Technology shifts in power electronics and electric motors for hybrid electric vehicles

A study of silicon carbide and iron powder materials

Master of Science Thesis

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Göteborg, Sweden, 2007

Abstract

This thesis has been conducted together with Volvo Powertrain, Hybrid Technology. The purpose is to see if technology shifts for power electronics and electric motors in heavy hybrid vehicles could be advantageous, compared to today's silicon (Si) based semiconductors and laminated steel based motors. The semiconductor material, which was examined, was silicon carbide (SiC) and for the electric motor the powder materials soft magnetic composites (SMC) and plastic bonded iron powder (PBIP) were examined. The data was collected through articles and interviews.

SiC has the ability to operate at high temperatures (up to 600°C) with a ten times higher breakdown voltage than that of Si. The switching speed can be higher, due to low capacitance in the devices. Losses are considerably low during turn-on and turn-off, because the reverse recovery is extremely small. Problems with SiC are wafer quality, gate isolation and packaging material. Several companies and universities are developing SiC technology, but still the leading actors are Cree and Infineon. The quality of SiC wafers is improving, but the size of the wafer is today small for good quality, maximum 3", while Si wafers of good quality can be up to 12".

Iron powder materials can be moulded to motor parts for the magnetic flux paths. The relative permeabilities (magnetic conductivity) are as low as 700 for SMC and 20 for PBIB, compared to 8000 for laminated steel. Despite this, the performance of the motors might be acceptable with a 3D design where the magnetic flux paths are shorter or where other benefits arise. The profit would be in lower manufacturing costs due to less manufacturing steps and less material waste during manufacturing. A negative impact of SMC is that it has more losses than steel sheets up to 1000 Hz. For PBIP no result has been noticed yet.

Conclusions that have been drawn are that a shift in the future to SiC in hybrid vehicles would reduce cooling equipment, size of passive components, losses and space. Taken together this could reduce the total cost. For the iron powder materials no conclusions about if they are profitable to use in electric motors can be made. To find the answer, a prototype of a motor for a hybrid vehicle should be built.

Keywords
silicon carbide, SiC, hybrid vehicles, soft magnetic composites, SMC, electric motor, plastic bonded iron powder, iron powder materials

Sammanfattning

Detta examensarbete har utförts i samarbete med Volvo Powertrain vid avdelningen för hybridteknik. Syftet är att se om ett teknikskifte för kraftelektroniken och elmotorn i tunga hybridfordon skulle vara fördelaktigt, jämfört med att behålla dagens tekniker med kiselbaserade halvledarkomponenter och motorer i laminerat stål. Halvledarmaterialet som har undersökts är kiselkarbid (SiC) och för elmotorn har järnpulvermaterialen mjukmagnetiska kompositer (SMC) och plastbundet järnpulver (PBIP) undersökts. Informationen har tagits från artiklar och intervjuer.

SiC kan arbeta vid höga temperaturer (upp till 600°C) och har en tio gånger högre genombrottsspänning jämfört med kisel. Switchhastigheten kan vara högre på grund av låga kapacitanser i komponenterna. Förlusterna är beaktningsvärt låga under påslag och avstängning av ström, eftersom återhämtningstiden (reverse recovery) är extremt liten. Problem med SiC är skivkvalitet, gate-isolation och packningsmaterial. Flera företag och universitet håller på att utveckla SiC-tekniken, men de ledande aktörerna är fortfarande Cree och Infineon. Kvaliteten på SiC-skivorna förbättras hela tiden, men skivornas storlek är idag bara max 3" för bra kvalitet, medan kiselskivor kan vara upp till 12".

Järnpulvermaterial kan gjutas till motordelar för de magnetiska flödesbanorna. Den relativa permeabiliteten (magnetiska ledningsförmågan) är så låg som 700 för SMC och 20 för PBIP, jämfört med 8000 för laminerat stål. Trots detta, kan prestandan kanske bli acceptabel med en 3D-design, där de magnetiska flödesbanorna är korta eller där andra fördelar kan dras. Vinsten skulle vara lägre tillverkningskostnader på grund av färre tillverkningssteg och mindre materialsvinn. En negativ effekt med SMC är att materialet har högre förluster upp till 1000 Hz. Hur förlusterna blir med PBIP är svårt att säga, eftersom inga resultat är noterade ännu.

Slutsatser som har dragits är att ett skifte i framtiden till SiC i hybridfordon skulle reducera kylsystem, storlek på passiva komponenter, förluster och utrymme. Sammantaget kan kanske total kostnad minska. För järnpulvermaterialen kan inga slutsatser dras om huruvida de är fördelaktiga att använda för motortillverkning. För att ta reda på detta skulle en verklig motor behöva byggas och testas.

Acknowledgements

Working on this master thesis has been a pleasure for us. To have the opportunity to work on subjects that can be revolutionary for the vehicle industry is filling our hearts with great joy. We would like to thank Volvo Powertrain and especially the department of Hybrid Technology that have supported us with a desk, computers and the ability to visit companies of interest for this master thesis. We would like to thank some people, whose help and advising have been invaluable for this thesis. These persons are:

> **Niklas Thulin**, Senior Engineer Hybrid Technology. Our supervisor, who has always taken the time to give answers to our questions.
>
> **Torbjörn Thiringer**, Associate Professor at the Department of Energy and Environment, Division of Electric Power Engineering, Chalmers University of Technology (CTH). Our examiner, who took the time despite his full schedule.

Also **Anders Kroon** and **Elisabeth Adolphsson** at Volvo Hybrid Technology, **Anders Lasson, Henrik Svenningstorp** and **Helena Berg** at Volvo Technology and all other persons that have been working near us earn an extra thank you.

We would also like to thank the persons that we have interviewed.

Mats Alaküla, Prof. Industrial Electrical Engineering and Automation, Lund University, **Maddalena Cirani**, Development Engineer, Volvo technology AB, **Martin Domeij**, Research Associate, Docent, TranSiC, **Bo Hammarlund**, M. Sc. Founder of TranSiC, **Niklas Henelius**, Director Sales and Marketing, Norstel, **Lars Hultman**, Business Area Manager SMC Components, Höganäs, **Göran Nord**, SMC Applications Specialist Development SMC Components, Höganäs, **Heinz Lendenmann**, Manager Intelligent Motion and Electrical Machines, ABB, **Joachim Lindström**, Research Engineer, Volvo Technology AB, **Leo Lorenz**, Prof. Dr. Infineon Technologies, **Ronald Rupp**, Dr. Project Manager Development silicon carbide, Infineon Technology, **Einar Sveinbjörnsson**, Prof., Dep. of Microtechnology and Nanoscience Microwave Electronics Laboratory, CTH, **Sonja Tidblad Lundmark**, Dr. Department of Energy and Environment, CTH

We would also want to express our gratitude to persons that have been with us our whole lives.

My (Henrik Horrdin) parents and family that always have encouraged me to expand my view and search for knowledge and higher education.

And my (Eva Olsson) family, who are always there with love and support.

Göteborg, January 2007

Henrik Horrdin

Eva Olsson

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Abbreviations

AC	Alternating Current
APEI	Arkansas Power Electronic Institute
BJT	Bipolar Junction Transistor
BLDC	Brushless DC
CoolMOS	Product name of a Power Metal Oxide Semiconductor
CTE	Coefficient of Thermal Expansion
DC	Direct Current
EMC	Electro Magnetic Compatibility
EMF	Electro Magnetic Force
EMI	Electro-Magnetic Interference
FEM	Finite Element Modelling
FET	Field Effect Transistor
GaAs	Gallium Arsenic
IGBT	Insulated Gate Bipolar Transistor
JFET	Junction Field Effect Transistor
MESFET	Metal Semiconductor Field Effect Transistor
MMF	Motor Magnetic Force
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
MPS	Merged PiN Schottky
PBIP	Plastic Bonded Iron Powder
PM	Permanent Magnet
PMSM	Permanent Magnet Synchronous Motor
RPM	Rotations per Minute
SBD	Schottky Barrier Diode
Si	Silicon
SEK	Swedish Krona
SiC	Silicon Carbide
SIT	Static Induction Transistor
SMC	Soft Magnetic Composites
TFM	Transverse Flux Motors

1 Introduction

In the following sections a short background and the purpose of thesis will be given. Also the hybrid vehicle will be explained.

1.1 Background

In a world where the oil price increases and the environmental effects are being more apparent (e.g. the increasing global temperature), companies and private persons are striving to keep their economics in god balance by cutting their costs and searching for vehicles that are more efficient [Hanson B. U., 2005].

The global warming is a fact. Reports have shown that the global warming is 0.6 ± 0.2 degrees over the 20th century. This can be seen in Figure 1. Also the sea level has increased with 10 - 20 cm globally.

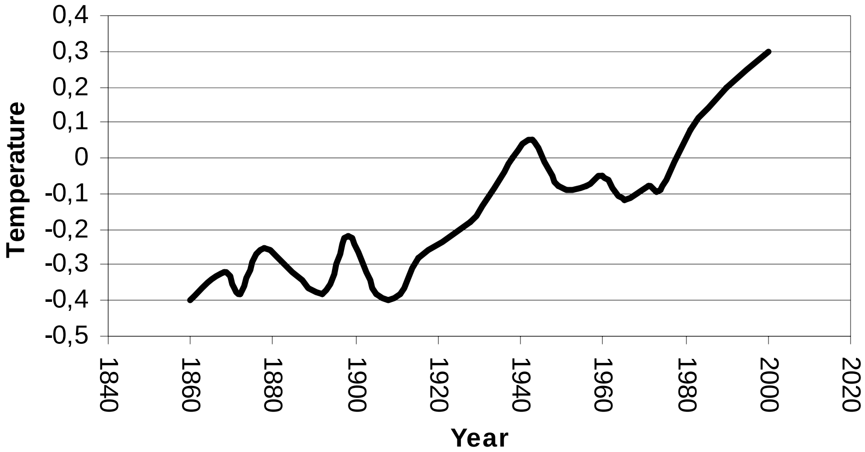

Figure 1. The line is the average decade by decade. The average temperature 1961-1990 is set to 0 [IPCC, 2001].

In a future perspective, if the existing development continues, there will be an increase in the global temperature of 1.4 - 5.8°C and the sea water will rise with 8 - 88 cm. There will also be more heavy rainstorms and dry periods over the earth [IPCC, 2001].

The oil consumption in the world is steadily increasing. An estimation of the world oil consumption, given by Energy Information Administration (EIA), shows that the oil consumption of 2003 will be increased by 50 % to 2030, see Figure 2. Scenarios for the oil production have been estimated and the two extremes are the IR scenario in Figure 3 and the ASPO (Association for the Study of Peak Oil and gas) scenario in Figure 4 [Rehrl T. et al, 2005]. As seen in these figures, the world oil production will soon be less than the estimated demand. The transport sector is the biggest consumer as seen in Figure 2. It represents about 60 % of the total oil consumption, and therefore it is desired to reduce it by new technology [EIA, 2006].

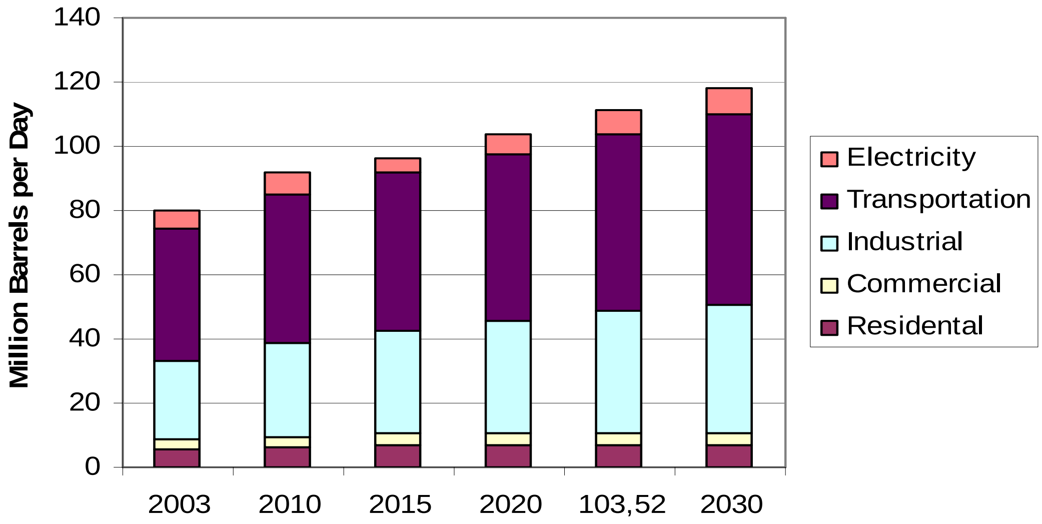

Figure 2. Estimation of the world oil consumption divided into sectors.[EIA, 2006]

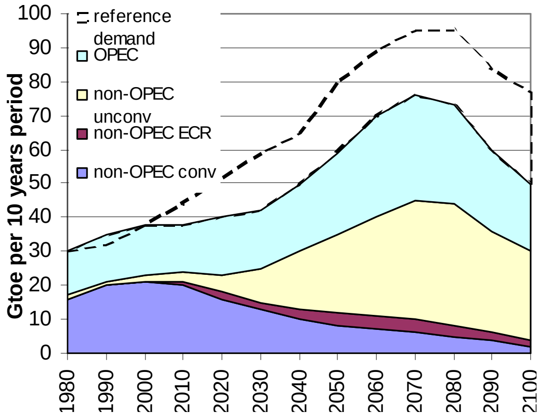

Figure 3. World oil production and demand. The IR scenario. [Rehrl T. et al, 2005]

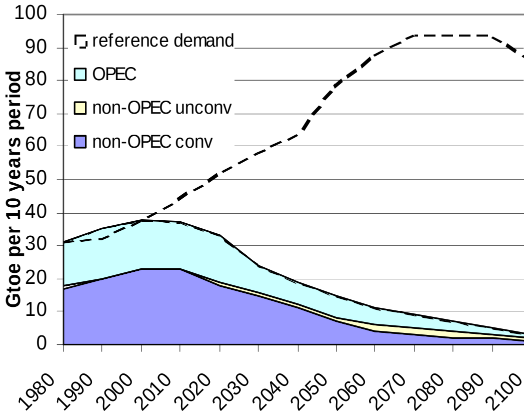

Figure 4. World oil production and demand. The ASPO scenario. [Rehrl T. et al, 2005]

1.2 Hybrid vehicles

The first electric vehicles were produced in 1830 and it looked like the electric car had a bright future. The electric cars were easily started and had no exhaust. The early combustion cars smelled, were unreliable and needed manual crank start. Everything spoke for the electric cars, but when cheap oil became available the combustion engine took almost all of the market shares. The easy refuelling and small tank changed the market. Today there is a rebirth of the electric motor in vehicles. Reasons for this are that the batteries have become better (they can store more energy on the same volume) and tougher laws against emissions.

Today hybrids are developed to lower the fuel consumption. There are two main types of hybrids, series hybrids and parallel hybrids. In the series hybrid the internal combustion engine is working constantly on a specific rotation per minute (rpm) and charges the batteries. The electric motor is then supplied by the batteries. In a parallel hybrid the engine takes over at high speeds and the motor operates at low speeds. The motor can also help the engine when it needs extra power. Which configuration that is to prefer is hard to say and depends on how the vehicle is going to be driven [Larminie J. et al, 2003].

1.3 Purpose of thesis

The main purpose of this thesis is to investigate some technical and economical possibilities that have aroused for electric systems in vehicles, due to the technical development of power electronic components and magnetic materials, for instance the implications of using silicon carbide (SiC) based components, instead of the traditional silicon (Si) components is of interest. Moreover, the impact that new ferromagnetic materials have on the design of electric motors is a target for investigation. For instance motor iron parts produced through injection moulding of iron powder, compared to the traditional electric motor, which is laminated, is an aim to study. An overall goal is also to collect knowledge and literature in these two areas.

One of our goals is also to investigate the operation characteristics for the SiC and Si in an inverter. Cost and operation benefits from the implication of SiC devices in current hybrids are other issues of interest.

For the electric machine produced with iron powder material, it will be an aim to compare it to the traditional laminated machine to try to decide which one of them is the most preferable for usage in a future hybrid truck. One of the main points to figure out is if it is even possible to build an electric traction motor by iron powder material, which has the right power and torque to match existing motors. If this turns out to be possible, it would be interesting to look at the effects of implementation of such a machine, for instance the resulting operational costs, manufacturing costs and power losses, and also compare them with the situation when using a machine of the original design. Then an aim would be to see if there is a need for further changes, such as design changes, with the implication on current hybrids.

The final goal will be to decide which are the leading actors in SiC processing and iron powder material and if it is worth to change from the existing machine and Si topologies, which have been developed for the market. It is also desirable to see if further investigation in these new technologies is necessary.

2 Method

This master thesis is mainly a quantitative thesis, where information has been gathered through literature studies and interviews. A lot of material existed on the development of SiC, but for alternative ways of motor manufacturing less information was found.

2.1 Databases

Articles were found in databases by using key words, such as SiC, power electronics, power converter MOSFET, diode, high power, injection moulding, electric motor, electric machine, SMC, iron powder. The databases that were used were IEEE Xplore, Science direct, Libris, Chans, Volvo Library Catalogues.

2.2 Books

Books, reports and thesis are used for the thesis. Books were mostly student literature that was used to explain some theory. The reports and thesis that have been used have been reviewed.

2.3 Internet

Websites of companies that are active in the areas were visited and information about their research and products were collected from these. Organisations (Freedom Car, Green Car Congress, Energimyndigheten etc.) also have webpages, where interesting information can be found and where it is possible to achieve news and follow the development within the areas. These webpages were visited occasionally.

2.4 Interviews

Persons to interview were found through published articles and supervisors. Prepared questions were asked during the interviews. Both of the authors of this thesis were present during the interviews and most of the interviews were recorded. Not all interviewees have been given the chance to review what has been written, due to lack of time. The purpose of the questions was to complement the knowledge that was achieved from the database searches. The interviews were also a way of achieving more sources, such as companies and persons, for further information within the area.

2.5 Volvo internal communication

Supervisor, director, project leaders, specialists and other employees at Volvo were contacted for information and discussion concerning subjects that needed to be solved. The Volvo internal information that was achieved contained information about what the prerequisites were for the converters and the electric motor.

2.6 Criticism of sources

The articles and books are the most reliable sources, since they have been reviewed. Since the technology areas that are treated are under development, the aim has been to find recent articles and reports. Opinions and commercial interests, which people may have, have been considered when information from persons that have been interviewed and information from companies' webpages were treated.

3 Silicon and Silicon Carbide limitations

The semiconducting material, which has been used so far for high power applications, is Si. It is, however, limited in high power operation, due to resulting high losses and heating. Also, the theoretical limits of the physical properties of Si have been reached for temperature and power densities. This, together with the higher demand from the industry, has led to a more rapid development of SiC [Chinthavali, M.S, et al, 2005]. SiC technology has the potential to improve the current limitations of today's power electronics. Its ability to withstand days or weeks in a harsh environment, instead of a few hours as for Si, is something that can be useful, because it provides the ability to integrate power electronics directly on a motor. SiC has a potential to save a lot of money for the user when the efficiency is raised and switching losses are decreased. Increased switching speed, power density and reliability will also contribute to a reduction in cost for the commercial market [Hornberger J. et al, 2004].

In this chapter the SiC material will be described in form of structure on a crystal level, moving on to looking at properties and the effect from them in power electronic components. Finally the difficulties of manufacturing SiC wafers is explained.

3.1 Crystal structures

The structures, or atom alignment, of Si and SiC can be seen in Figure 5.

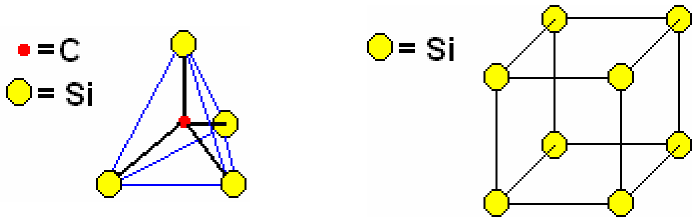

Figure 5. Structures of SiC (left) and Si (right).

SiC has the ability to form different structures. In Figure 6, the crystal structures of 4H-SiC and 6H-SiC are shown. The structure repeats after every 4th and 6th layer, respectively. There are also other polytypes, but the ones presented here are the two most interesting and the only structures that are used in semiconducting devices.

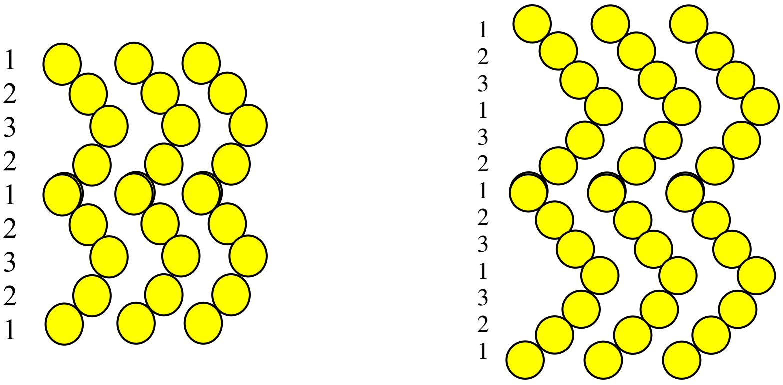

Figure 6. Crystal structures of 4H-SiC (left) and 6H-SiC (right) [Carlsson, 2003].

4H-SiC is preferred over 6H-SiC in most electronic applications, because it has more isotropic properties and a higher mobility. Even though the electrical properties are different, the mechanical and thermal properties are almost the same, independently of which polytype is being used [Ayalew T., 2004].

3.2 Properties

In Table 1 the properties for different semiconducting materials can be seen. The effect of the properties will be explained beneath each heading below. It is the fundamental properties of SiC that decide the pros and cons for SiC devices [Ayalew T., 2004, Hornberger J. et al, 2004].

Table 1. Properties of various semiconductors [Hornberger J. et al, 2004].

Property	**6H SiC**	**4H SiC**	**GaN**	**GaAs**	**Si**
Energy band gap (eV)	2.9	3.26	3.39	1.43	1.12
Electric breakdown field (*10^6V/cm @ 1kV operation)	2.5	2.2	3.0	0.30	0.25
Dielectric constant	9.6	9.7	9.0	12.8	11.8
Intrinsic carrier concentration, n_i, (cm^3 @ room temp)	10^{-6}	$8.2\text{x}10^{-9}$	$1.9\text{x}10^{-10}$	$2.1\text{x}10^{6}$	10^{10}
Electron mobility, μ_e (cm^2/V's @ room temp)	330-400	700-980	1,000 2,000,2DEG	8,500	1,400
Hole mobility, μ_h (cm^2/V's @ room temp)	75	120	200	400	450
Saturated electron drift (x10^7 cm/s @ E>2x10^5 V/cm)	2.0	2.0	3.0	1.0	1.0
Coefficient of thermal expansion (CTE), (ppm/K)	4.5	5.1	4	5.73	4.1
Young's modulus (GPa)	400	400	181	70	156
Thermal conductivity (W/m K @ room temp)	500	500	130	55	150
Density (g/cm^3)	3.2	3.2	6.15	5.3	2.3

3.2.1 Energy bandgap

SiC can operate at as high temperatures as 600°C, which is a limit that is 5 times higher than for Si, because it has a bandgap that is three times wider [Hornberger J. et al, 2004]. Because of the wider bandgap, the electrons need higher activation energy to be able to jump up to the conduction band. Unwanted conduction at high temperatures is thereby prevented in SiC material [Ayalew T., 2004].

3.2.2 Electric breakdown field

The fact that the electric breakdown field for SiC is approximately ten times higher than for Si means that breakdown avalanches are prevented at ten times higher electric field strengths compared to Si. This leads to advantages, such as higher possible doping concentrations. As the doping concentration rises, the electron and hole diffusion length and lifetime are reduced and thereby the length of the device can be made shorter. The reduction in length leads to higher switching speeds, possibly up to the GHz area, while still having a high electrical breakdown field [Hornberger J. et al, 2004]. Another effect of higher doping is that the current density will change. SiC has about 1.5 times higher current density for a component with the same doping and active area as a Si device. If the doping is doubled, which is possible for SiC, the current density will be around 3-3.5 times higher [National academy press, 1995], but the blocking voltage is decreased at the same time. If the same blocking voltage is aimed for, the drift region needs to be increased in this case, hence the component becomes larger. [Mohan N. et al, 2003]. The effect of a high breakdown field is also that the new smaller devices can be packed closely together, which allows high device density in integrated circuits [Ayalew T., 2004].

3.2.3 Thermal conductivity

SiC has a thermal conductivity, which is 2.5-3.3 times higher than for Si. This thermal conductivity is higher than in any metal and allows SiC to operate at high power levels and still being able to dissipate the heat generated in it [Ayalew T., 2004, Hornberger J. et al, 2004].

3.2.4 Mobility

If the electron mobilities are compared, see Table 1, it is clear that the SiC has a disadvantage compared to Si. The lower mobility for SiC will actually lower the switching frequency for SiC, but this is only an effect at low voltages. At higher voltages, the mobility is not the dominating property: the saturated electron drift is [Hornberger J. et al, 2004].

3.2.5 Saturated electron drift

The saturated electron drift, which is 2 times higher for SiC, allows a higher operating frequency [Ayalew T., 2004]. In the case of high voltages, the dominating factor is the saturated electron drift. Together with the mobility, which is low for SiC, the overall effect will be an increase in switching frequency at high voltages, because the operating point will be in the saturated area most of the time [Hornberger J. et al, 2004].

3.3 Manufacturing of wafers

The main features for the SiC processing are the same as for Si, thus old process lines, which were originally made to produce Si, could also be used for SiC. The difference that exists is the processing temperature. SiC is a more compact material than Si and therefore a much higher temperature is required to activate implanted dopant atoms to make the pn-junctions. SiC is also very resistant to letting dopant elements or any substances come in to the material. During the process when the doping is activated and positioned, SiC needs to be heated to 1600°C, while silicon only needs 900°C. Because of this, special ovens would be needed to complement old Si process lines for SiC manufacturing [Sveinbjörnsson E., 2006].

It is difficult to grow large SiC rods. Small hollow cores, which extend in the growth direction, so called micropipe defects, are often created during the manufacturing. Today 3" SiC wafers are produced, compared to up to 8" or 12" Si wafers [Ayalew T., 2004]. 4" wafers of SiC are also available, but the defects of these wafers are higher compared to 3" wafers. The number of micropipes on the best-quality 4" wafer is below 15/cm^2, while it is possible to get micropipe free 3" wafers [Cree]. If the size of the good quality SiC wafer could be increased to 4", a lot of money could be saved, because there are many old Si process lines for this diameter, which could be used [Sveinbjörnsson E., 2006]. The problems of producing large SiC wafers have to do with the stability of the material. SiC does not melt at high temperatures, but sublimes gradually at 1800-2400°C. This makes it impossible to form large single polytype rods by pulling SiC from a smelt as being done for Si. To grow SiC, a modified sublimation process is used instead and this process limits the diameter to 4" [Ayalew T., 2004].

The growth rate for producing the wafers made of SiC is today 100 times slower than for Si. It could be in the future, that the growth rate is decreased by half, down to 50 times the Si growth rate, but whether that is going to happen or not is not clear. The growth rate is almost the same, independently of the area of the wafer, but bigger wafers have more micropipes, which leads to worse process results [Henelius N., 2006].

Today the price is about 100 times higher for SiC than for Si. This high price is related to the growth rate. It would be possible to reduce the component price by making larger wafers. This is further explained in Section 5.5.1 [Henelius N., 2006]. One 3" SiC wafer can cost 3000 to 4000 dollar, compared to a Si wafer, which costs 30-40 dollar today [Sveinbjörnsson E., 2006].

4 Silicon Carbide in semiconducting devices

In this chapter the SiC diodes and transistors that exist on the market as well as those that are being developed are discussed. Temperature performance and power losses are issues that are brought up.

4.1 Availability and development of SiC components

There are not many SiC devices for commercial use. The first SiC device that was made available for the market was the SiC Schottky power diode. The diode was presented during the Power electronics conference, Graz, Austria in 2001. There is also a SiC MESFET available on the commercial market, but this transistor is a normally-on device, mainly for high frequency applications and therefore it is not of further interest in this thesis [Hornberger J. et al, 2004, Sveinbjörnsson E., 2006].

The SiC Schottky diode can be purchased from at least two companies, Cree and Infineon [Infineon]. Other products, such as SiC insulated gate bipolar transistors (IGBTs) and SiC MOSFETs, will probably be on the market around 2008 [Ny teknik, 2005]. A bipolar junction transistor (BJT) is being manufactured by the Swedish company TranSiC. They are now evaluating samples from their first batch and are expected to be on the commercial market in 2008 [TranSiC, 2006].

Junction Field Effect Transistors (JFETs) have been developed, but are not yet on the commercial market. This transistor can operate at high powers, but is a normally-on device. This is not wanted because it is difficult to protect against control system failures, which could cause all power devices switching on and shorting power to ground [Bartos F. J., 2006]. SiC PiN diodes, Merged PiN Schottky (MPS) diodes, Power MOSFETs, Si Gate Turn-Off thyristor (GTO) and Static-Induction-Transistors (SITs) (SIT is mainly for high frequency applications) are all currently under development by companies like Cree, Infineon, Northrop-Grumman, USA army research lab and Rockwell Scientific. None of these components are available on the commercial market yet, but a rapid increase in research opens up a world of new possibilities for applications with these new devices [Hornberger J. et al, 2004].

It should be mentioned that a SiC commutated Gate Turn-off Thyristor (SiCGT) with a rating of 4.5 kV 100 A and a switching frequency of 500 kHz has been developed. This is more than 10 times faster than for a Si GTO. However, this component is not of interest for vehicle systems [Kansai, 2006].

In Appendix B cross-sections of most of the transistors and diodes that are mentioned in this thesis are illustrated.

4.2 Diodes

The big advantage of a Schottky diode is its excellent switching characteristics. Although silicon Schottky diodes are only available up to 200 V, the SiC Schottky diodes can operate at much higher voltages [SiCED]. The disadvantage with a Schottky diode is the relatively high leakage current [Hornberger J. et al, 2004, Sveinbjörnsson E., 2006].

The switching speed for SiC-PiNs has shown an improvement of a factor of 100 compared to Si. The PiN has large forward voltage drop and reverse recovery current, but no leakage current in off-state. The SiC-PiN is superior in the area from 1200-5000 V compared to Si [Hornberger J. et al, 2004].

An MPS diode has the off-characteristics of a PiN diode and the on-characteristics of a Schottky diode (no leakage current and low forward voltage drop). The performance of the SiC MPS diode is better than Si diodes in the area 600-1500 V [Hornberger J. et al, 2004].

The majority of the SiC devices show a 100 times less resistance than Si devices [Hornberger J. et al, 2004].

4.2.1 Power loss investigation

Cree has developed a SiC Schottky diode, which has the ratings 600V/75A and was tested in a 55 kW inverter. The SiC Schottky diodes were used together with Si-IGBTs and compared to inverters with only Si components. The SiC-Si inverter showed lower losses than today's Si inverters. The cooling of the inverter was 20°C at test 1 and 70°C at test 2 and at the lower cooling temperature the loss reduction from using the SiC-Si inverter was the most significant. In the first experiment the converter was connected to an R-L load and in the second the inverter was connected to a motor. The loss reductions can be seen in Table 2 and Table 3 [Ozpineci B. et al 2005].

Table 2. Loss reduction for an inverter with SiC diodes connected to an R-L load.

	DC-voltage input to inverter (V)	Power (kW)	Cooling (°C)	Load	Loss reduction with SiC diodes (%)
Test 1	250	35	20	R-L	33.6
Test 2	250	35	70	R-L	27.5
Test 1	325	35	20	R-L	33.2
Test 2	325	35	70	R-L	19.4

Table 3. Loss reduction for an inverter with SiC diodes connected to a motor.

DC-voltage input to inverter (V)	Power (kW)	Torque (Nm)	Cooling (°C)	Load	Loss reduction with SiC diodes (%)
325	35	100	70	Motor mode	10.7
325	35	150	70	Motor mode	9.51
325	35	200	70	Motor mode	7.7
325	35	100	70	Regenerative breaking	11.2
325	35	150	70	Regenerative breaking	12
325	35	200	70	Regenerative breaking	12.7

The reason why the difference in loss reduction between the two configurations at higher cooling temperature is not so significant is because the IGBT losses increase and become the dominating factor.

An experiment was performed by SiCED, where an IGBT inverter module was tested for 600 V DC and load current 15 A. The free-wheeling Si pn diodes rated 75 A were changed to two in parallel coupled SiC Schottky Barrier Diodes (SBDs) rated 7.5 A. The switching losses in the two cases can be seen in Figure 7. It shows clearly that the peak current when the SiC diodes are used becomes much lower than when the Si diodes are used, hence the losses are lower. The figure also shows the impact of temperature on both cases [SiCED].

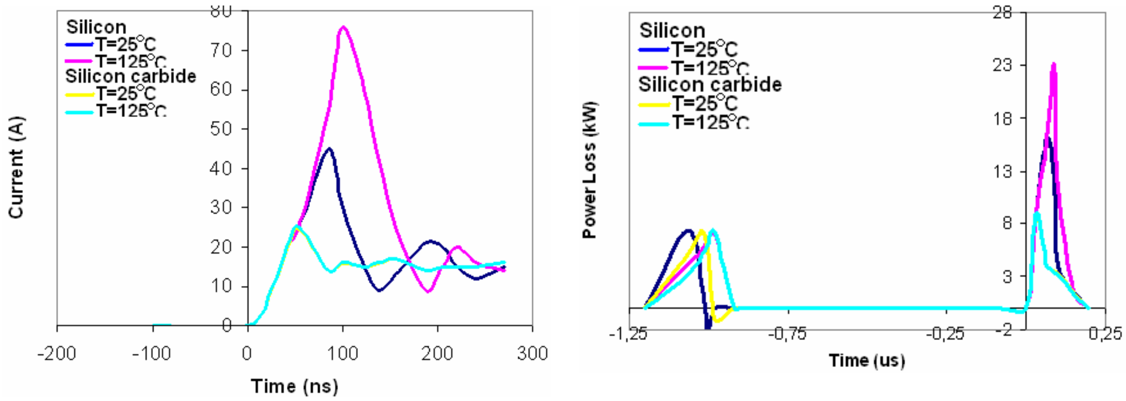

Figure 7. Turn-on currents and losses in an inverter. Diodes were changed between a 75 A Si pn and 2x7.5 A SiC SBDs [SiCED, presentation].

The losses are reduced by more than half in the configuration using SiC diodes, according to Table 4.

Table 4. Comparison of losses with Si and SiC [SiCED].

Dynamic energy loss	**Silicon pn**	**SiC SBD**
$E_{ON, IGBT}$ (mWs)	1.78	0.65
$E_{OFF, IGBT}$ (mWs)	0.81	0.82
$E_{OFF, DIODE}$ (mWs)	1.21	0.04
$E_{LOSS, TOTAL}$ (mWs)	3.81	1.51

Another experiment performed by SiCED also compared Si and SiC diodes. The switching behaviour with a SiC Schottky used as free-wheeling diode, compared to a Si pn used as free-wheeling diode, was tested in the configuration in Figure 8. The transistor was in both cases a Si IGBT. The results are shown in Figure 9.

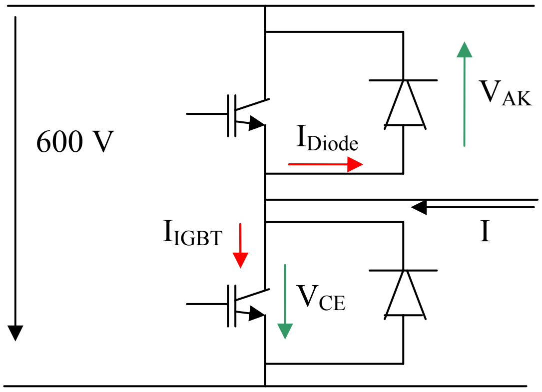

Figure 8. Test circuit.

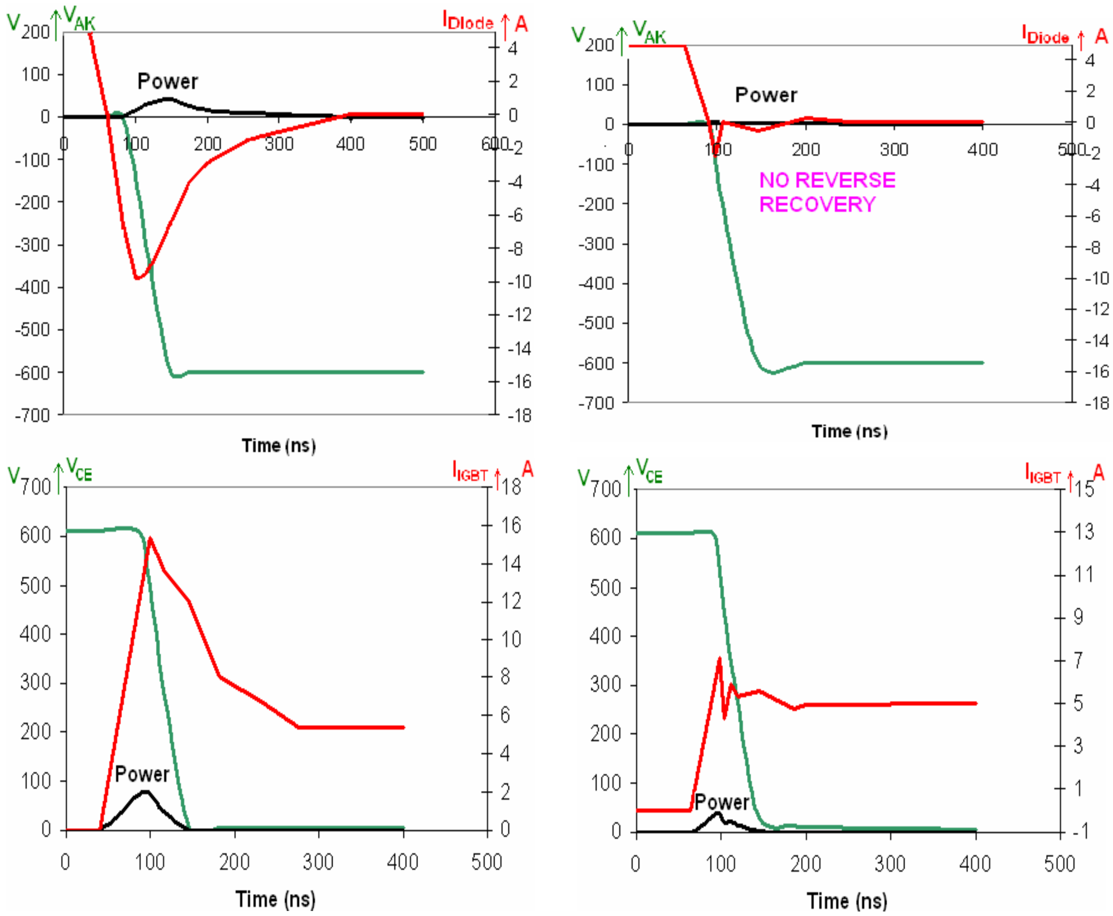

Figure 9. Switching at junction temperature 125°C. To the left: Fast Bipolar Si diode (1200V) is used and to the right: SiC Schottky diode (1200 V) is used, in both cases together with a Si IGBT [SiCED].

As can be seen the reverse recovery of the Schottky diode is excellent. The losses are reduced and hence the efficiency is increased.

4.2.2 Temperature investigation

Diode comparisons have been made for different temperature ranges. The tests were conducted by having a buck converter with a Si IGBT as switch. The test frequency was 20 kHz and the duty ratio was 25 %. The diode in the full bridge converter was changed between Si and SiC diodes and was tested for different temperatures. Tested diodes can be seen in Table 5.

Table 5. Ratings of the tested diodes.

Diode	Voltage rating (V)	Current rating (A)
Si	300	10
SiC	300	10

The temperatures tested were 27, 61, 107 and 151°C (SiC was also tested for 200°C). As seen from the measurements in Figure 10, the temperature have little effect on SiC, while Si is highly affected. The losses are also much lower than for Si, independently of the temperature. Overall, SiC is much more efficient than Si [Chinthavali, M.S, et al, 2005].

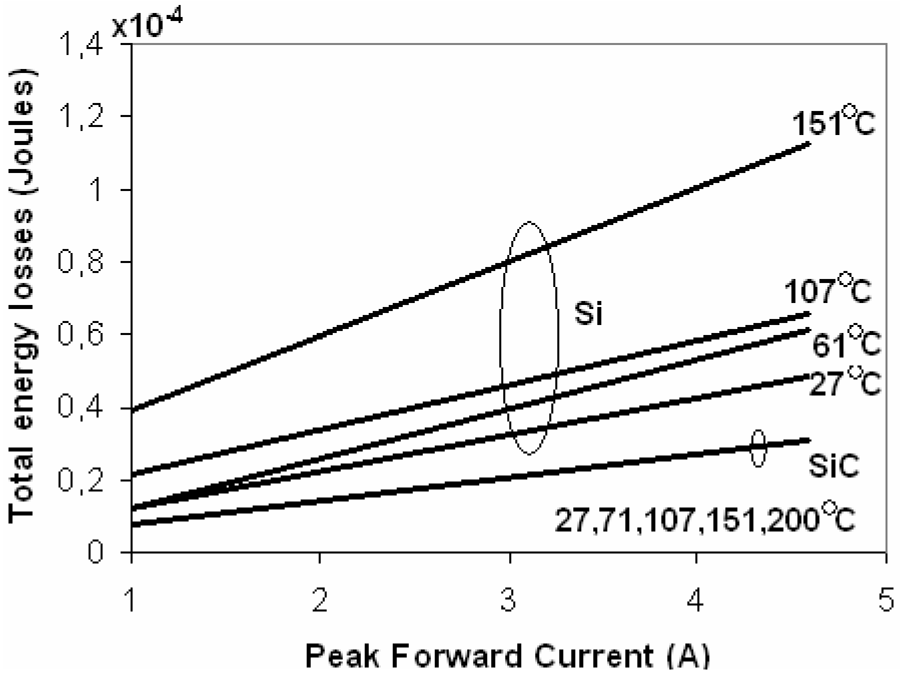

Figure 10. Losses at different temperatures and forward currents [Chinthavali, M.S, et al, 2005].

4.2.3 Resistance

For low breakdown voltages a constant on-resistance is dominating, because of the constant substrate resistance. To increase the breakdown voltage, a lower amount of doping should be used, which causes the drift layer to increase. Both doping and drift layer has an impact on the on-resistance. At high breakdown voltages (for Si and Gallium Arsenic (GaAs) >20 V and for 4H-SiC >200 V) the electric field becomes the dominating factor for the resistance, see (1) [Weitzel C. E., 1996, Ayalew T., 2004].

$$R_{ON,SP} = \frac{V_B^2}{\varepsilon_S \mu_n}\left(\frac{3}{2E_B}\right)^3, \qquad (1)$$

where $R_{ON,SP}$ is the specific on-resistance, V_B is the breakdown voltage, ε_S is the permittivity, μ_n is the mobility and E_B is the electrical field. At which point the SiC has lower on-resistance depends on all parameters in (1), but also the specific resistance up to a certain blocking voltage value will impact. But it is clear that at voltages high enough, SiC will have a lower on-resistance. Figure 11 shows a typical curve [Weitzel C. E., 1996]. (1) is only valid for unipolar devices such as MPS, SBD, MOSFET and JFET [Ayalew T., 2004].

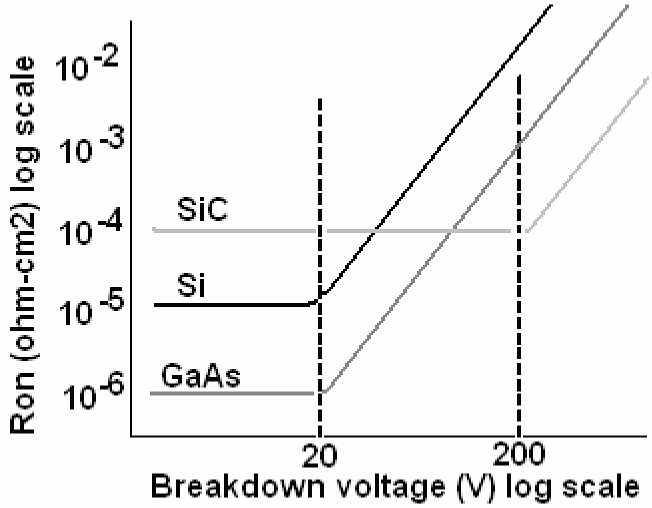

Figure 11. On-resistance for different breakdown voltages.

Another parameter that will affect the resistance is the temperature. The resistance increases with an increased temperature, thus the resistance has a positive temperature coefficient. A positive temperature coefficient increases the losses at high temperatures, hence it is perfect for current-sharing through paralleling [Chinthavali, M.S, et al, 2005].

4.3 Transistors

There are not yet any SiC transistors for power electronic applications available on the market, but there is a lot of research on the area and MOSFETs and BJTs are being developed. Also other Field Effect Transistor (FET) devices are investigated, but since they are normally-on devices, they are not to prefer, see 4.1.

4.3.1 MOSFETs

SiC Power MOSFETs are expected to have the same advantages compared to Si MOSFETs as the SiC diode has compared to the Si diode, such as operation at higher temperature, lower switching losses and smaller devices. A feature that will differ is the gate voltage, which needs to be twice as high for SiC MOSFETs [Hornberger J. et al, 2004]. SiC UMOSFETs (1200 V) are projected to have a 15 times greater current density than Si IGBTs (1200V) [Weitzel C. E., 1996].

In Appendix A it is shown that the switching losses in a SiC MOSFET will be about 1/70 of the losses in a Si MOSFET with the same blocking voltage and on-resistance [Sei-Hyung Ryu et al, 2004].

4.3.1.1 Temperature performance and resistance

An interesting aspect of SiC, which is seen in Figure 12, is that for MOSFET construction, the on-resistance is decreasing when the temperature rises from -50 to 50°C degrees. After 50°C, the on-resistance starts to increase again [Chinthavali, M.S, et al, 2005]. This could be compared with the Si MOSFET characteristics, where the on-resistance is increasing for the range -50 to 200°C, see Figure 12. At Chalmers University of Technology, they have succeeded to develop SiC MOSFETs with very low density of defects at the oxide/SiC interface and the result is that the temperature characteristics is similar to Si, but with a significantly lower on-resistance [Sveinbjörnsson E., 2006].

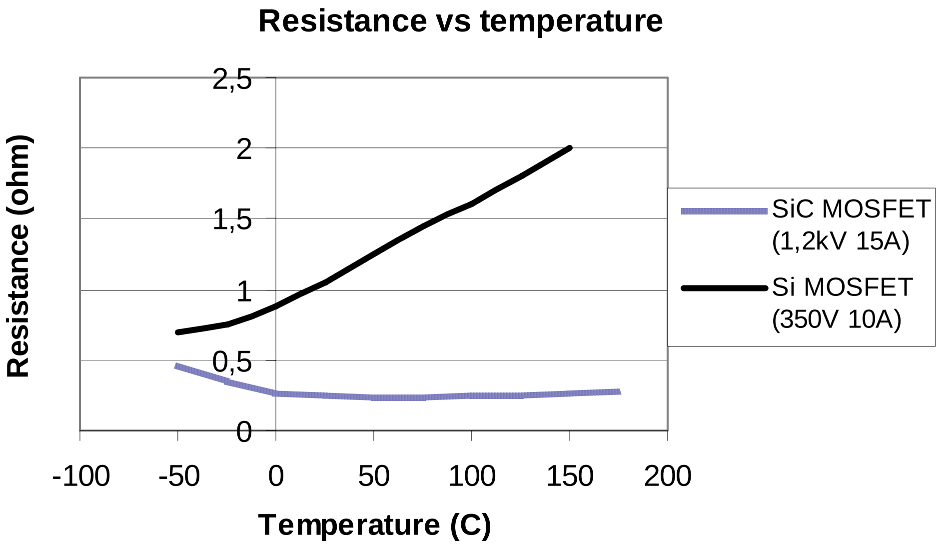

Figure 12. SiC MOSFET [Chinthavali, M.S, et al, 2005] and Si MOSFET [Venugopal R. G. et al, 1997].

4.3.1.2 Capacitances

Tests have been done on different transistors to compare the capacitances, which is a parameter that affects the switching behaviour. The tested devices were:

1. 1200 V Si MOSFET (PowerMOS)
2. 800 V CoolMOS
3. 2.3 kV 4H-SiC DMOSFET

The silicon MOSFET and the CoolMOS are the best transistors available on the market and is therefore chosen to be compared to the SiC DMOSFET. The results can be seen in Table 6 [Sei-Hyung Ryu et al, 2004].

Table 6. Comparison between semiconductors [Sei-Hyung Ryu et al, 2004].

	APT PowerMOS	**Infineon, CoolMOS (SPP11N80C3)**	**Cree, SiC DMOSFET**	**Reduction with SiC DMOSFET in %, compared to**	
				PowerMOS	**CoolMOS**
V_{dss} (V)	1200	800	2300		
R_{on} (Ω)	1.4	0.45	0.48	66	-7
Input capacitance (pF)	2030	1600	377.64	81	76
Output capacitance (pF)	309	800	100.2	68	87
Reverse transfer capacitance (pF)	60	40	18.52	69	54

As seen in Table 6, the capacitances of the SiC DMOSFET are sufficiently lower than those of the Si components. The output capacitance is the one that determines the switching speed. If high switching speed and low on-resistance is wanted, the SiC DMOSFET is to prefer [Sei-Hyung Ryu et al, 2004].

4.3.1.3 Frequency

It is expected that the 4H-SiC MOSFET will become a factor of 100 times smaller, compared to a Si MOSFET with the same blocking voltage and on-resistance ratings. This will give a driftlayer charge that is 10 times smaller than for Si and, consequently, the switching characteristics will improve 10 times [Sei-Hyung Ryu et al, 2004].

In FET devices, the three parasitic capacitances are the main factors of limitation of the switching frequency. In the case of a SiC FET, the device is smaller and this affects the behaviour of the parasitic capacitances as they are proportional to the area of the device [Chinthavali, M.S, et al, 2005].

4.3.1.4 Blocking voltage

Because of the ten times higher electric breakdown field, a SiC MOSFET will have a theoretical blocking of ten times higher than a Si MOSFET [Chinthavali, M.S, et al, 2005].

4.3.1.5 Isolation problems

The interface between the silicon dioxide (SiO_2) and the SiC is often of poor quality [Lori A. et al, 1999]. The problem with the poor quality oxide between the gate and the channel is that it after some time of operation starts to leak current and eventually breaks down and the device is thereby irreversibly damaged. This is a big problem for SiC MOSFETs [Sveinbjörnsson E., 2006]. The problem can be related to the electrical field. According to Gauss' law (2) and (3) are valid, which imply which quantities are important for the insulating layer. The critical limits for these parameters should be higher than for SiC. It is desirable that the intrinsic properties of SiC are the ones that limit the operation status and not the insulating layer between the SiC and gate.

$$\varepsilon_{SiC} E_{SiC\_Normal} = \varepsilon_{oxide} E_{oxide\_Normal} \tag{2}$$

$$E_{SiC\_Parallel} = E_{oxide\_Parallel} \tag{3}$$

In SiC the field shall not be over 2MV/cm because it will lead to Fowler-Nordheim tunnelling between the gate and the SiC area. Usual insulating, however, can not withstand this field and therefore breakdown will occur and a new oxide is desired. A solution to this problem has been found: If a polysilicon is implanted in the device it will take care of the higher field and the limiting of the MOSFET will be due to the intrinsic properties of SiC as desired. A configuration of this can be seen in Figure 13 [Ali T. et al, 2004].

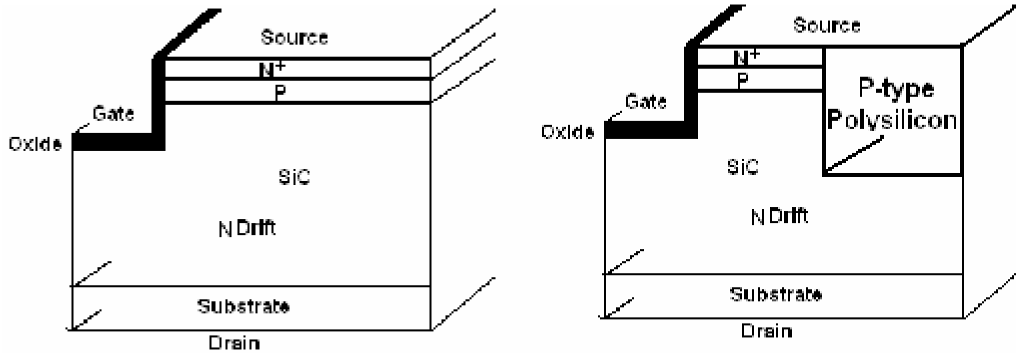

Figure 13. Trench MOSFET without (left) and with (right) polysilicon.

A number of different oxides have been tested to see if there are any good replacements for SiO_2 see Table 7, but most of them have problems with leakage current at high temperatures. Only ONO and SiO_2 could handle the temperature with help of a method of both dry and wet oxidation [Lori A. et al, 1999].

Table 7. Characteristics of dielectrics and SiC.
****The dielectric constant decreases when an electric field is applied.***
‡ Estimated values [Lori A. et al, 1999].

Material	**Dielectric constant ε**	**Critical field E (MV/cm)**	**Operational field E_0 (MV/cm)**	**εE_0 (MV/cm)**
SiC	10	3	3	30
Thermal SiO_2	3.9	11	2	7.8
Deposited SiO_2	3.9	11	2	7.8
Si_3N_4	7.5	11	2	15
ONO	6	11	~2	~12
AlN	8.4	10-12	~3‡	~30
AlO:N	12.4	8‡	~1‡	~12
$Si_xN_yO_z$	4-7	1	~2	~8-12
$(Ba_2Sr)TiO_3$	75-250*	2‡	~0.1	~8
TiO_2	30-40	6	~0.2‡	~4
Ta_2O_5	25	10	~0.3	~7.5

An important parameter here is the bandgap of the dielectric, which needs to be as large as possible (this means that TiO_2 and Ta_2O_5 are not at all suitable). E_0 is the highest field that the dielectrics are expected to withstand. As seen in Table 7, AlN would match SiC perfectly (look at εE_0), but the leakage current is a problem, as well as the performance at high temperatures. (AlN has a bandgap of only 6.0 eV compared to SiO_2 that has 9 eV, this means that there will always be more leakage through the AlN than SiO_2) [Sveinbjörnsson E., 2006].

4.3.2 Bipolar Junction Transistors

A SiC BJT will be commercially available in the year of 2008, according to the Swedish company TranSiC. Currently they have made their first batch, which they now are evaluating. The ratings of the BJT component are 1200 V and 6 A and are expected to increase to 1200 V 50 A in the future. So far the switching time has shown a turn-on of 60 ns and a turn-off slightly longer. The forward voltage drop of a 1200 V BJT design is theoretically 0.5 V at 100 A/cm^2, but the best that TranSiC have achieved so far is 0.9 V, which is well below the value for IGBT, which is 2.5 V [TranSiC, 2006]. Second breakdown[1], which exists in Si BJT and was the reason that the Si MOSFET was the component of choice instead of Si BJT [Gao Y., 2006], does only occur in SiC BJTs at extremely high current densities, due to the higher doping in the drift layer [TranSiC, 2006].

4.3.2.1 Stacking problems

ABB were looking into SiC bipolar diodes during the years 1994-2002. They saw potential in using these devices for high voltages and currents, in range of thousands of Volts and a few hundred Ampere. The research project was ended, because gradual degradation in the material after a time of operation was occurring. The forward voltage drop increased severely and it was discovered that the reason for this was formation of so called stacking faults by the carrier recombination energy. Stacking faults are atomic layers in the structure that have become dislocated [Lendenmann H. et al, 2002]. It starts from a single dislocation in the basal plane and therefore the solution would be to make clean SiC substrates with no basal plane dislocations. Since the time when ABB was conducting research on this subject, the manufacturing process has developed and material has become more pure. Thereby faults, such as micro-pipes and stacking faults have decreased [TranSiC, 2006].

ABB made pn diodes which were vertical and recombination occurred through the whole lowly doped epilayer, see Figure 14. In the bipolar transistors that TranSiC makes, on the other hand, recombination takes place in a relatively small volume close to the top surface, which makes it easier to prevent stacking fault formation.

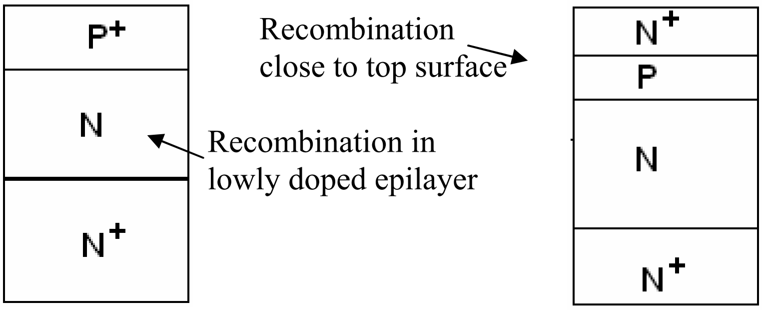

Figure 14. To the left vertical pn diode and to the right BJT from TranSiC.

Since stacking starts from dislocations in the basal plane, a design such as in Figure 15 would stop the growth of stacking. Parts of the bulk material on the basal side are removed for this design and, by doing this, the dislocation is stopped at the borders. Cree has tested this technique and has shown that it is an effective way of decreasing the bipolar degradation [TranSiC, 2006].

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[1] For more information about second breakdown, see e.g. “Power electronics” from Mohan et al, 2003

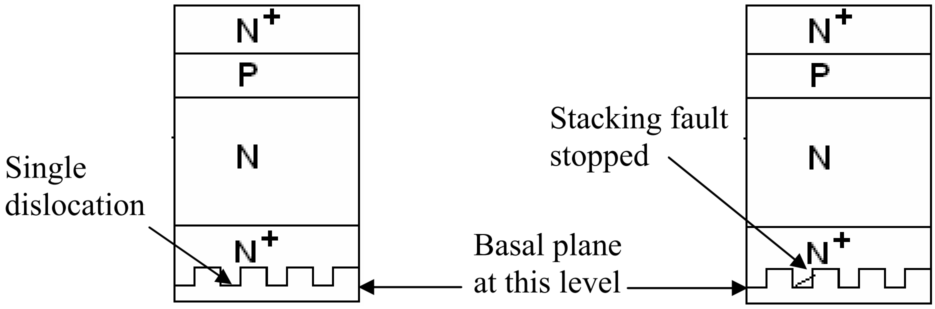

Figure 15. To the left: design to stop stacking and right: a stacking fault stopped at the border.

4.3.2.2 Heat dissipation

The SiC wafers are still thicker than what is necessary for the active devices. Since power devices are normally only cooled from the backside, this thickness will lead to a not so effective heat removal. The temperature is depending on the thickness according to (4).

$$T \propto \frac{1}{\lambda} L , \qquad (4)$$

where λ is the thermal conductivity of the material, L is the length between the pn-junctions, where the most heat arises, and the bottom side of the wafer, where the cooling is placed, and T is the temperature in the pn-junctions. To use the heat removal benefit of SiC compared to Si, the SiC wafers need to be made thinner than today's common wafer thicknesses, which are in the range of 300-400 µm, while Si wafers are as thin as 50 µm [Si-Mat]. Otherwise the heat removal might be similar to the one in a Si IGBT. However, there will still be a significantly smaller heat generation in the SiC component [TranSiC, 2006].

4.3.2.3 Current gain

It has been a problem with difficulties of achieving a high current gain in SiC BJTs. Currently the highest achievable gain has been around 60 and the industry is interested in gains above 40. In Section 4.5 achievements can be seen [TranSiC, 2006].

4.3.2.4 Challenges

According to TranSiC, the manufacturing of the epitaxial layers is still a challenging process. It can be difficult to achieve correct thicknesses of the different doping layers, which would result in the desired breakdown voltage. The availability of high-quality 4" wafers in the coming years, will fit TranSiCs process line better and thereby production efficiency will be improved [TranSiC, 2006].

4.4 Packaging

Packaging is the interface between the Schottky or Ohmic contacts on the SiC device and the electrical system. Packaging also provides electrical isolation and environmental and mechanical protection. Heat spreading and removal of heat is provided through the packaging [Johnson R. W. et al, 2005].

It would be satisfying if the SiC could be able to operate at full peak power density, which would bring the junction temperature up to 600°C. Although SiC itself can withstand high temperatures, the packaging is a major problem. Currently, all areas of electrical packaging are inadequate for high temperature operation and reliability. The solder melts at 300°C and today's available packaging material can withstand 200°C [Hornberger J. et al, 2004]. This is sufficient for Si, which is typically specified for operating at a maximum temperature around 125°C [Sveinbjörnsson E., 2006].

Little research has yet been done in this area and more research is sufficient to attain all the benefits that SiC offers. If the improvement of packaging is not reached, the weight and volume will not decrease [Hornberger J. et al, 2004]. The research that has been done has resulted in packaging that can withstand heat of 300-350°C for 2000 hours [Johnson R. W. et al, 2005]. Arkansas Power Electronics International (APEI) has a research group working on a plastic material for packaging that will withstand 400°C [Hornberger J. et al, 2004]. The packaging does not only need to withstand high temperatures, but also has to have the same coefficient of thermal expansion (CTE) to be able to cooperate with SiC during usage [Johnson R. W. et al, 2005].

4.5 Leading development and actors

Figure 16 to Figure 19 show the theoretical limits of SiC and Si and which SiC components that have been accomplished in a research stage. It is shown that the SiC components have on-resistances lower than the Si limit [Östling M. et al, 2006].

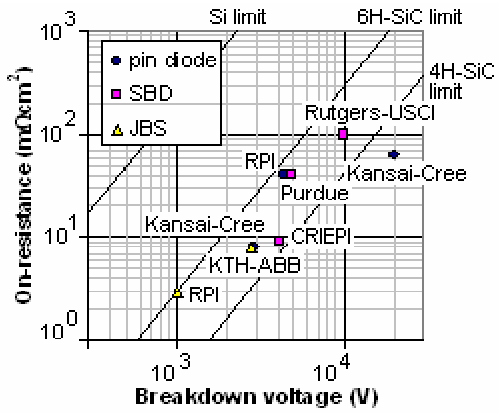

Figure 16. SiC diodes from different actors [Östling M. et al, 2006].

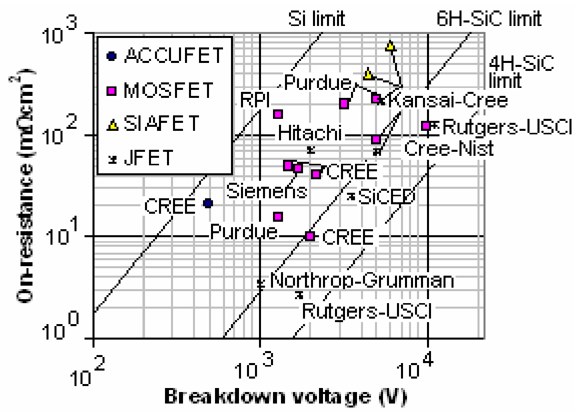

Figure 17. SiC FETs from different actors [Östling M. et al, 2006].

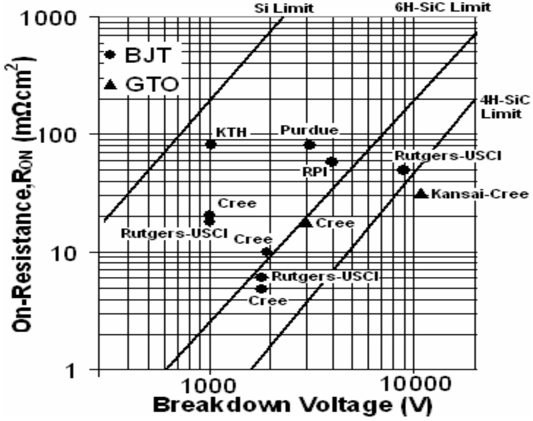

Figure 18. SiC BJTs from different actors [Östling M. et al, 2006].

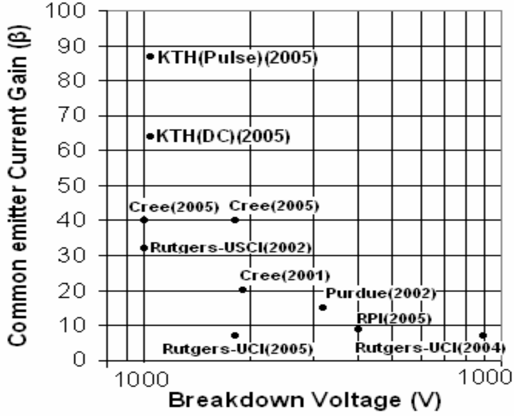

Figure 19. SiC BJTs. Current gain vs. breakdown voltage [Östling M. et al, 2006].

Companies and universities that have reported results in Figure 16 to Figure 19 are stated in Table 8 below and are marked with *. Other companies and schools that have been found doing research on SiC are also included in Table 8. Notice should be taken that ABB does no longer perform any research and has sold all their patents to Cree [Ny Teknik, 2003]. Companies highlighted in bold are the ones which the authors of this thesis think are the biggest in the area. The two main suppliers of SiC (diodes) are Cree and Infineon [Power electronics Europe, 2006]. Cree is not just one of the dominating component manufacturers, but also one of the biggest wafer producers, with 90% of the market [Henelius N., 2006].

Table 8. Actors in the SiC market.

SiCED*	Company	ABB*	Company
Cree*	Company	CRIEPI*	Institute
Infineon	Company	Rutgers-USCI*	University
Fraunhofer	Company	PURDUE*	University
Northrop-Grumman*	Company	KTH*	University
TranSiC	Company	RPI*	University
Teledyne (Rockwell Scientific)	Company	**APEI**	University
Hitachi*	Company	Linköping University	University
Siemens*	Company	Chalmers University	University
ROHM	Company		

5 Converter analysis

In this chapter the utilization of SiC components in converters will be studied. Resulting performance is estimated and an economical model is made for component costs. The economical effect of using SiC in converters is also studied.

In the vehicles there is a need to convert the voltage from the battery to the loads. An AC/DC converter is needed to convert electric power from the battery to the electric motor and vice versa. For other functionalities in the vehicle, such as spotlights, panel lights and radio the voltage needs to be decreased by a DC-DC converter. There are several types of converters that can be used to transform DC to DC and DC to AC. A full-bridge DC/DC converter and a three-phase inverter will be presented as examples. The full-bridge DC/DC converter is preferred for high power applications, because the transformer can be half of that in a half-bridge and the current through the switches will be halved. The three-phase inverter is commonly used for AC machines and is therefore chosen [Mohan N. et al, 2003]. Moreover, in these examples the voltage of the battery has been chosen to be 600V and for the electrical machine to be 400 V AC.

5.1 Full-bridge DC/DC converter

The DC/DC converter, which is stated as an example, is a full-bridge converter that transforms the voltage from the 600 V battery to a supply level of 28 V. In Table 9, the input and output voltages and nominal output power for the converter are given.

Table 9. Requirements for the DC/DC converter.

Property	Value
Input voltage	600 V DC
Output voltage	28 V DC
Output power	10 kW

It is preferable that the converter is as light and small as possible. The converter should also be protected from electromagnetic interference (EMI). For the full-bridge DC/DC converter, 4 switches are needed, together with 4 switch diodes, 2 rectifying diodes, 2 capacitors, an inductor and a transformer, as seen in Figure 20. This is the schematic view of the converter, practically several components might need to be connected in parallel to be able to handle the amount of power. [VIC, Mohan N. et al, 2003].

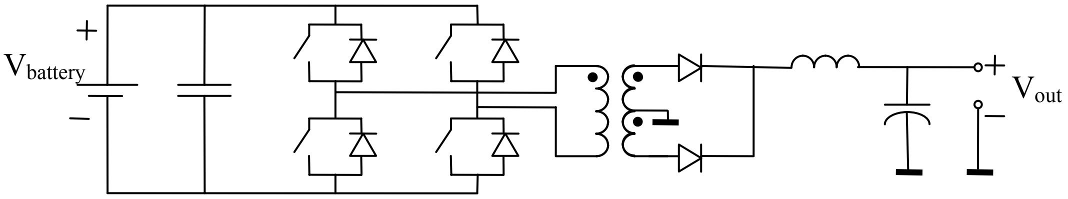

Figure 20. DC/DC converter design.

5.2 Three-phase inverter

The three-phase inverter, which is being studied as an example, should be able to convert power between the battery DC voltage of 600 V and the electric motor three-phase AC voltage of 400 V or vice versa. A reasonable power level of an electric motor for hybrid trucks is 70 kW continuous and 120 kW peak. In Table 10, the requirements for the inverter are summarized [VIC].

Table 10. Requirements for the inverter.

Property	Value
Input voltage	600 V DC
Output voltage	400 V three-phase AC
Output power	120 kW

The configuration of the AC/DC converter is shown in Figure 21. 6 switches and freewheeling diodes and a capacitor are schematically needed for this converter design, although parallel coupling of more components could be necessary.

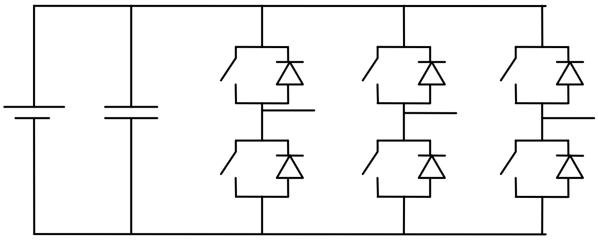

Figure 21. AC/DC converter design.

5.3 Ratings for the switch devices

Si IGBTs and MOSFETs have so far been the alternatives for transistors in power applications. IGBTs have the advantage of managing high powers, while MOSFETs have the ability to work at higher frequencies.

In the suggested DC/DC converter the continuous current will be 16 A. Because of peaks that occur in Si devices at turn-on, the current rating would have to be higher. A suitable rating would then be around two to three times higher, compared to the continuous current. This rating (600 V, ~45 A) is within the MOSFET operating range [Mohan N. et al, 2003]. The MOSFET that is used can be of the CoolMOS type, which have 1/3 of the gate charge and 2/3 of the switching losses of a "normal" power MOSFET. Also, the CoolMOS can operate at much higher temperatures [Dupont L. et al, 2004, E6002]. In Appendix B figures of the transistor structures can be seen. In the AC/DC converter the continuous voltage and current are 600 V and 170 A. Also here there are high peak currents, which need to be considered for current ratings when Si devices are used. For this two Si IGBTs (600 V, 200 A) can be used in parallel.

5.4 Technical effect of application

In this section, consequences from the application of SiC technology for the automotive industry are considered. Schottky diodes are the only SiC components that are reliable and fully established on the market in the high power area at the moment. Around 2008 the SiC MOSFET and BJT technologies are likely to be on the commercial market, see Section 4.1. In the first subsection the impact of diodes in the converters will be considered, since this component can be bought and used today. In the second subsection, a future solution with a fully equipped SiC converter is considered.

5.4.1 Effect of using SiC Schottky diodes

If SiC Schottky diodes are used instead of Si diodes, there are some advantages. The peak current during switch-on is significantly lower and during switch-off no reverse recovery occurs, as was illustrated in Section 4.2.1. In some cases to handle the switching peaks, snubber circuits are used. In the case with SiC no peaks occur and hence the snubber circuits can be removed. Even though snubber circuits can be used it should be avoided, because it increases the losses and reduces the switching speed. For a Si diode topology without snubber circuits the peaks are so high that the switching components would need a current rating four times higher than the continuous current see Section 4.2.1. If a SiC diode is used instead, the rating can almost be the same as the continuously drawn current. Besides the advantage of being able to use lower rated components, the switching losses are also decreased when SiC diodes are used.

With previously used diodes parallel coupling was necessary to handle the high currents. Because the current density in SiC can be about 3 times higher, a configuration of three parallel coupled Si diodes could be replaced by one single SiC diode, but this leads to lower blocking voltage for the component, see 3.2.2. For the same blocking voltage the SiC diodes could decrease as much as ten times in size, but then the current density is not increased. It is a design question if one wants fewer components or smaller components.

Due to the lower overshoots during turn-on and turn-off, the EMI will be reduced. Therefore the packing of switches and diodes can be done denser.

The excellent turn-on and turn-off properties also contribute to a reduction in weight and volume of converters. Due to that the frequency can be raised, capacitances and inductors can be reduced in the same proportion. This raise/reduction can be up to ten times. An effect of the reduced number of components will reduce the amount of connecting wires and assembly work.

The SiC diodes' performance is not affected by ambient temperature. This could lead to a total reduction of the cooling if it was not for the Si switches, which still need cooling. However, due to reduced switching losses less cooling is needed, approximately 70% of the cooling capacity is needed [Toshiba].

Even though only the diodes have been exchanged, profits in both weight and volume are gained and, in addition, the efficiency for the converter is increased from approximately from 93.5% to 94.5% [Toshiba].

5.4.2 Suggestion on a solution with SiC Schottky diodes and SiC transistors

The advantages will be even greater if both the diodes and the switches are changed to SiC devices. All the benefits from the SiC diodes described in Section 5.4.1 will be drawn plus the advantages from SiC transistors. SiC transistors can withstand a higher electrical breakdown field for the same size as a Si transistor, as a consequence the transistor component can be downsized in the converter.

The resistance in the transistors will be lower according to 4.3.1.1. The lower resistance implies that the losses in the transistors are going to be reduced. In the SiC transistors the losses are lower and the switching speed can be higher. According to Cree, the conversion losses in the inverters could be decreased by 50% in the future, with help from the new SiC technology compared to Si technology. This would save a tremendous amount of energy [Kansai, 2006].

As for diodes the current density can be higher with increased doping and fewer components need to be parallel connected or a reduction in component size is possible, if the doping is unchanged.

If both diodes and MOSFETs are changed to SiC components, the switching losses will be reduced and less cooling is needed, approximately 20% of the cooling capacity is needed. The efficiency will also rise from today's 93.5% up to 98% [Toshiba]. If a topology of SiC is used, the operating temperature can be higher. Liquid cooling might not be necessary and air cooled converters could be realized. This is a more problem free solution, because no plumbing and pumps are needed for the fluid.

5.5 Costs for components and converters

In this chapter, the manufacturing and component prices today and in the future are estimated and then the converter costs are estimated based on today's price picture. All estimations are based on the information that has been collected.

5.5.1 Future manufacturing and component costs

In the new SiC technology there are some problems with the manufacturing of the SiC rods. The structure of SiC material is more sensitive for contamination and therefore the wafer sizes are small, 2" or 3" today. The process to grow SiC rods is slow. Because of these factors, the prices of SiC wafers are high [Henelius N., 2006].

The current Si processing technology has a wafer size that lies between 3"-8", this can be seen in Figure 22. There are 12" wafers available, but no manufacturers use those yet and no move to 12" is forecasted [Yole, 2006].

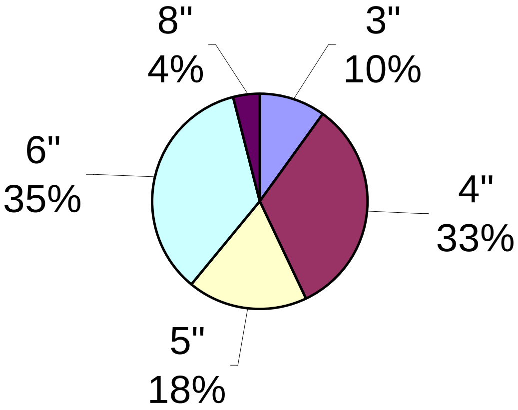

Figure 22. Diameter distribution of silicon wafers (statistics made on 82 power devices fabs) [Yole, 2006].

To predict the future for SiC, an economical model, which shows how the SiC component prices in relation to Si component prices can change, has been developed. The model is based on the parameters presented in Table 11.

Table 11. Parameters that affect component price.

Parameter	**Comments**
TW – How many times longer the manufacturing time (growth time) of a SiC wafer is, compared to a Si wafer.	Production can be increased and wafer price decreased if the time it takes to grow SiC is made shorter, which could be the case if manufacturing technology is developed further.
DW - Wafer size (diameter).	Wafers of larger diameter would fit more components. The problem has been to keep the number of impurities in large SiC wafers down. The manufacturing time of a wafer is independent of the diameter.
OKC – Rate of components that are OK through the process.	If the share of good quality components is large, it is beneficial for the component price.

It can be assumed that the wafer price is proportional to the manufacturing time, TW [Henelius N., 2006]. This gives a price per SiC wafer, relative to the price for Si wafer, PW:

$$PW = TW \tag{5}$$

Today TW (and PW) is about 100. The number of SiC components that can fit on a wafer, in comparison with how many Si components would fit on a Si wafer of same diameter, NC_D, is 10 times as many according to

$$NC_D = \frac{1}{SC} = 10, \tag{6}$$

where SC is the size of a SiC component compared to a Si component and this is set to 1/10.

If the wafer size increases, the number of components on each wafer increases. The number of components that could fit on each wafer (for SiC in relation to Si), NC, can then be described as:

$$NC = \frac{1}{SC} \cdot \frac{DW_{new}^{\ 2}}{DW_{today}^{\ 2}} = 10 \frac{DW_{new}^{\ 2}}{DW_{today}^{\ 2}}, \tag{7}$$

where DW_{today} and DW_{new} are the diameters of a SiC wafer today, which is assumed to be 3", and the new SiC wafer diameter, respectively. Note that the manufacturing time of a wafer is almost the same, independently of wafer diameter [Henelius N., 2006]. This can also be supported by the fact that the prices for 2" to 6" Si wafers are almost the same [silicon quest], see Table 12.

Table 12. Price for a Si wafer today. [silicon quest]

Silicon quest international Si wafers							
Size	2"	3"	4"	5"	6"	8"	12"
Price ($)	10	10	12,5	10	17	N/A	142

If the price per SiC component compared to the price of corresponding Si components, PC, should be calculated it is also important to look at the parameter OKC, which is the rate of how many of the produced SiC components are of accepted quality. (8) is the result, which constitutes the component price model:

$$PC = PW\frac{1}{NC}\frac{1}{OKC} = TW\frac{DW_{today}^{\ 2}}{10DW_{new}^{\ 2}}\frac{1}{OKC} \tag{8}$$

Today, the amount of OK components through the process is about 60 % [micromagazine].

In Table 13 below, the changed parameters for different scenarios are listed together with the resulting prices for SiC components. The prices are presented in terms of how many times higher they are compared to the prices for Si components of same ratings.

Table 13. Estimated new prices for SiC components with different scenarios. The costs are in relation to Si prices.

	TW	DW_{today}	DW_{new}	OKC	Times higher cost
Today	100	3	3	0,6	16.67
Scenario 1	50	3	3	0,6	8.33
Scenario 2	50	3	3	0,7	7.14
Scenario 3	50	3	4	0,6	4.69
Scenario 4	50	3	4	0,7	4.02
Scenario 5	100	3	3	0,7	14.29
Scenario 6	100	3	4	0,6	9.38
Scenario 7	100	3	4	0,7	8.04
Dream	10	3	6	0,8	0.31

The scenarios 1-7 are made with realistic parameter values, while the dream scenario lies much further away and the figures are close to the theoretical limits of what is possible. It can be seen that increasing the wafer size to 4" and the OKC to 70% have the same effect on the price as lowering the manufacturing time to half, see scenario 1 and 5. This is the cost for normal performance devices. The cost will reduce even more for high voltage/current applications, because Si has operating problems at these high ratings, due to blocking voltage, temperature etc.

Today, the prices for SiC devices are more than 10 times higher for low voltage/current ratings. For high voltage/current ratings, the price is approximately 3 times higher for SiC diodes, compared to the most expensive Si diodes, which have the same current and voltage rating (600 V). This comparison is not completely fair, unfavourably for SiC, because for SiC diodes, the current ratings can be 30 % smaller, due to lower peak currents, and also the losses are less, which contribute to lower cooling costs. Switching devices are comparable with diodes, but here it is more reasonable to compare the on-state resistances. If a CoolMOS, which is the best performing Si FET today, is compared to a SiC MOSFET, the price is ~6 times higher at 600 V and ~2 times higher at 1000 V [Rupp R., 2006]. This means that for high voltage applications the prices would look like in Figure 23.

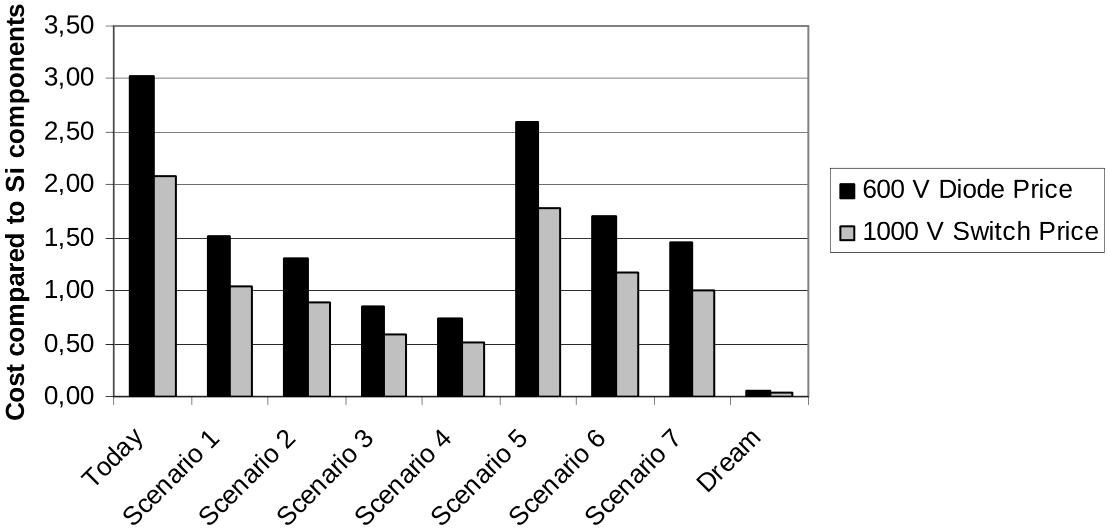

Figure 23. Costs for high rating devices.

5.6 Cost with new technology

A total analysis of the costs is very hard to achieve and it needs more time than has been given for this work. Even though a full cost analysis is hard to make, a presentation of costs that can be supported by the data that have been collected is done. The cost analysis that is made is done for both the DC/DC and AC/DC converters described in Sections 5.1 and 5.2 and the case where both diodes and transistors are made of SiC instead of Si is being considered.

5.6.1 Full-bridge DC/DC converter with SiC diodes and SiC MOSFETs

In this type of converter there are diodes both on the low voltage and high voltage side. In our example a voltage rating of 28 is enough on the low voltage side and 600 V on the high voltage side. On the low voltage side the SiC diodes will be ten times more expensive according to 5.5.1. Due to lower overshoots, higher current density and lower losses, an assumption is made that 50% less diodes can be used. On the high voltage side diodes are used in parallel with the MOSFETs. The diode and the MOSFET are in the same module and this can be de-rated with up to 50% in its current rating if SiC diodes and SiC MOSFETs are used. Smaller MOSFETs results in a higher frequency capability [SiCED]. The capacitors and inductors can be decreased because of the increased switching frequency. The reduction in cost of capacitors can be as much as 83%[2]. For the inductors no component value that lies in the area that is needed has been found, an estimation of the cost is real hard for the inductor, but one thing that is certain is that the cost will not increase. The cost change for the converter components can be seen in Table 14. The component numbers are a result of Volvo internal information.

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[2] One 47 uF costs 10 SEK and 6 of these are needed. In the new configuration one 47 uF is enough. [ELFA, Elektrolytkondensator, 105°C typ RVS och RVJ Y]

Table 14. Cost changes with SiC technology in a DC/DC converter[3]. (SEK=Swedish krona)

Component	Number of components with Si	Component price with Si (SEK)	Number of components with SiC	Component price with SiC (SEK)	Change (SEK)
MOSFET with diode	4	3300	4	19800	16500
Low voltage side diode[4]	12	19.2	6	118.2	99
Capacitor	6	60	1	10	-50
Inductor	4	N/A	4	N/A	
Total component cost		3379.2		19928.2	16549

As seen in Table 14 the component cost for the DC/DC converter becomes around 6 times higher.

5.6.2 AC/DC converter with SiC diodes and SiC MOSFETs

In the AC/DC converter, modules including an IGBT together with a free-wheeling diode are often used. The IGBTs constitute the dominating costs in the AC/DC converter. With the new technology SiC MOSFETs could replace the IGBTs. One of these new MOSFETs will cost 4950 SEK the same as for the DC/DC converter. As was mention in Section 5.3 two Si IGBTs in parallel are needed to handle the current spikes, with SiC MOSFETs one would be enough, because of lower current spikes. In Table 15 the impact on the converter price is shown.

Table 15. Cost change for AC/DC converter with SiC technology[5].

Component	Number of IGBTs with Si	IGBT price (SEK)	Number of MOSFETs with SiC	MOSFET price (SEK)	Difference (SEK)
IGBT/MOSFET	12	15700	6	29700	14000

As seen the AC/DC converter becomes around 2 times more expensive.

5.6.3 Other parameters that will affect the total cost

As expected the costs for the converters will increase if SiC technology is used in the converters. However, this investment might still be profitable. The efficiency in the case of the AC/DC converter increases from 94% to 98%, which means that the price is 5500 SEK per % gained efficiency. Other improved parameters that are hard for us to put specific values for are decreased cooling, less weight and less volume. There are probably more consequences from using this technology, which we have not brought up in this section, but to identify them will require a deeper analysis.

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[3] Price information from Volvo knowledge if not other stated.

[4] Price information from Toshiba.

[5] Price information from Volvo knowledge if not other stated.

6 Electric motors

In this chapter the function of a brushless DC (BLDC) motor will be explained. The explanation is made to better understand the function of a permanent magnet synchronous motor (PMSM). The requirements on a traction motor for a hybrid truck will also be discussed.

6.1 Theory of brushless DC motor operation

The BLDC motor is a basic motor and therefore it is good to use as an example, while explaining the function of motors containing permanent magnets (PMs). BLDC motors are driven by a DC source which is switched. The motor consists of a PM and coils wound around an iron core. The PM constitutes the rotor and the iron core is the stator, as can be seen in Figure 24.

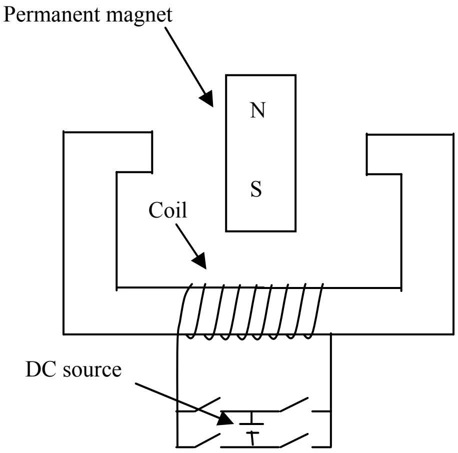

Figure 24. BLDC motor.

Magnetic flux will be created inside the coil if two switches are closed, due to that current flows through the coil. This will magnetize the ferromagnetic material and a north and south pole will be created, see Figure 25. The PM will now start to move in an anticlockwise direction, because the opposite poles will attract each other.

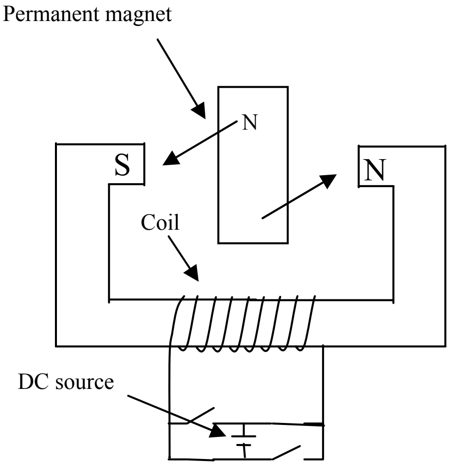

Figure 25. A connected voltage source will make the PM start to rotate.

When opposite poles reach each other, the switches are turned off and the PM will continue to rotate in anticlockwise direction, see Figure 26.

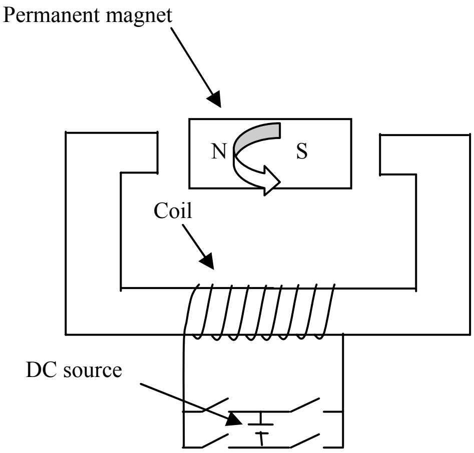

Figure 26. The voltage source is disconnected and the PM will continue to rotate.

After the PM has passed the vertical position (north side down and south side up) the other switches will close and a current will flow in opposite direction through the coil and hereby create a new south and north pole on the iron core, as in Figure 27.

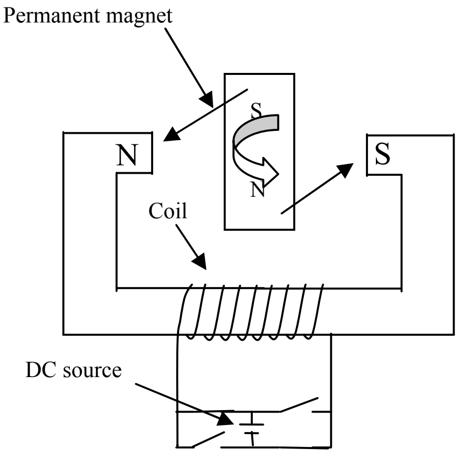

Figure 27. The voltage source is connected again, but in the opposite way, thus the poles of the electromagnet are changed.

The PM continues to rotate like this, cycle after cycle, while magnetic flux alternates in the iron core. In this simply arranged motor the torque will be unsteady. A way to increase the torque steadiness is to have more coils on the stator. In Figure 28 a two pole motor configuration can be seen, which includes three coils. First the current will flow through coil B, which will attract the PM. After the PM reaches B, the current starts to flow through coil C and so on. When the PM has turned 180°, coil B is turned on again, but this time the current flows in the opposite direction, so that the PM will be attracted.

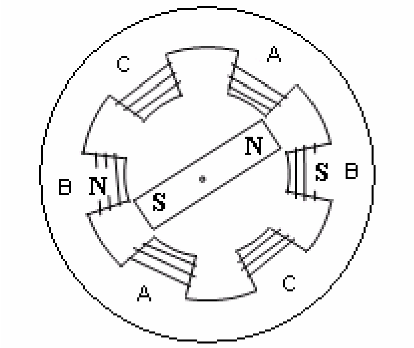

Figure 28. BLDC motor with three coils [Larminie J. et al, 2003].

When the motor rotates, a back EMF (Electro Magnetic Force) will be induced in the coils. The back EMF is proportional to the speed and at a specific speed the back EMF will be equal to the applied voltage. At this point the back EMF counteracts the applied voltage and hence the current will decrease, due to the relation in (9).

$$I = \frac{V_{applied} - E_{EMF}}{R} \tag{9}$$

When the current decreases the torque also decreases, because the torque is proportional to the current. In bigger motors there is a limitation in current to prevent overheating of the wire, due to the losses, RI^2 [Larminie J. et al, 2003].

6.1.1 Permanent magnet synchronous motor design

The principle for a PMSM is the same as for the BLDC motor, but instead of having current flowing in only one coil at a time, a three-phase AC is used to supply the machine.

For this thesis, where a traction motor is the object, the outer-rotor configuration would be the most preferable configuration. This design can give a higher torque density, because the rotor force acts further away from the axis, compared to inner-rotor design [Tidblad Lundmark S, 2005].

In Figure 29 a traditional outer-rotor motor design is shown. The right part of the figure shows the stator with its windings and the left part shows the rotor with its permanent magnets. When the motor is put together and operating, the flux goes out from a coil and into the permanent magnet. In Figure 30 the flux path is shown.

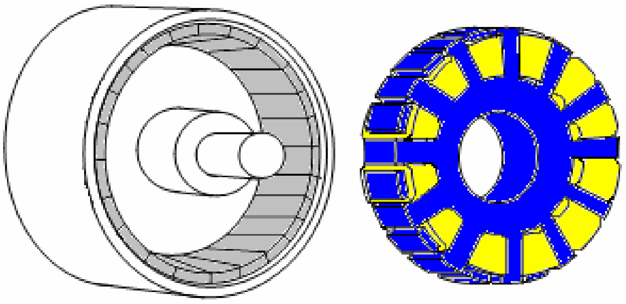

Figure 29. Stator and rotor of an outer rotor PM motor [NTNU].

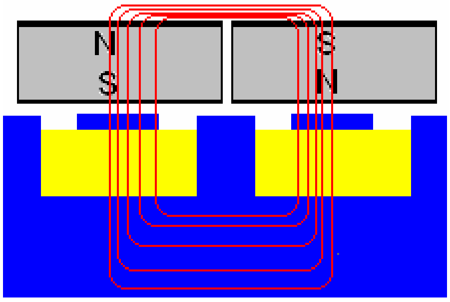

Figure 30. Magnetic field through an outer rotor PM motor.

6.2 Ambient motor conditions

Ambient conditions, such as heat, dangerous acids and water vapour, are issues that the motor will be exposed to. As an example in a parallel hybrid truck, where the motor is placed between the diesel engine and the transmission, the temperature at the motor position can be up to 125°C. The lowest temperature can be as low as -40°C in arctic areas [Lindström J., Cirani M., 2006, VIC].

6.3 Specification of motor performance

There are certain specifications that the electric motor needs to fulfil. The shape of the motor should prevent that water and other contamination is collected and, to some extent, the motor must be able to withstand these types of agents. It must also withstand the vibrations that will come from the driving of the truck. To achieve a smooth gearing operation, the inertia needs to be kept small. The material in the motor should be recyclable, either all of it or a major part. The electromagnetic compatibility and interference (EMC and EMI) should be in an order, such that the motor is not disturbed and does not disturb surrounding components.

Figure 31 shows a common engine torque-speed curve of a truck with the main purpose to drive inside the city and performing some short distance operations between cities. As can be seen, the torque is very low at low speeds and therefore it would be good to have an additional application that has a high torque at low speeds, such as the electric motor. The common characteristics of any electric motor are that the torque is at its maximum at low speeds.

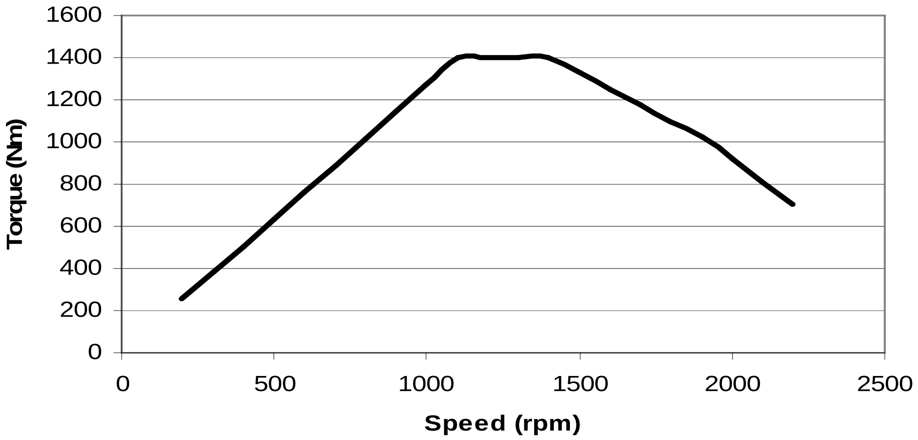

Figure 31. Speed vs. torque for the diesel engine.

The continuous torque rating is set to 450 Nm. The motor should be able to handle intermittent torque, because sometimes more torque is needed for short periods e.g. start in a heavily inclined road. The maximum intermittent torque is set to the double of normal operation, i.e. 900 Nm, and the electric motor should be able to work at this torque for 10 s. The heat generated should be transferred away within 50 s before the motor can work at 900 Nm again. In Table 16 the requirements of the electric motor can be seen and a graph of the torque vs. speed for the electric motor is seen in Figure 32.

Table 16. Requirements for the electric motor.

Requirement	Value	Comments
Continuous shaft torque	450 Nm	0-1500 rpm
Continuous shaft power	70 kW	1500-3000 rpm
Intermittent shaft torque	900 Nm	10 s every 60 s
Intermittent shaft power	130 kW	10 s every 60 s
Crank torque	800 Nm	0-350 rpm
Nominal DC voltage	600 V	
Operational speed range	0-3000 rpm	Burst speed >4500 rpm
Constant power speed range	1500-3000 rpm	
Constant torque speed range	0-1500 rpm	Minimum requirement

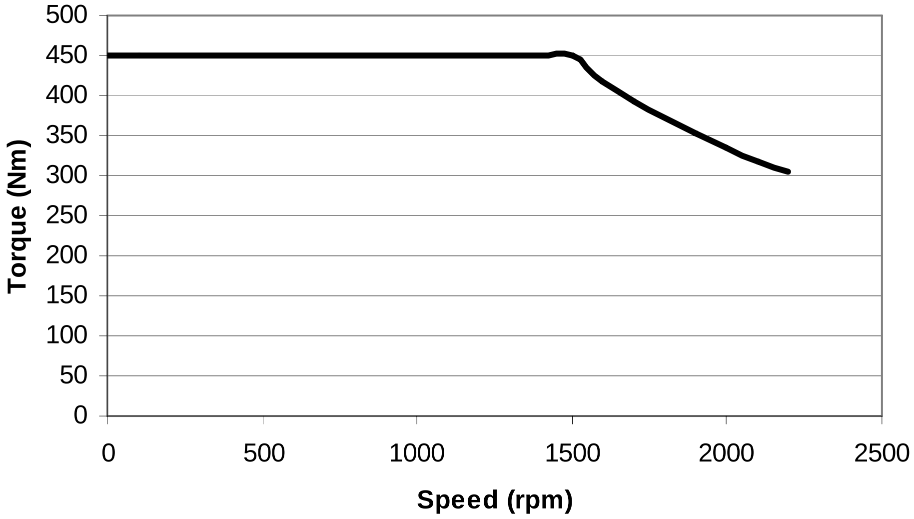

Figure 32. Speed vs. torque for the electric motor.

The torque-speed characteristic of the combined driveline will be the sum of the characteristics for the electric motor and the diesel engine and it is shown in Figure 33.

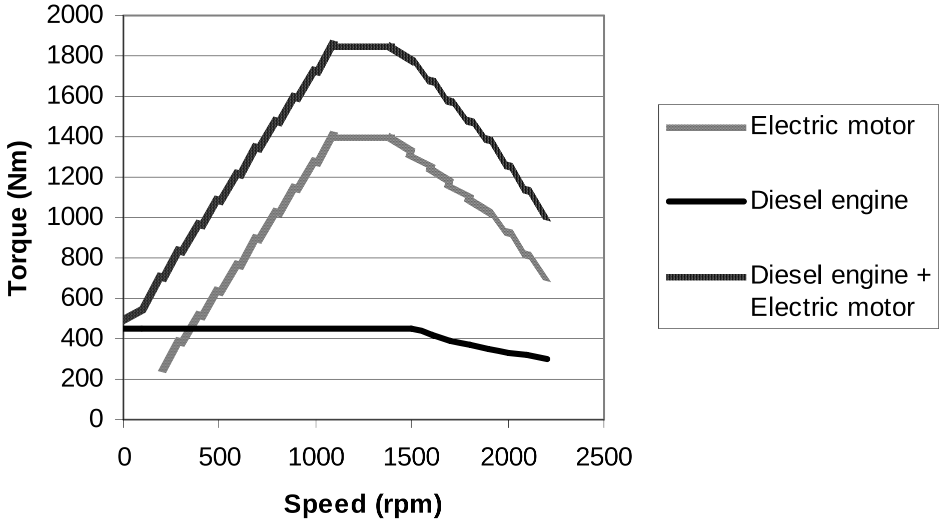

Figure 33. Speed vs. torque for the combined driveline.

7 Soft magnet materials

Laminated steel motors have been developed for many years, but recently other materials have started to be developed, which could replace laminated steel as the conductor of magnetic flux. Soft magnetic or ferromagnetic material, which could be used in electric motors, will be described below. The three magnetic materials, which are brought up, are laminated steel, soft magnetic composites (SMC) and plastic bonded iron powder (PBIP). The main subjects for this chapter are material production and properties.

7.1 Manufacturing of metal powder and steel sheets

The processes of making steel sheets for laminated steel motors and iron powder for SMC and PBIP are shown in Figure 34.

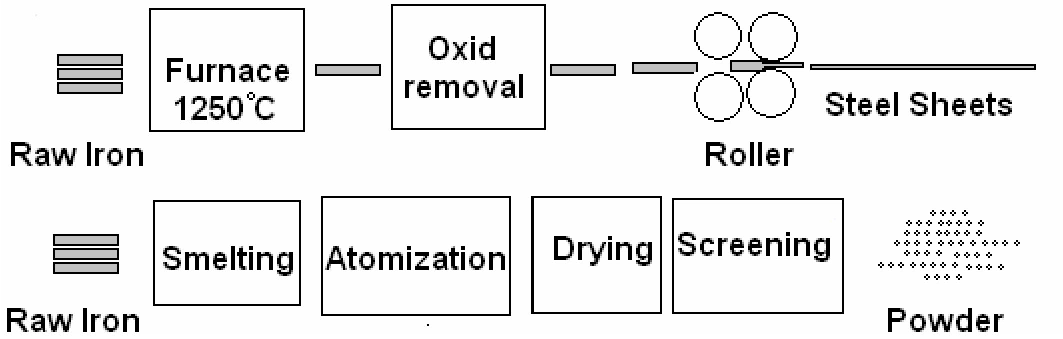

Figure 34. Processes for making steel sheets and iron powder.

Steel sheets are produced from raw iron that is heated in a furnace and when it is hot enough the oxides are removed. A last step is to let the heated raw iron pass through rollers to attain thin steel sheets. From the 11 m long raw iron ingots one can get 2 km of steel sheets [SSAB].

Powders can be produced by either gas or water atomization, see Figure 35 and Figure 36. Gas atomized powder is produced by first smelting raw iron. The liquidized iron is then placed in the top of a tower, filled with nitrogen gas, where it is sprayed out (like a snow cannon). During the fall in the nitrogen gas fine spherical powder is created. After this the powder is dried to remove stresses in it. Last the powder is screened to get hold of the particles with the right sizes. Water atomized powder is made by letting the smelt run through a nozzle and the stream of smelt is then hit by high pressure water. When the smelt is stiff and cool it is porous. The porous material is then crushed to powder. The gas atomized powder becomes more spherical than water atomized powder, see Figure 37 and Figure 38 [Höganäs]. The particle sizes can be in the nanometre range and up [Hultman, Nord, 2006].

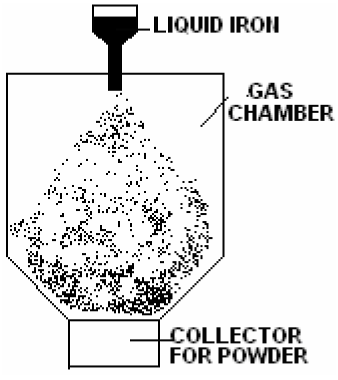

Figure 35. Gas atomization [Epma].

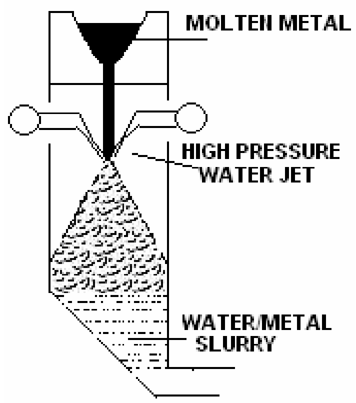

Figure 36. Water atomization [Epma].

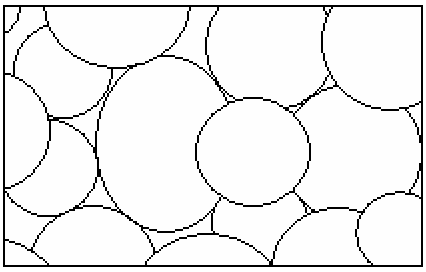

Figure 37. Gas atomized powder [Epma].

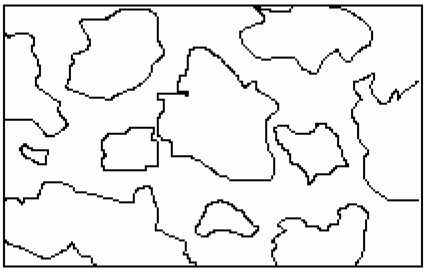

Figure 38. Water atomized powder [Epma].

7.2 Laminated steel

For over a hundred years, laminated steel sheets have been used for electric motors. The sheets are stacked on top of each other with an isolating membrane in between. The isolation between the sheets limits the eddy current loop area. At higher frequencies, thinner steel sheets are needed to keep the dynamic losses low [Andersson O., 2001]. The steel sheets are normally between 200 and 1000 µm thick [Hultman L. et al, 2002].

The process of making parts for electric motors can be described in four process steps [U.S. Steel]:

1. Punching the sheets to laminates of desired shape.
2. Annealing the laminates. During this step the magnetic characteristics are optimized and an isolating oxide layer is added to the surface.
3. Putting the desired number of laminates together.
4. Winding the coil wire around the core of laminates.

During the punching process, the shape of the rotor or stator steel that is going to carry the magnetic flux in the motor is achieved. The annealing process reduces the stress in the punched sheets and provides them with an insulating layer and thereby stopping eddy-current from flowing between the laminates. A rough matte finish is used to prevent the sheets to stick together during the annealing. Stacking is when desired number of sheets are put together to build the stator or rotor core. The sheets are held together with welding, bolting or any other interlocking type. The final step is to wind copper or aluminium around the core to get the final component [U.S. Steel]. Due to the sheet construction, the windings are wound around sharp corners. Because of this, the isolation layer on the wire needs to be thick and, since the winding can not be bent 90°, the thermal contact becomes rather low [Andersson O., 2001].

It is of great importance that the narrow sheets have as little waviness as possible to facilitate the punching process. A high hardness and yield strength-to-tensile strength ratio is also important [U.S. Steel]. A problem is that the punching process results in deformation of the steel sheets, which causes deterioration to the magnetic properties. The problem increases with thinner steel sheets [Hultman L. et al, 2002].

Laminated steel sheets do not have any isotropic properties, which mean that the magnetic flow is limited to two dimensions [Andersson O., 2001]. The magnetic properties are extremely good for two dimensions, with relative permeabilities up to 8000 [Tidblad Lundmark S., 2005].

7.3 Soft magnetic composites

SMC consists of iron powder, where each iron particle has an alloy coating on the surface, which serves as electrical insulation, see Figure 39. The iron powder is then compacted together with a lubricant and a binder. The lubricant is used to ease the compacting process and prevent the coating from being destroyed during this step. The binder increases the mechanical strength of the SMC material [Hultman L. et al, 2002].

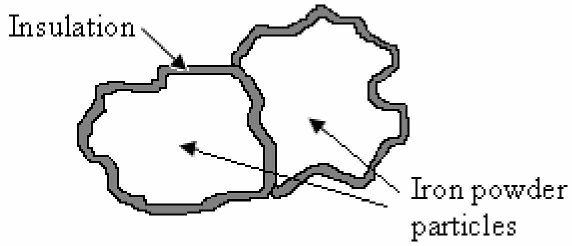

Figure 39. Insulating layer to prevent eddy currents [Pennander L.-O. et al, 2006].

The factors that determine the properties of the SMC material are the sizes and shapes of the iron particles, the coating, the choice of lubricant and binder and the compaction and after heating processes [Hultman L. et al, 2002].

The material is made of water atomized powder. The spherical shape, which can be obtained by gas atomization, is not desired, because the mechanical strength will be to low when the particles are not bound together by friction. However, it is desirable to have a shape with a volume to achieve isotropic properties [Hultman, Nord, 2006].

For the coating and binder a rule is that good magnetic properties are achieved if less additives are used. The additives contribute to the effective air length and thereby a lower permeability. However, with less additives used, eddy currents can arise and the mechanical strength of the material be lowered [Krogen Ö. et al, 2000].

The powder mix is compacted at high pressure in either a cold or warm surrounding [Andersson O., 2001]. Higher pressure leads to higher density and thereby better permeability and saturated induction [Krogen Ö. et al, 2000]. A problem with too much pressure is that the particles will be deformed and lose some of its magnetic properties [Hultman L. et al, 2002]. Notice should be taken that SMC is not sintered, because that would make it lose its properties and become a solid mass without isolation. Limited heating is, however, necessary to relieve the stresses in the iron and thereby improving its magnetic properties. The hysteresis losses in SMC will be higher than for laminated steel, due to the limitation in heat treatment [Krogen Ö. et al, 2000]. Another consequence of SMC not being sintered is a lower mechanical strength compared to laminated steel [Andersson O., 2001]. This lower mechanical strength has to be considered in constructions with SMC. SMC has a dimensional stableness throughout the whole process, i.e. the parts will not shrink and lose dimensional properties [Hultman, Nord, 2006].

The brittleness of SMC has an environmental aspect, which is positive. When recycling an SMC part, it is just to crush the compound and then separate the copper windings and the iron with a magnet [Andersson O., 2001].

The advantages of SMC are isotropy (laminated steel only works in two dimensions) [Andersson O., 2001] and that the eddy current losses will be low due to the insulation between the particles [Krogen Ö. et al, 2000]. The relative permeability is affected by the insulation in a negative way. For SMC it is only around 400-700 [Pennander L.-O. et al, 2006].

The eddy current losses are lower in SMC compared to laminates, but the hysteresis losses are higher. The eddy current losses depend on the square of the frequency and the hysteresis losses are depending linearly on the frequency. There will be a cross-over frequency, where it is advantageous to use SMC instead of laminates. Unfortunately this cross-over point is higher than the interesting frequency of a normal electric motor, where the maximum usually is a few hundred Hz [Hultman L., et al, 2002].

Table 17 presents the properties of different SMC materials and laminated steel. The relative permeabilities, saturation flux density and iron losses at different frequencies can be seen. It is not possible to predict the exact behaviour of the SMC material and the range of the values presented from different researchers is wide. However, the iron losses are lower in standard laminations all the way up to an as high frequency as 1000 Hz, where it is about even. For lower frequencies the iron losses are significantly smaller in laminations. The saturation flux density is not much lower for SMC compared to laminated steel, which is the case for unsaturated flux density [Tidblad Lundmark S., 2005].

Table 17. Permeability, saturation flux density and iron losses at different frequencies of different SMC materials and laminated steel [Tidblad Lundmark S., 2005]. *Figures are from Höganäs [Hultman, Nord, 2006].

	Somaloy™ 3P*	**Somaloy™ 500**	**Somaloy™ 550**	**ATOMETEMI**	**Standard motor lamination**
Initial relative DC permeability	740	500	550	290	8000
Saturation flux density	1.7 T at 10kA/m	1.7 T at 30 kA/m and 1.4 T at 10 kA/m	1.7 T at 30 kA/m and 1.5 T at 10 kA/m	1.5 T at 20 kA/m and 1.3 T at 10 kA/m	2.0 T at 30 kA/m and 1.8 T at 10 kA/m
Iron losses at 1.0 T/60 Hz	5.5 W/kg	8 W/kg	9.5 W/kg	11 W/kg	2 W/kg at 1.0 T/50Hz
Iron losses at 1.0 T/400 Hz	43 W/kg	65 W/kg	80 W/kg	77 W/kg	11.5 W/kg
Iron losses at 1.0 T/1000 Hz	125 W/kg	150 W/kg	220 W/kg	218 W/kg	140 W/kg

7.4 Plastic bonded iron powder

The development of PBIP material has only been going on for a few years and is still in its infancy. A project by the name of DAMIA, Design and manufacturing of interpreted actuators, started in the end of 2004 under the leadership of professor Mats Alaküla. The aim of the project is to investigate the possibility of moulding the active parts of an electric motor. Participating companies are Höganäs, Sura Magnets, Callo Sintermetall and Silenco (a fan company) [Lth-nytt, 2006]. Since no other research is going on, on this material [Alaküla M., 2006], Mats Alaküla's research team has more or less been the source of what is written about PBIP in this report.

The two ingredients of PBIP material are metal powder and plastics. The properties for PBIP should be such that electric currents are kept from flowing inside it, while magnetic flux is let through, thus low conductivity and high permeability is aimed for. To achieve these properties, the metal particles in PBIP are surrounded by insulating plastic material. Depending on the shape of the metal particles and the choice of plastic material, the properties of PBIP differ.

For quality reasons, the best way of producing components in this material is to use centrifugal moulding. This means that metal powder and plastic material are mixed together and then exposed to centrifugal force. In this way, the metal particles are better arranged and packed, than if the material was just moulded without the centrifugation. It is important that the material is not too dense, because if the metal particles come in contact with each other, the material would start to conduct electrically.

Opposite to the SMC process, the PBIP does not need to be heated again after the moulding process, because the tensions are not that high, thus at least one process step is eliminated compared to SMC.

The relative permeability of PBIP is in the range of 20-30. This value is considered very low for magnetic flux path applications. This affects the performance negatively, because the magnetic field strength will be lost along the flux paths. The low electric conductivity of PBIP, on the other hand, implies low iron losses, hence the eddy currents are negligible compared to laminated steel at high frequencies.

Because it is a new technique, mapping over the magnetic, electrical, mechanical and thermal properties of different PBIP material has just been started. The aim is to see how different metal particle shapes, plastic material and manufacturing processes affect the PBIP [Alaküla M., 2006].

7.5 Actors

There are five big actors on the iron powder market, where Höganäs AB has the largest market share. The distribution can be seen in Table 18 [Hultman, Nord, 2006].

Table 18 Actors in iron powder technology.

Actor	Market share (%)
Höganäs AB	34
Hoeganaes Corporation	23
QMP	12
KOBELCO	11
JFE	7
Others	13

Out of these actors the only one that has shown motors made of iron powder material is Höganäs. Höganäs, JFE and QMP are the only ones that have a specific powder made for magnetic applications.

8 New motor designs

By using moulding technique, motor constructions with complicated magnetic circuits can be made, while the electric circuits preferably are kept simple. Thereby the complexity of integrating several coils is avoided. The opposite has been applied with the laminated iron constructions, where the magnetic flux is moving in only two dimensions and complicated windings constitute the electric circuits [Alaküla M., 2006].

With isotropic materials a world of new possible motor designs, other than the traditional motor designs, opens up. Alternative motor designs will be described below, starting with the claw-pole motor. The focus in this chapter will be on design and not material. The material aspects in motor construction are considered in Sections 7.2 to 7.4.

8.1 Claw-pole design

In a claw-pole machine each pole is represented by a claw, as the name implies. Claw-pole rotors with slip rings, working together with conventional stators have been used as generators in vehicles for decades. This configuration can yield a significantly higher power density, compared to a conventional motor design, to the cost of a much lower power factor. With new technologies designs, where a claw-pole stator is working together with a PM rotor, might be an alternative in applications where conventional motors are used today. In the claws of a claw-pole stator alternating flux will occur and therefore solid steel claws would yield too much eddy currents. Laminated claws are not an option because of the complex geometries [Tidblad Lundmark S., 2005].

A modelled section of a claw-pole stator for an outer-rotor configuration and the flux path in it can be seen in Figure 40 (although in this particular illustration, one claw could be mistaken for two claws). In the stator winding an AC current, I, is flowing.

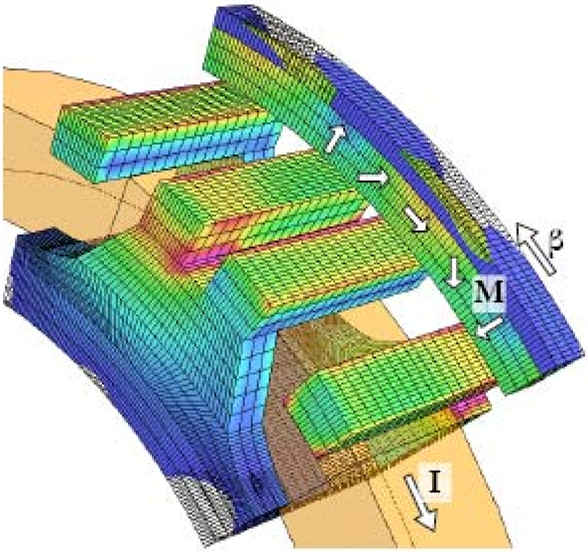

Figure 40. Simulation of magnetic field in a claw-pole motor [Reinap A. et al, 2006]. With permission from Avo Reinap.

The flux induced by the AC current in the stator winding goes up in one claw, into the magnet of the rotor, then down in the next claw, under the winding and then up again. The force for the rotor movement arises because the magnetic field of the rotor wants to align with the magnetic field of the stator. Some of the flux leaks between the claws tangentially through the air. The leakage leads to a low power factor and thereby also a low efficiency. To prevent this leakage, the claws should not be placed too close to each other [Tidblad Lundmark S., 2005].

Since the pole number is independent of conductor area, which is not the case in the conventional motors, the pole number can be high, resulting in a high torque density. The high torque density can be explained by the fact that the distance between the claws is shorter and thereby more force is achieved. Another explanation is that the stator current works over all poles and therefore becomes more utilised by having more poles. However, the leakage between poles limits the pole number. Further more, many poles mean lower speed for the motor, alternatively higher frequency (electrical) [Tidblad Lundmark S, 2006].

The number of phases is increased by adding single-phase claw-pole motors on the shaft in axial direction, thus the length of the motor increases with number of phases [Tidblad Lundmark S., 2005].

8.2 Other transverse flux motor designs (3d design concepts)

There are other so called transverse flux motors (TFMs), in addition to the claw-pole type, see Figure 41.

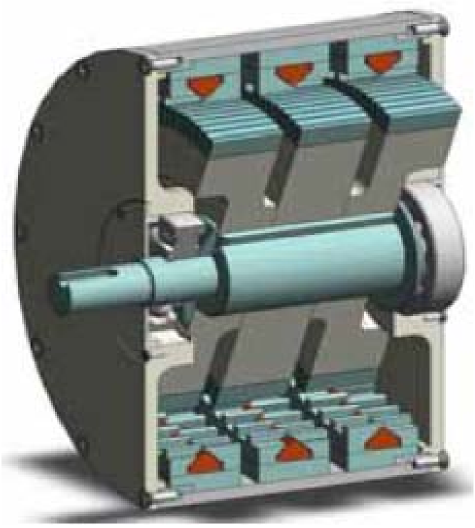

Figure 41. An example of a three-phase TFM for a propeller shaft [Hultman, Nord, 2006]. With permission from Höganäs AB.

The concept of the operation is common for all TFMs, but they are more or less efficient, depending on the design. Possible torque densities of up to five times higher for TFMs (25 Nm/kg has been constructed in SMC in Newcastle and did not need cooling [Hultman, Nord, 2006]), compared to conventional motor designs, have been estimated. The complexity in manufacturing and the low power factor have been the reasons why they are not commercial [Tidblad Lundmark S., 2005].

8.3 Motor design with SMC

SMC can be an alternative to laminated iron. Motors have been known for more than a hundred years. During these years, not much has happened to the motor geometry. An issue to the lasting geometry is that there have not been isotropic materials with properties that are good enough. In the last years, materials have been developed that make it possible to construct motors in new ways [Krogen Ö. et al, 2000].

The applications that suit the SMC material best are motors with a large effective airgap, such as PM motors. The permanent magnets can be seen as airgaps. The flux path permeability will be dominated by the effective airgap, hence the permeability of the SMC is off less importance [Krogen Ö. et al, 2000].

By just replacing the laminated sheets in a traditional motor with SMC, the performance will not be improved, at best the performance will be the same. The advantage lies in that more freedom can be used in the design of the motor and thereby manufacturing of more optimized designs can be done [Krogen Ö. et al, 2000].

The three dimensional freedom makes it possible to have motor designs without sharp corners for the windings. With a rounder tooth, the windings can be wound tighter and smoother to it, compared to the case with laminated constructions, see Figure 42. The impact is that less isolation is needed in corners, compared to laminated steel constructions and also 27% less copper wire is needed, which leads to decreased copper losses. Moreover, the slot fill factor of the copper winding increases from 44 to 66%, due to the winding can be pre-wound. The thermal coupling when using SMC is higher than for laminated constructions, because there is less isolation and the windings have contact the whole way around [Andersson O., 2001, Persson M et al, 2006].

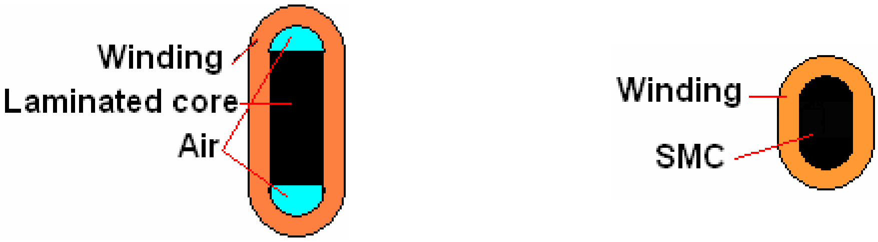

Figure 42. Laminated core and SMC core with same effective core.

An example of using SMC to improve the traditional laminated steel motor technology could be to replace the teeth by rounded SMC teeth. Further, the teeth could be constructed in such a way that pre-wound windings could be used during the assembly [Hultman, Nord, 2006].

The claw-pole motor described in Section 8.1 can also be made in SMC. Two SMC parts and a winding constitute the stator. The winding is first placed inside one SMC part and then the other part is attached [Tidblad Lundmark S., 2005], see Figure 43. The most critical places of the stator bulk considering the mechanical strain are in the claws. The dimensioning of the claws has to be done in such a way that the brittleness of the SMC material is considered [Tidblad Lundmark S., 2005].

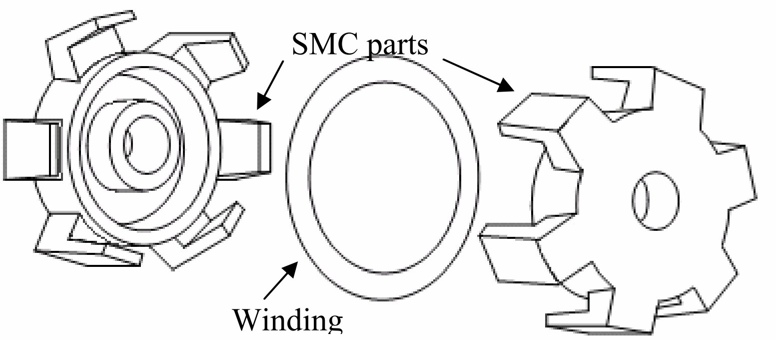

Figure 43. The figure illustrates how the parts are put together to a claw-pole stator with SMC technology.

8.4 Motor design with PBIP

As with SMC, PBIP has the advantage of three dimensional designing for the magnetic flux paths in motor applications. PBIP uses centrifugal moulding, where the three dimensional shapes can be achieved.

For motor component construction with this method, coils can be integrated during the centrifugation. This means that the winding process can be done easily before and then PBIP will adapt to pre-wound windings during the centrifugation. Besides the benefit of an easy winding integration, the fill factor will be better when the coils are not wound in the traditional way. For these windings pre-wound bondable wire, which is heat treated to stay in desired position, is used [Alaküla M., 2006]. A bobbin made out of polyamide is placed outside of the coil. This bobbin, which is reminding of a necklace, separates the claws from each other and keeps the coil in place [Reinap A. et al, 2006]. The thermal connection between the windings and the bulk will be much better than in laminated steel constructions, resulting in the prevention of overheating in the windings when the motor is running [Alaküla M., 2006].

A stator for a claw-pole motor is presented in Figure 44. 3 such stators have been built at Lund University with a pole number of 40 and estimated motor power of 25-30 W. This is for a single-phase outer-rotor configuration. The rotor, which is placed outside the stator, is a simple ring of permanent magnets [Alaküla M., 2006].

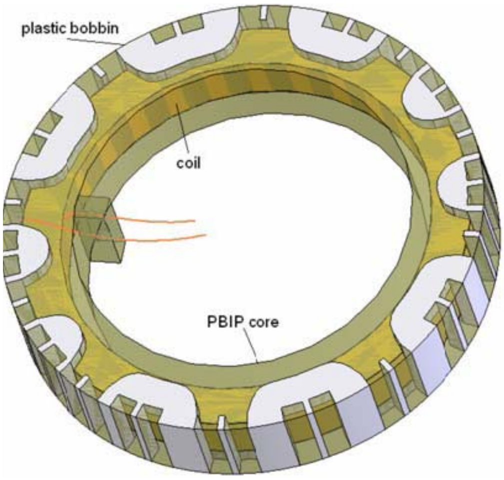

Figure 44. A claw-pole stator, made with PBIP [Reinap A. et al, 2006]. With permission from Avo Reinap.

The particle shapes of the metal powder that were used for the claw-pole stator were irregular. A problem that could occur with these irregular shapes is unsatisfied packing when the material has gone through the centrifugation, but it turned out that the components show good performance [Alaküla M., 2006].

Since the torque of any motor depends on magnetic flux, high permeability in the motor core is aimed for. To compensate for the low permeability of PBIP, the magnetic flux paths are preferably kept as short as possible. This can be done by taking advantage of the design freedom and the good high frequency properties that PBIP offers, which allows a high pole number and therefore shorter paths [Alaküla M., 2006].

A big advantage with PBIP is the manufacturing process of motor components, because there are few and uncomplicated production steps needed for it. The production steps for the outer-rotor claw-pole stator that has been made are the following [Alaküla M., 2006]:

1. The metal powder is mixed with the plastic material and heated.
2. The plastic bobbin, together with the coil is placed inside the mould, against the wall of the inner radius.
3. The hot PBIP mix is poured up in the mould and then the mould is rotated.
4. The component is ready as soon as it is taken out of the mould.

In principle one can say that there is only one production step and that is the centrifugation, number 3 in the list above.

An example that shows that costs and cooling can be reduced is an inductor built with PBIP. The inductor core consisted of PBIP and pre-wound windings were baked in to the core during centrifugation. The mould consisted of two frying pans welded together to achieve a cheap solution for manufacturing. This inductor, was then successfully used as a filter for grid power application. Considering the reduction of cooling equipment and production costs, the savings from using this PBIP inductor instead of the usual inductors can be as much as 50 % in production [Alaküla M., 2006].

In Table 19, differences between laminated steel, SMC and PBIP are shown.

Table 19. Comparison of electric motor constructions.

	Laminated Steel	**SMC**	**PBIP**
Manufacturing steps	Many	Moderate	Few
Permeability	~8000	~700	~20
Degree of freedom	2D	3D	3D

9 New technology for traction motors

In the following subsections the aim is to clarify if the new motor technologies can match the demands, how soon they could be on the market and how the cost would change if these technologies would be used.

9.1 New technologies' ability to match the specifications

The SMC technology has the ability to match all the torque and power demands, although brittleness of the motor could be a problem. One has to consider that the strength of SMC is not as high as it is for laminated steel. The recycling demands can easily be fulfilled with SMC, see Section 7.3. Moreover, contaminations that the motor might be exposed to, such as acids, water, oil etc, is not a problem for SMC, because the iron particles are already coated with an insulator and this together with a treated component surface makes a suitable protection [Hultman, Nord, 2006]. Depending on the construction of the motor, the size of it can both be bigger and smaller than would be the case of a conventional motor.

Also PBIP seems to have no particular problems with the upscaling to a traction motor for heavy vehicles. Whether the volume could be kept reasonably small, considering the low permeability remains to see.

9.2 Time estimation to availability

The SMC technique is available, but there are no motors "to buy" today. The knowledge and idea of how they can be constructed exists. PBIP is at a stage where a patent will be applied for, which indicates that the aim of motor production with this technology exists.

9.3 Cost changes with new motor technology

The price of powder is about twice that of steel sheets. The powder can be even more expensive if better powder quality (better strength) is desired [Hultman L., 2004]. As more and more powder is being produced, the price ratio between steel and powder is expected to decrease [Lindskog P., 2004, Hultman L., 2006].

For motor parts the cost can be decreased if a material as SMC or PBIP is chosen instead. SMC and PBIP are cost competitive materials for high frequencies, because the price for laminated steel increases much when the sheets have to be made thinner. For SMC and PBIP the manufacturing is not frequency dependent.

SMC can be cost competitive if it is possible to make larger and fewer components per motor. There is also the benefit that it is possible to make more efficient designs. The copper windings can also be better utilised and 27% savings in copper cost can be made, see Section 8.3 [Andersson O., 2001]. Tools for manufacturing of SMC parts are in the price range 100 000 SEK [Hultman, Nord, 2006].

PBIP uses the same powder as SMC, but with less manufacturing steps. The fewer manufacturing steps reduces the cost and hence a cheaper product is made for the motor. The potential exists of a 50% reduction in production cost.

The degree of utilization is different for sheets and powder. In powder processes less than 5 % [Hultman Nord, 2006] is wasted during the process, but for the sheets up to 50% can be wasted when products are made [Hultman L., 2006]. If the utilization is low, more transports are needed to support the manufacturer with material and the waste material has to be transported away from the manufacturing plant. SMC and PBIP will save transport costs for the motor producer [Hultman, Nord, 2006].

If the PBIP method is used, there can be reduced cooling, because of the material and the less amount of copper that is used for wiring, which saves money both in cooling equipment and energy consumption. Also with SMC the cooling could be reduced. In the case of the TFM in Section 8.2 it was even removed.

10 Discussion

Two major areas, SiC material for power electronic components and SMC and PBIP material for motors, were investigated. We have mainly focused on if technology shifts are possible and the big differences that the new technologies can contribute with. To get a deeper analysis one has to take a small part of our work e.g. the MOSFET and perform calculations and build a model of it in a converter for hybrid vehicles to see all the details the change would cause.

For both the switching devices and the motor, the possibilities of future cost reductions exist, if the new technologies are found to be preferable for the vehicle industry and large production is performed by many manufacturers. On the other hand, the price could rise if the production is limited to few manufacturers. Standardizations of voltage levels and motor torque and power after developing an optimal solution with the new technologies would contribute to lower costs, as it has been for Si devices and current electrical motors.

Below discussions regarding SiC and electric motors will be treated separately.

10.1 SiC

The effort that was made to collect economical data by contacting companies in the business of SiC technology did not result in any response in most of the cases. Infineon, which has SiC components for sale, did however respond to our questions about their view of component cost. The same view was presented by Toshiba at a conference in Yokohama 23-28 October 2006.

No investigation was done on how the space reduction of the converters would affect the overall picture for the hybrid truck. It would require a master thesis itself to look at changes in plumbing, cooling and position of the converters and the economical effects of them. The economics will also be affected by other factors than entirely material, e.g. number of assembly line workers.

Integration of power electronics on the electric motor with SiC technology is a matter which has not been considered. Obstacles, such as EMI and high temperature, might be problematic to overcome. If it was possible to reduce cables and needed space for the converter a lot could be won, but this area needs further investigation.

Many big companies that we think have development have not been found in articles e.g. Toyota, Fuji and Toshiba etc. A reason for this could be that they do not want to show others how far they have come in their development.

10.2 Electric motors

In this area of the thesis a big problem has been the small number of actors, especially for the PBIP, where only one research group has been found. Even for SMC the source of information has been limited due to few manufacturers of iron powder. Höganäs, JFE and QMP are the only ones that have a specific powder made for magnetic applications, but Höganäs is the only one that has concentrated on motor applications.

PBIP is a new area of technology and no measurements and only a few papers exist. We have searched for information during a long period of time, but the yield has been low.

If a motor of PBIP or SMC would be used in the future a deeper analysis of the impact of the higher pole number need to be investigated, since a higher number of poles needs a higher supply frequency for the same rpm.

To see the total effect from the use of new motor designs, where e.g. cooling and space is considered, demands a closer cooperation with companies like Höganäs. For example how well the TFM, which was built in Newcastle, would be suited in a hybrid vehicle could then be explored.

11 Conclusions

The conclusions of SiC and electric motor technology that has been drawn throughout the thesis will be summarized below.

11.1 SiC

SiC has properties that would make it work in temperatures of up to 600°C. The packaging is limiting the operation temperature today to 175°C. Packaging that can withstand 300-350°C has been developed at a research stage.

The blocking voltage of a SiC component can be ten times higher, compared to an equally large Si component, which makes it more suitable for the automotive industry. In addition, the resistance is lower at voltages over 200V compared to Si.

Schottky diodes are the only commercially available SiC devices today, which are of interest for the high power system of the hybrid trucks. SiC MOSFETs and BJTs are expected to be on the market in 2008.

No reverse recovery exists for the SiC Schottky component, which gives lower losses and less EMI. Keeping the EMI at a low level allows a more dense packing of the converter components.

The switching speed of a converter containing SiC devices can be increased and thereby the passive components can be of lower ratings. Consequently, the converter can be made significantly smaller.

Due to lower losses in the SiC components, less amount of cooling will be needed and consequently reduced cost will be achieved.

The manufacturing of SiC wafers are today more complicated than for Si and the size of the wafers are limited to 4", but the maximum diameter where wafers free from faults can be found is 3", compared to 8" and 12" for Si wafers.

The cost analysis shows that components will be more expensive: for low voltages ~10 times and above 600 V ~6 times for switches and ~3 times for diodes. If 4" wafers could be achieved, the price would almost be half of today’s price. An efficiency increase from 94% to 98% would cost 16500 SEK for the full-bridge DC/DC converter and 14000 SEK for the three-phase inverter, which are given as examples.

Deeper and further work in the area of SiC is strongly recommended, even though the component prices are higher for SiC than Si. Auxiliary devices can be reduced in amount or ratings, which overall can decrease the total cost.

11.2 Electric motors

Due to the lower permeabilities of the metal powder materials (SMC 700, PBIP 20), compared to laminated steel (8000), new innovative designs will be required for the new motor materials to be competitive.

The concept of moulding motors is relatively new and no measurements on motor characteristics have been reported. There are no obvious obstacles to why it would not be possible to build a traction motor, but it is still uncertain how high the power factor and efficiency could be.

Three actors in the field of manufacturing of magnetic metal powder have been found, but only one has shown the ability of producing SMC parts for motors. As for SMC, there is only one research team looking into PBIP technology.

The potential of a lower motor cost exists, due to the fewer manufacturing steps with the moulding technology and up to 27% copper savings can be made.

With a shift towards powder technology the transports of material can be reduced, which would save money and environment.

12 Future work

A deeper investigation of SiC components and their ability to stand up to the expectations would be desirable. For example a simple converter with SiC components could be built and measured.

To try to build high power motors in metal powder material would be of great interest. Simulations can be made, to see if the theoretical results could match the demands for trucks and which design would be of interest.

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Appendix A

A simple calculation shows how the switching losses in a SiC MOSFET can decrease to 1/70 of the switching losses in a Si MOSFET with the same blocking voltage and on-resistance. This can be shown through the steps below, starting with (10).

$$R_{ON,SP} = \frac{V_B^2}{\varepsilon_S \mu_n}\left(\frac{3}{2E_B}\right)^3 , \qquad (10)$$

where $R_{ON,SP}$ is the specific on-resistance, V_B is the breakdown voltage, ε_S is the permittivity, μ_n is the mobility and E_B is the electrical field. If the new values for SiC are used ($E_{B,SiC}$=10 $E_{B,Si}$ and $\mu_{n,SiC}$=0.7 $\mu_{n,Si}$) the $R_{ON,SP}$ becomes:

$$R_{ON,SP,SiC} = \frac{V_B^2}{\varepsilon_S \mu_{n,SiC}}\left(\frac{3}{2E_{B,SiC}}\right)^3 = \frac{V_B^2}{\varepsilon_S 0.7\mu_{n,Si}}\left(\frac{3}{2\cdot 10E_{B,Si}}\right)^3 = \frac{1}{700}R_{ON,SP,Si} \qquad (11)$$

If the blocking voltage and on-resistance should be the same for a SiC MOSFET as for a Si MOSFET, the area of the device has to be changed.

$$R_{ON,SP} = \frac{\rho \cdot l}{A}, \qquad (12)$$

where R is the resistance, A is the area of the device, ρ is the resistivity and l is the length of the device. If the resistance should be equal to a Si MOSFET and ρ and l are constant the only thing that can be changed is A. By making A=1/700 the resistance can be kept the same. The switching losses can now be calculated according to (13).

$$P_{SiC,swlosses} = \frac{1}{3}A_{SiC}\, f\varepsilon E_{C,SiC}V_B = \frac{1}{3}\frac{A_{Si}}{700}\, f\varepsilon 10E_{C,Si}V_B = \frac{1}{70}P_{Si,swlosses} \qquad (13)$$

As seen in (13), switching losses between comparable MOSFETs devices are very low for SiC [Sei-Hyung Ryu et al, 2004].

Appendix B

Cross-sections of diodes and transistors, which have been mentioned in the thesis, are presented here.

Cross-sections of diodes

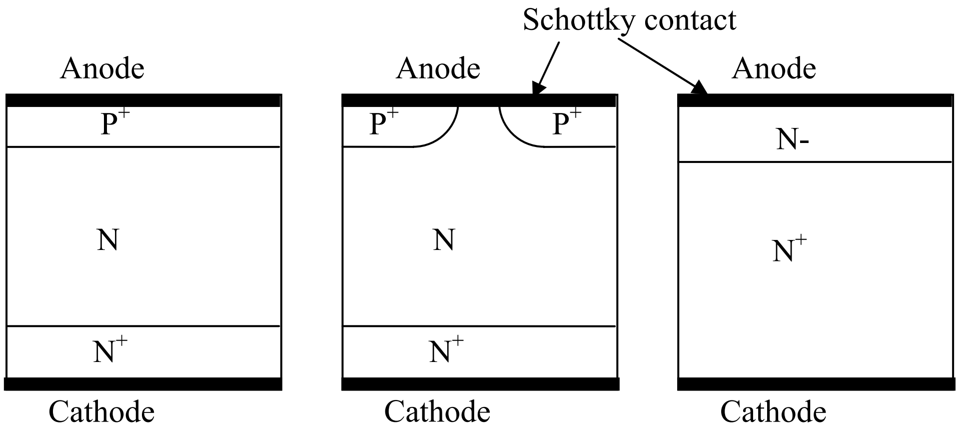

Figure 45. Three different rectifiers. From left: PiN diode, MPS diode and Schottky diode [Baliga B. J., 1996].

Cross-sections of FETs

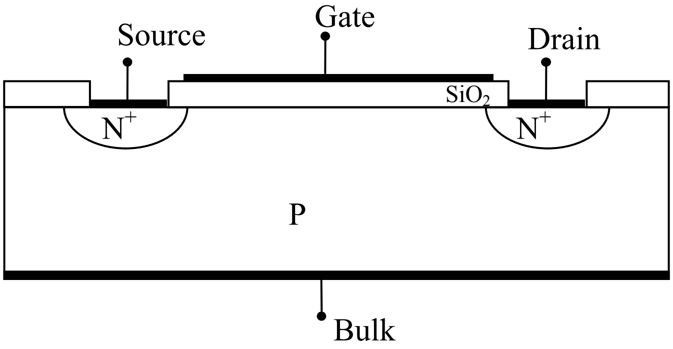

Figure 46. Basic MOSFET.

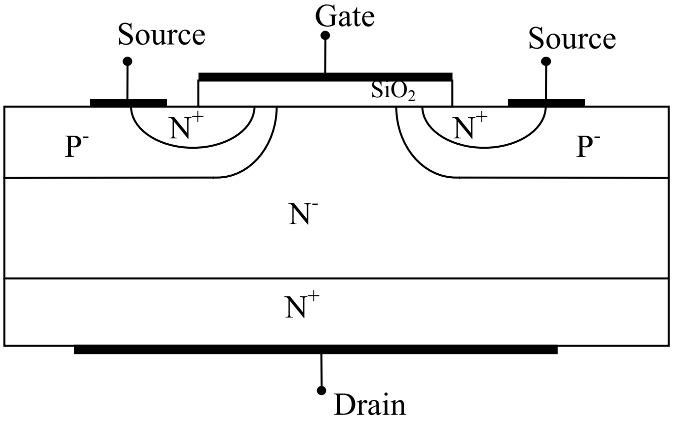

Figure 47. DMOSFET.

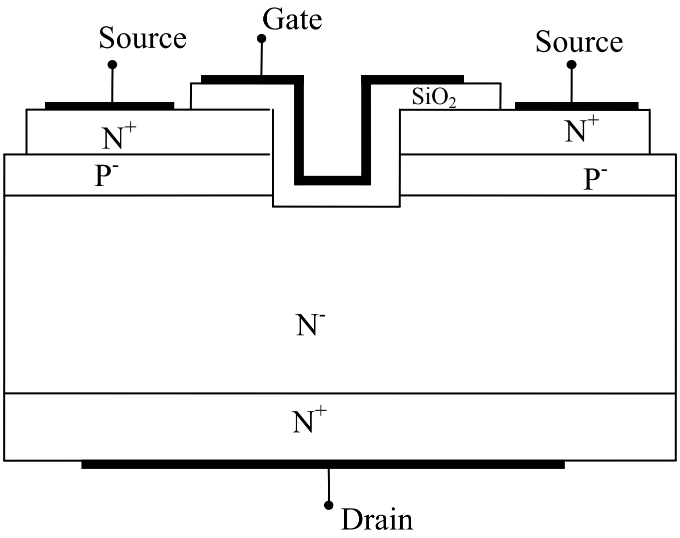

Figure 48. UMOSFET.

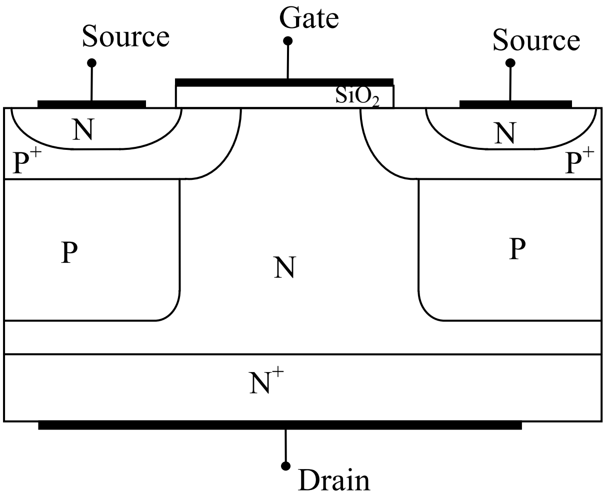

Figure 49. CoolMOS.

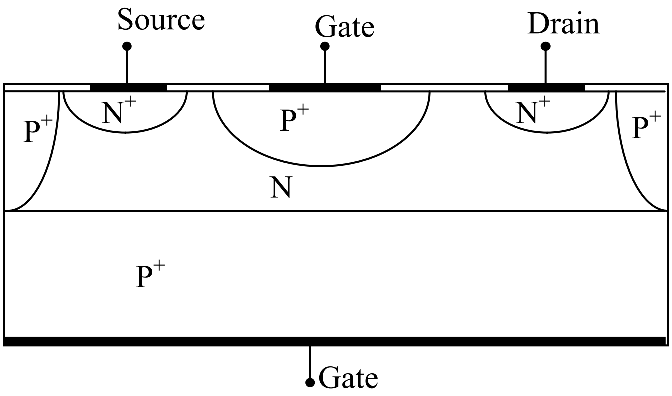

Figure 50. JFET.

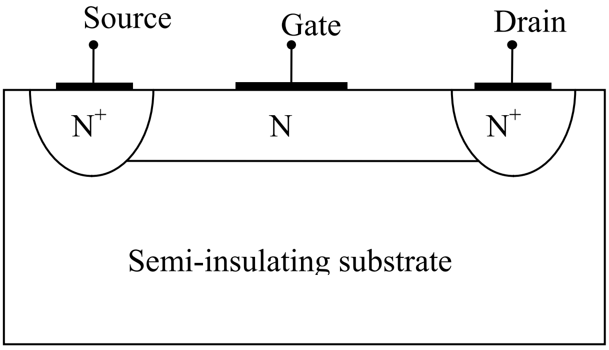

Figure 51. MESFET.

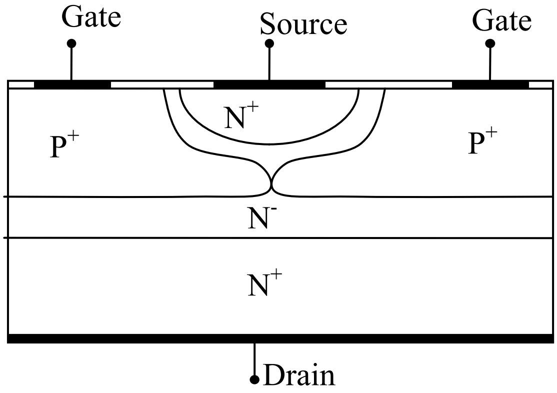

Figure 52. SIT.

Cross-section of a BJT

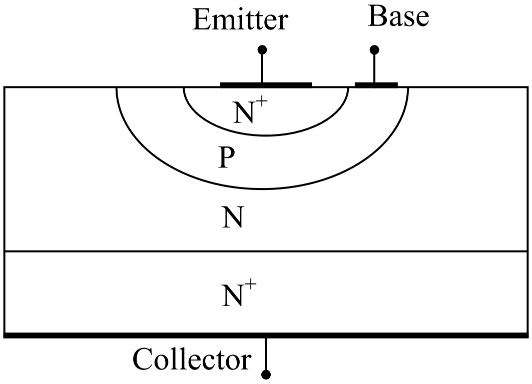

Figure 53. BJT.

Cross-section of an IGBT

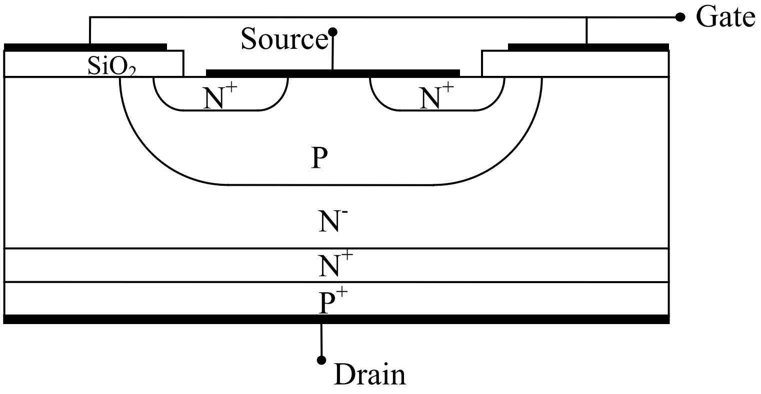

Figure 54. IGBT.