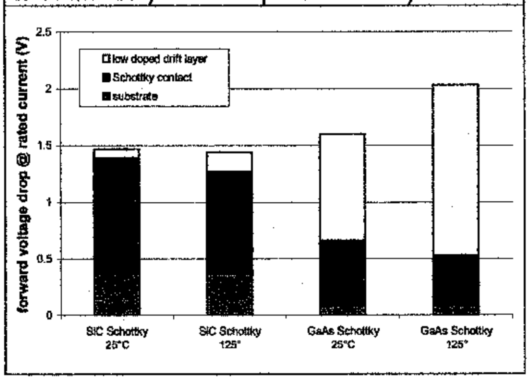

Fig. 11: Split up of forward voltage contribution of the different device components for GaAs and SiC Schottky diodes at 25 °C and 125 °C.

The large contribution of the drift layer in case of the GaAs diode makes fabrication control of the forward properties extremely difficult, because this layer is epitaxially grown and has a comparatively large scatter of key parameters like thickness and doping (typically ±10 to 15 % on 4 inch GaAs).

Both SiC and GaAs Schottky diodes are unipolar devices and therefore they are suffering from a similar mechanism in their temperature dependence of the n- drift layer resistance. This number is proportional to 1/µ (µ: electron mobility (cm²/Vs)) and µ is depending on temperature in a $\mu \sim T^{-k}$ manner with k being in the range of about 2.5 for low doping. On the other hand, highly doped semiconductors (substrate material) have nearly no temperature dependence of their resistivity, specifically for SiC substrates (doping $5 \cdot 10^{18}$ cm^{-3}) we measured a resistivity increase of less than 5 % between room temperature and 150 °C. Finally the voltage drop across the Schottky contact, i. e. the knee voltage of the rectifier, has a negative temperature coefficient.

In case of 300 V SiC Schottky diode these different temperature dependencies compensate each other up to temperatures of 175°C giving a nearly temperature independent V_F in this T-range at rated current. Opposite to this the GaAs Schottky diode shows a significant increase in V_F with temperature due to the fact, that the resistivity component with the largest positive temperature coefficient is dominating.

The typical forward characteristic of both diodes at room temperature and 175°C is displayed in Fig. 12. The strong increase of the on-resistance with temperature shown by the GaAs Schottky diode is crucial for overcurrent stress situations. The positive feedback by heating of the device by electrical power losses and resistivity increase can cause quick destruction of the device by thermal runaway.

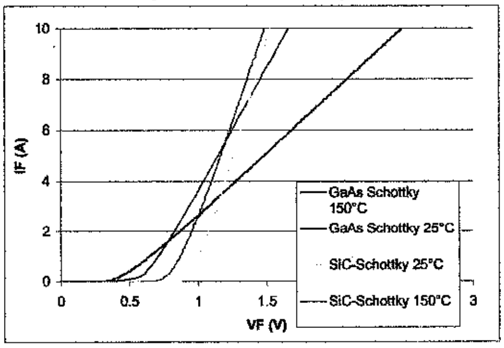

Fig. 12: Forward characteristic at room temperature and 150 °C for a 250V/10A GaAs- and a 10A/300V SiC-Schottky diode in comparison. (Measurement conditions: isothermal, pulsed with 350µs)

Further it is an important fact that GaAs has a 9 times lower heat conductivity than SiC. Together with the above mentioned strong conductivity reduction this lead to a very limited peak current capability of the GaAs diodes ($I_{FSM}<2*I_F$) in comparison to the SiC Schottky diodes ($I_{FSM}=3.6*I_F$). Even under high frequency pulse conditions (20 kHz) and small duty cycles (< 0.2) a damage of the GaAs Schottky diodes may occur due to large mechanical stress caused by huge temperature differences and the very brittle behavior of GaAs.
Based on these facts we can state a significant reliability advantage for the SiC Schottky diode in all applications where overcurrent stress is to be expected.

Design with SiC vs. GaAs Schottky diodes

Power losses in a Schottky diode can be distinguished into conduction, switching and leakage losses. Let us estimate the total power losses for 10A/250V GaAs and 10A/300V SiC Schottky diodes under following conditions – continuous conduction mode rectifier operating at 300kHz, peak current is 10A, voltage stress is 200V, duty cycle is 40%, T_J=125°C.
As it can be seen from Fig. 13 the total power losses are 13% lower in case of SiC diode due to lower voltage drop during the conducting stage. Please keep in mind that SiC diodes are rated to 300V, not to 250V like GaAs Schottky diodes. Even with its higher breakdown voltage SiC Schottky has lower voltage drop.
The 13% less total power losses seem to be a little advantage, but what does it mean for the thermal management? Fig. 14 shows the required total thermal resistance from junction to ambient for $T_{ambient}$=50°C.
SiC Schottky diode will require a heat sink 30% smaller than necessary for GaAs diodes due to two reasons:

- SiC diode produce 13% lower power losses (or heat);
- SiC has better thermal conductivity as GaAs and in turn better thermal resistance from junction to case.

If a designer would replace a GaAs Schottky diode with one in SiC technology the efficiency will increase and heat sink can be reduced by 1/3.

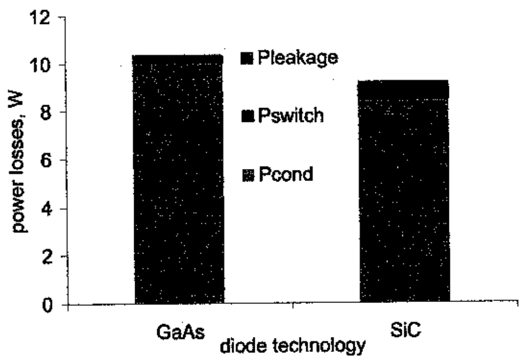

Fig. 13: Total power losses in secondary side rectification diode

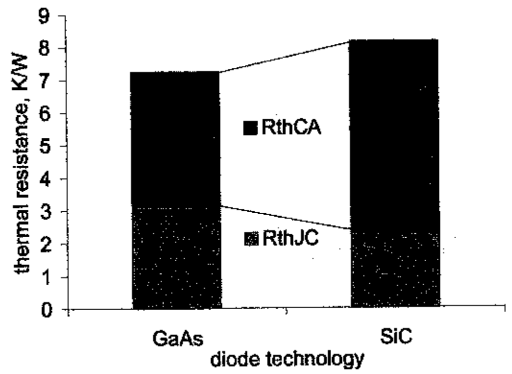

Fig. 14: Total thermal resistance in this case

Conclusion

With the properties of SiC thinQ!™ Schottky diodes described above, circuit designers now have a new degree of freedom in optimization of hard switching applications.
Power handling capability per Ampere rated current sets a new reference in design rules. Design rule of 130°C junction temperature seems to be passed by with new semiconductor material – SiC.
SiC as well as any new technology has great cost reduction & extension potential compared to existing ones. We expect powerful cost reductions over the next years. With SiC, a second source to GaAs Schottky exists now, and this second source can help to improve systems reliability and efficiency.

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