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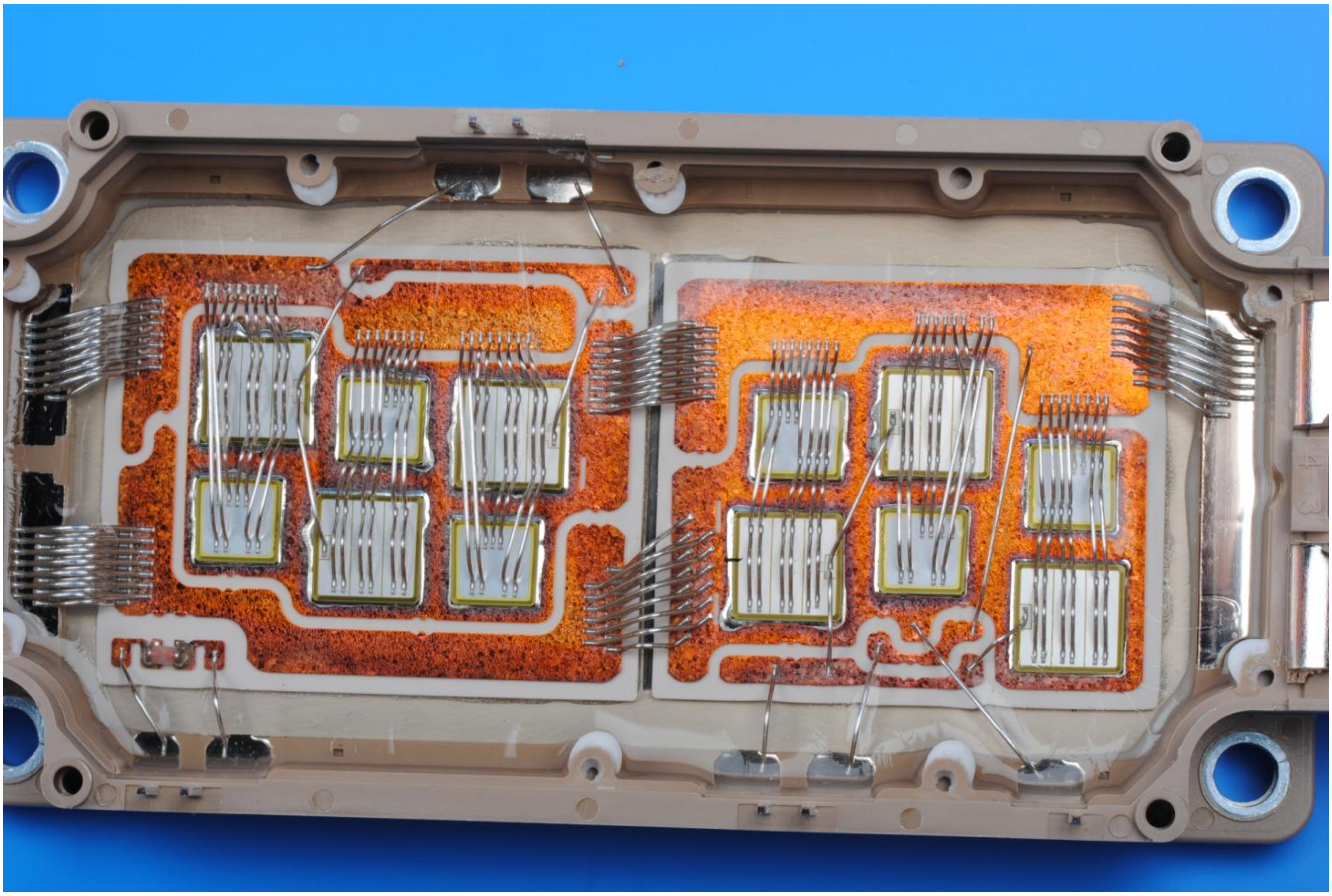

Reliability analysis of power electronics for heavy hybrid vehicle applications

Master Thesis, Electric Power Engineering

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Department of Electric Power Engineering
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2014

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Cover:
Inside of a power electronic module

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Abstract

The purpose of the thesis report is analyze the reliability of power electronics for heavy hybrid vehicles. The failure modes of the power electronics are investigated, along with lifetime analysis with respect to different current levels and compared with the lifetime information provided by the manufacturer. In the power electronics module both the IGBTs and the diodes are tested. The report focuses on active power cycling. Passive cycling is when the test object is thermally cycled from the surrounding temperature and active power cycling is when the test object is heated up by a current, during cool down the current is stopped. The time for heating up is 2 s and the cooling down time is 2 s, generally for short time cycles the bond wire is the major cause of failure, for longer time periods solder delamination becomes a problem.

The tests are done with an on time of 2 seconds, with this time cycle the bond wires are the part most likely to be the cause of failure. The lifetime of the modules varied between 56 000 and 380 000 cycles depending on the temperature swing, ΔT, and if it is a diode or an IGBT. For the highest temperature swing, of both the diode and the IGBT, the result is as expected when compared to the manufacturers lifetime curve. For the other temperature swings the lifetime is longer than expected.

Since it seems that the failure were caused by the bond wires, longer time periods are needed if the test should be done to find when the modules fails because of solder delamination. Also passive cycling should be investigated together with other types of tests such as vibration and chemical tests to investigate if the modules are suitable for operation in a heavy hybrid vehicle.

Keywords: “Power electronics”, “IGBT”, “Diode”, “Active power cycling”, “Vehicle”, “Hybrid”

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The work of this thesis has been performed at Scania in Södertälje. First, I want to thank my supervisor at Scania, Dr. Samer Shisha, and my supervisor in Chalmers, professor Torbjörn Thiringer, for their support and guidance during the project. Furthermore I would like to thank the employees at Scania who have given me advices and ideas during the work. Lastly, I give my thanks to my family and friends who have supported me during the work of the thesis as well as during the rest of my studies.

Martin Strängberg, Södertälje 2014

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Symbols and abbreviations

AC - Altering current

BJT - Bipolar transistor

DBC - Direct bonded copper

DC - Direct current

GTO - Gate turn off thyristor

IGBT - Insulated gate bipolar transistor

MOSFET - Metal-oxide-semiconductor field effect transistor

PE - Power electronic

1. Introduction

1.1. Background

The need for environmental friendly energy is increasing since the temperature on earth is increasing due to greenhouse gases [1]. The transportation sector uses large quantities of energy every year, most vehicles are using fossil fuel, for trucks and buses, diesel is the most common fuel. Since fossil fuels produce greenhouse gases, many companies within the transportation industry focus on introducing electric motors in their vehicles, either as hybrid or as fully electric vehicles. Electric motors are in general more efficient than combustion engines and the electricity could be produced from sources with very low CO_2-pollution.

Except from greenhouse gases, fossil fuel emissions have other effects on human health, which may lead to cancer and heart- and lung-dieses [2]. Also the noise from traffic may cause stress. Hybrid and/or electric vehicles are a way to reduce these negative factors on human health, for example a bus which charge the batteries when breaking for a bus stop reduces the noise pollution as well as the air pollution.

1.2. Challange description

Also truck and bus companies are now looking into hybridisation and electrification of their vehicles. Since this is a relatively new technology for the industry, the electrical components needs to be tested in order to ensure reliability. Electric motors are also more quiet than combustion engines, hence a vehicle with an electric motor emits less noise in cities. Hybrids, or electric vehicles, can also regenerate when braking the vehicle, which reduces the fuel consumption and is more economical.

This thesis focuses on the power electronic modules including IGBT and diode chips. Power electronics are used in the inverter between the battery and the motor in a hybrid electric or pure electric vehicle. Since batteries are direct current (DC) sources and electric motors are often of altering current (AC) type, then some conversion of the voltage is needed. When the vehicle brakes, the power can be regenerated and charge the battery, the power electronics convert the energy from AC to DC. The power electronic modules have both IGBT chips and diode chips, the diode chips are anti parallel to the IGBT chips and are used for AC-DC conversion. The IGBT chips are used for the AC-DC conversion.

Knowing the approximate lifetime is important when dimensioning the electrical drivetrain. Also the industry needs to establish test methods for this new application area of power electronics, ensuring the components to have the expected reliability and quality.

1.3. Aim

The purpose of the thesis is to analyze the reliability of power electronics for heavy hybrid vehicles. Theoretical determination of lifetime based on Wöhler curves is to be done. In addition the expected lifetime is given from the test results and the failure modes evaluated.

1.4. Scope

This thesis will focus on the reliability of power electronics that is suitable for heavy hybrid vehicle applications, the voltage range is roughly 500 – 1000 V and the current is in the range of 200-600 A. For this power level, IGBTs are most suited and therefore these will be the only type of semiconductor for DC-AC conversion that is investigated. Since AC-DC conversion is common for electric vehicles diodes will also be investigated. Environmental tests that can affect the power electronics, for example vibrations and chemicals, will not be included within the scope of this thesis. The gate driver and the control will not be taken into account, it is only the IGBT-module itself that will be investigated.

Wöhler curves based on the test result for the diodes and the IGBTs are given. The expected lifetime can be approximated depending on the condition. The reason for not having several curves with different mean temperatures for IGBTs respectively diodes is time limit. Test equipment can not handle more current than the rated current of the IGBT-module. However, it would be possible to have smaller temperature swings but then the test would take too long time.

2. Theory

This chapter will give the necessary introduction to insulated gate bipolar transistor (IGBT) modules. An IGBT is a semiconductor which can be explained as a combination of bipolar junction transistor (BJT), metal-oxide-semiconductor field effect transistor (MOSFET) and gate turn off thyristor (GTO). The switching time as well as on-state losses of an IGBT is between a comparable BJT and MOSFET, IGBTs can also blocks negative voltages like GTOs[3]. The nomenclature and figures are modifications from MOSFETs and BJTs, the positive connector is called collector and the negative connector is called emitter, like a BJT.

2.1.Pn junction

Silicon atoms have four valence electrons and four more is needed to fill the shell. Semiconductors with pure silicon is called intrinstic semiconductors. In room temperature some electrons are broken from their atom by the thermal energy and move around as free electrons. As an electron breaks away from the atom, an empty spot is created, known as hole, and another electron may connect to it. The free electrons are needed for the semiconductor to conduct current. However, intrinstic semiconductors cannot conduct current very well. To improve the property, the semiconductor is doped. A semiconductor can be doped, either n-doped or p-doped. A semiconductor that is n-doped, is doped with atoms with five valence electrons, which results in free electrons. P-doped semiconductors are doped with atoms with three valence electrons, which results in extra holes.

The doping of semiconductors can also be done with a high or low concentration of the doping atoms. High concentrations are refered to as $^{+}$ and low concentration as $^{-}$, for example a semiconductor with high concentration of n-doping is refered to as n^{+} and a semiconductor with low concentraion of p-doping as p^{-}.

In semiconductors two processes results in a current, drift and diffusion. The drift current is caused by an electric field over the semiconductor, forcing the holes and free electrons to move, thus creating a current. The diffusion current is caused by concentration differences of the semiconductor. For a pn-junction there is a barrier voltage between the p- and n-layer. The barrier voltage comes from the different potentials of the p- and n-layer.

For a pn junction the drift current and diffusion current have equal magnitude but opposite direction when no current is applied. When a forward bias voltage is applied, the barrier voltage is decreased and the drift current increases, the drift current becomes much bigger than the diffusion current and a current flows through the device. If a reverse current is applied, the barrier voltage increases and the drift current decreases and becomes smaller than the diffusion current. However, since the diffusion current is very small, no significant current will flow through the device, the current is simplied seen as zero for this case [4].

2.2. The Chips

2.2.1. IGBT chip

The IGBT have the same silicone structure as a MOSFET and BJT but with an extra p^{+} layer next to the drain/collector for a n-channel IGBT, as can be seen in Figure 1.

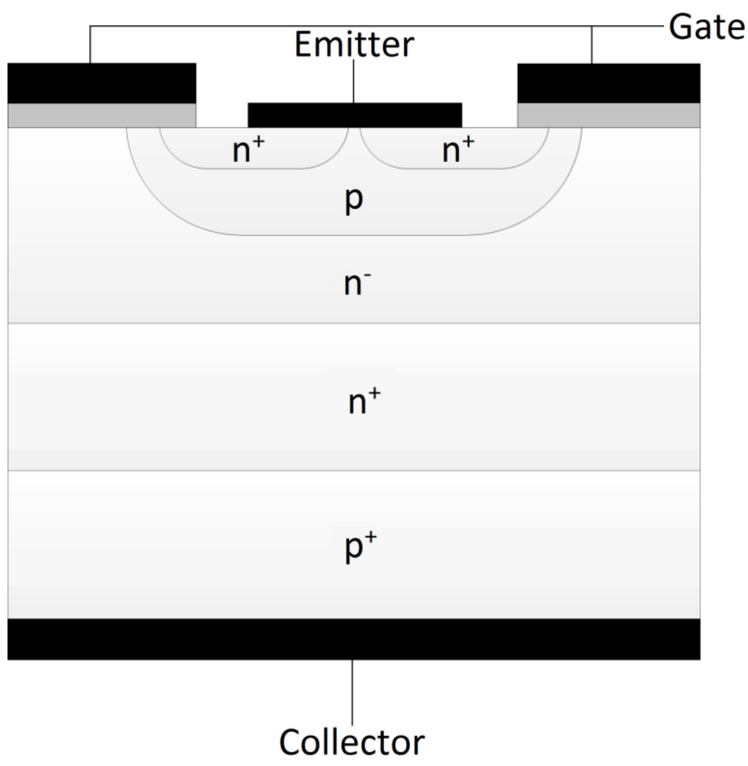


Figure 1: The semiconductor layers in an IGBT chip [3].

Just like the MOSFET an inversion layer is formed between the n^- and the n^+ layer when the voltage over the gate and emitter is higher than the threshold voltage. When the inversion layer is formed a current can flow from the collector to the emitter. When the gate-emitter voltage is lower than the threshold voltage the device is in off state, no current, except for a small leakage current, is flowing through the IGBT [3].

When the IGBT is in on-state there is a voltage drop over the device where one part comes from the voltage drop of a pn-junction and one part from the resistance of the channel in the chip. There is also a voltage drop caused in the drift layer, but it is less than in the MOSFET and if the IGBT is of the punch-through type, the voltage drop in the drift layer is even smaller. A punch-trough device has its depletion layer expanding all over the drift region and when the complete depletion layer have been expanded into, the electric field flattens out. For non punch-trough devices the depletion layer is not completely expanded. Punch-through phenomeon is more common for devices with short depletion layers [3].

2.2.2. Power diode chip

The power diode works like a regular diode, but it is adapted for high power levels. In Figure 2 it can be seen that a n^- layer is added to the regular diode which only have one p and one n layer. The width of the n^- layer is depending on what voltage level the diode is operating at, a thicker layer can handle higher voltage. The current goes into the anode and exits trough the cathode. Also the diodes can be punch-trough or non punch-trough [3].

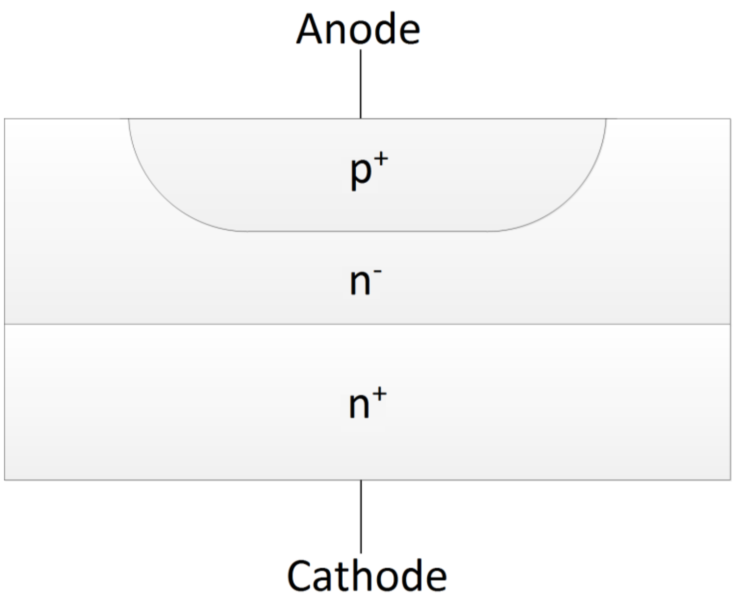


Figure 2: The semiconductor layers in a power diode chip.

2.3.PE module

In a power electronic (PE) module for motor drive at least one IGBT and diode chip is needed. Motors are inductive and the current and voltage will not be in phase, therefore the diode is needed as a freewheel diode. If the load was purely resistive a diode chip would not be needed for creating a three phase voltage from a DC voltage (inverter). If the operation for a purely resistive load requires three phase voltage to be converted to DC voltage (converter) an anti-parallel diode to each IGBT is needed.

A PE module for inverter operation can either have three legs in it or one leg, three legs are needed to produce a three-phase AC voltage. One leg is also called half bridge where the middle point is the AC-terminal. For this project, the modules also have anti-parallel diodes. Figure 3 shows one half bridge.

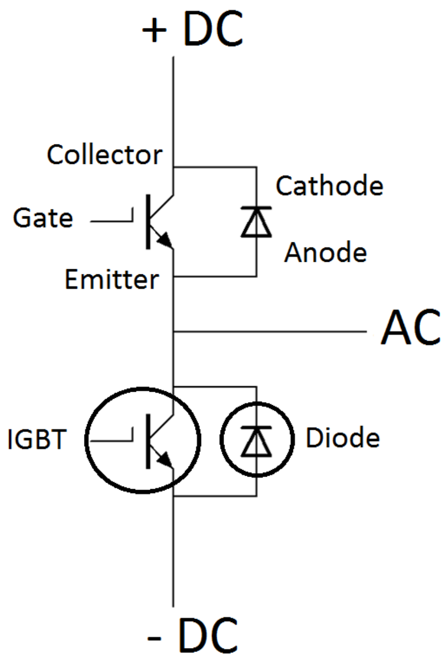


Figure 3: One phase leg of an IGBT.

Each IGBT can consist of several IGBT-chips that are parallel connected. All IGBT-chips are connected to the same gate, switching at the same time. The chip is connected with several bond wires on the emitter and soldered/sintered on the collector. Also the anti-parallel diode can consist of several chips, which are, as the name indicates, connected parallel with the IGBT but in the opposite direction, hence the diode conducts in the opposite direction than the IGBT.

An actual PE module can be seen in Figure 4. The IGBT and diode chips are soldered on top of a layer of direct bonded copper (DBC), which is connected to a DBC insulator. Under the DBC insulator another layer of DBC copper is connected. The connection between the insulator and the copper is made at a temperature over 1000°C where the copper bonds to the insulator with a copper oxide eutectic. The insulator is usually made of Al_2O_3 but could also be made of AlN. The bottom layer of the DBC copper is flat and solid while the top layer of the DBC copper, where the current flows, is etched out hence the current is forced to pass by the diode or IGBT. The top copper layer is isolated from the bottom copper layer with the DBC layer [5].

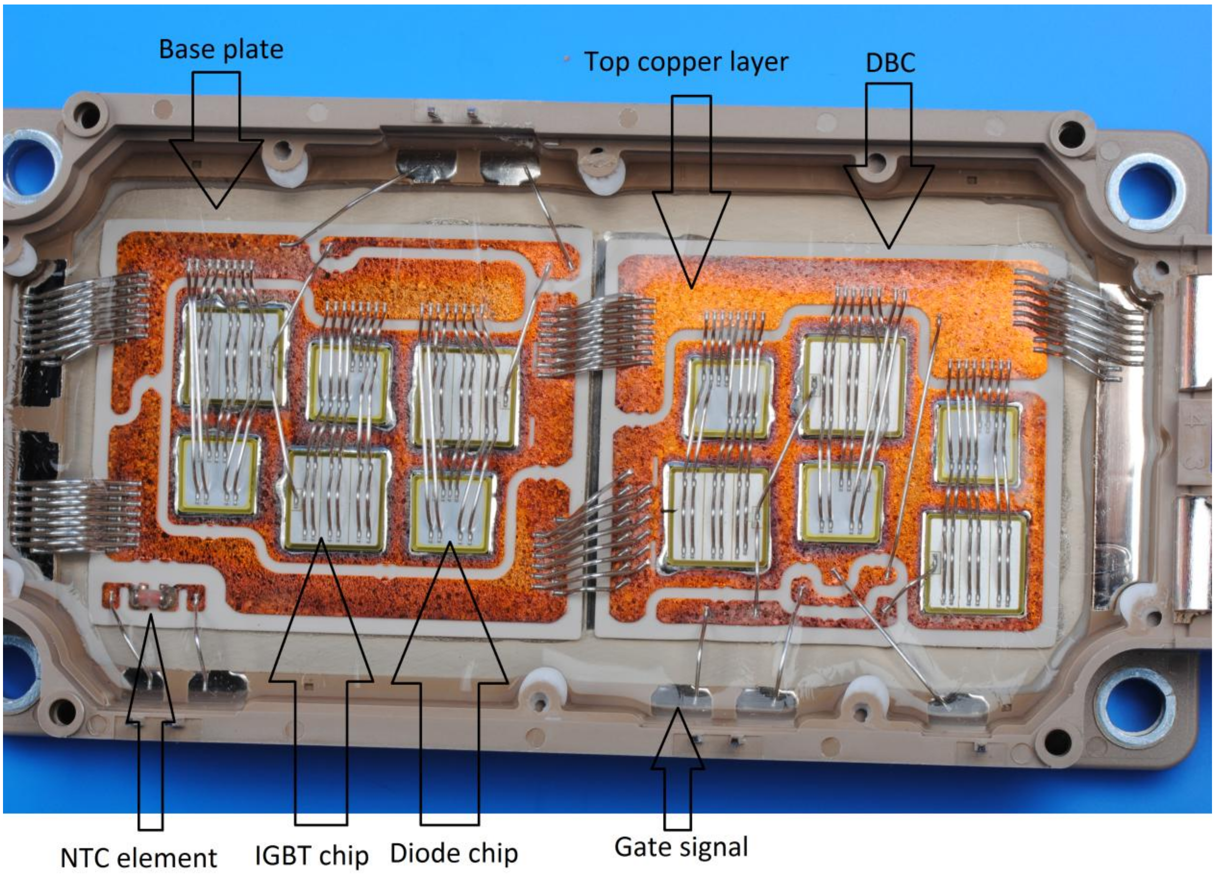


Figure 4: A PE module with three chips for each diode and IGBT.

For some PE modules the chip is not soldered on the DBC but sintered. For sintered modules, silver powder is placed between the DBC and the chip, the connection is then heated up and pressed together [6].

The DBC can be soldered to a base plate, which in turn is placed and pressed to a heat sink with a thermal interface paste that fills small pockets of air which increase the thermal resistance [5]. Some manufacturers do not use a base plate, hence the bottom layer of the copper is placed directly to the heat sink [6]. If no base plate is used, the issue with reduced lifetime related to solder delamination between the bottom layer of the copper and the base plate is eliminated.

To protect against moisture and dust accumulating on top of the copper, bond wires and surface of the chip, the whole module is covered in a thick layer of silicone.

In Figure 5 the sectional image of a PE module can be seen, to make the overview easier the thickness or the relation between the layers is not representing an actual module.

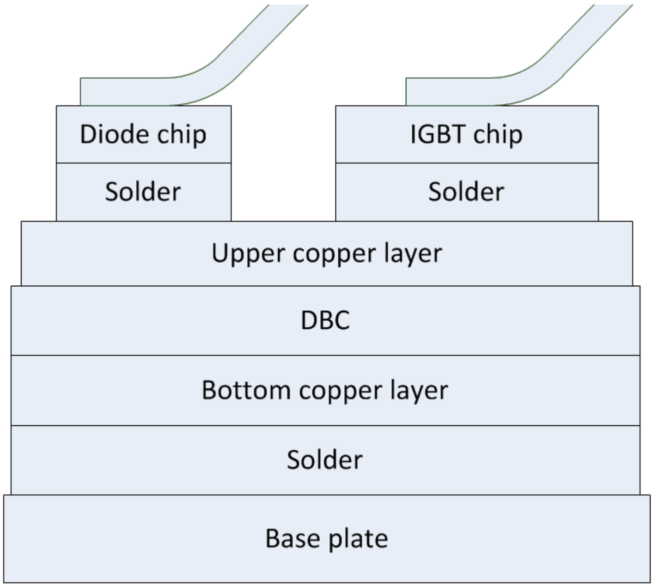


Figure 5: A sectional image of a PE module.

In Table 1 the different properties of common materials in PE modules can be found. It can be seen that silver sinter has a thermal expansion coefficient that is closer to copper and silicone than to regular solder, which means that there are less stresses between the materials as they expand and contract. Silver sinter also have higher thermal conductivity, hence more heat can pass through the material. Also AlN have much higher thermal conductivity than Al_2O_3, but it is placed between the two copper layers which have a thermal expansion coefficient which is a bit closer to Al_2O_3. However, the thermal expansion between the DBC and the copper layers attached to it is not a problem compared with the solder layers and bond wires, for that matter choosing AlN instead of Al_2O_3 is a question of maximizing the heat conduction. The reason why manufacturers uses Al_2O_3 over AlN is that Al_2O_3 is cheaper than AlN.

Table 1: Some properties for common materials in PE modules [7], [8], [9].

Material	Thermal expansion coefficient 10^{-6}/K	Thermal conductivity W/(mK)	Specific heat capacity J/(gK)	Density ρ g/(cm3)
Silicon	2,5	170	0,707	2,33
Copper	16,8	400	0,385	8,96
Al_2O_3 (DBC)	6,7	27	0,88	3,8
AlN (DBC)	4,5	190	0,74	3,3
AlSiC (base plate)	7	200	0,75	3
Aluminium	23,2	238	0,903	2,7
Solder (Sn 60 Pb 40)	24	50	0,15	8,5
Solder (Sn Ag base)	28	70	0,14	8,4
Silver sinter	19	250	0,23	8,5

2.4. Literature study

2.4.1. Power cycling

Power cycling of IGBTs is widely published. The common method is to carry out the cycling using DC current, rather than pulse width modulation (PWM). This might sound strange because the application in field will most likely be PWM. But the desired effect by power cycling is to perform thermal cycling of the module internally which can be done using a DC current.

For PWM testing, a PWM signal is fed to the driver which creates the proper signal to turn on/off the IGBTs in the module. For this, the gate resistors of the IGBT drive has to be chosen more properly, since the switching losses will be a bigger part of the total losses. The gate resistor is located on the gate driver and choosen to reach an optimal time constant of the IGBT [3]. This PWM signal is fed for a time, t_{on}, then it stops for a time, t_{off}, during the off time the temperature is decreasing to the starting temperature. Then the cycle is repeated until a failure is detected. This method can be used to achieve the same temperature swings as DC power cycling. The failure reason with the PWM signal was solder delamination, however, due to the relatively long cycle time, which can result in solder delamination it can not be determined if the solder delamination comes from the PWM cycling or the cycle time [10].

The DC power cycling performed as follows: An on signal is sent to the IGBT which forces the module to start conducting. After a certain time an off signal is sent and the IGBT stops conducting and the cooling down starts. The cycle time for the device can be chosen in different ways. The minimum on time that can be chosen is the time it takes for the junction temperature to reach the desired temperature swing, the off time may then be chosen so there is enough time for the temperature to decrease down to its starting value. If the test is made to detect other failure mechanisms such as assembly failure modes, longer times should be chosen [11].

Table 2: According to reports in the area the following on and off times during power cycling are given.

T_{on} (s)	T_{off} (s)	Time for 100 000 cycles	Reference
10	20	34,7 days	[10]
15	30	52,1 days	[11]
23	35	67,1 days	[12]
0,6 – 4,8	0,4 - 5	1,2 – 11,3 days	[13]
2,5 - 5	-		[14]

Table 2 shows the t_{on} and t_{off} times for a few reports in the area of active power cycling. For the last entry no t_{off} time is given [14]. For the last two cases in Table 2 it was different cycle times for different temperature swings [13]. The case with t_{on} 10 s and t_{off} 20 s is for a test when the on time were PWM-cycled [10]. For each of the different cases the time for a test with 100 000 cycles are presented, it can be seen that cycle times over 10-20 s take a long time, beyond what can be accepted for this project. The case with 23 s t_{on} and 35 s t_{off} are using significantly higher ΔT and as a consequence of that the number of cycles before failure were in the range of 1000 – 5000 cycles [12].

Bond wire fatigue has been the main reason for short power cycles in older technology IGBTs, but there have been improvements in the bond wire design, which have increased the needed t_{on} time for bond wire issues. Furthermore the implementation of RoHS forces the solder to be lead free. With lead free solder, the t_{on} time for solder delamination issues have decreased. These changes have moved the t_{on} times for solder layer delamination and bond wire fatigue issues closer to each other [14].

For the test with t_{on} between 2,5 s and 5 s, the bond wire is the biggest issue. The analysis shows that the welding between the bond wire and the aluminium metallization is not causing failure, rather it is the characteristics of the bond wire that causes cracks. The cracks are not in the joint between the bond wire and the chip surface but in the bond wire itself. Some solder delamination can be seen on the edges of the chip [14].

One way to speed up test time is to use thermoelectric coolers. Based on the Peltier effect, to remove heat from the heatsink during cool down. During heating up the thermoelectric coolers moves heat towards the heatsink [15]. The test described by [15] used a Peltier cooler and DC power cycling. During the on phase, the IGBT was conducting and the thermoelectric element heated the IGBT until the junction temperature reached the target temperature. Then the IGBT is turned off and the cooler removes heat from the IGBT until the minimum temperature limit is reached. With this method each cycle takes a long time, about a minute, but since the ΔT becomes as high as 150°C, the number of cycles becomes relatively few. Hence, the total test time is still reasonable [12].

In [16] a lifetime estimation of the PE modules is modelled. The base plate temperature is measured on the edge and this temperature was related to the target junction temperature using (1). During the test, current flows through the module when being heated and stopped when cooling down. The water flow is also cycled, it is turned off during t_{on} and on during t_{off}. The lack of cooling during heating up reduces the time for heating up the device. The cycle time used is 30 s in the beginning of the test. The definition of a module end of life is 20 % increase of the junction temperature, but the test was continued until the module failed completely. It is stated that a slow increase of the collector/emitter voltage is related to solder delamination and a quick increase of this voltage is due to bond wire lift off [16]

$$T_j = T_c + R_{th}P \tag{1}$$

where T_j is the junction temperature, T_c the case temperature, R_{th} the thermal resistance and P the power losses.

Different manufacturers have different definitions of when the end of the lifetime has been reached. Fuji electric have specified that the module reaches its end of life when the tested component becomes an open end or a short circuit [17]. Other definitions are 5 % increase of voltage or 20 % increase of voltage. Semikron has several definitions of end of life for the semiconductor, 20 % increase of collector-emitter voltage, 20 % increase or decrease of threshold voltage and 100 % increase of the gate leakage current, if any of these parameters is reached the module is considered to have failed.

2.4.2. What parameters have effect on lifetime

Chip size is one factor that affects the lifetime, in [18] it is stated that a decrease of the chip size reduce the lifetime of the module. For a smaller chip the thermal resistance becomes higher and the temperature increases more than for a bigger chip. An increase of the chip size leads to bigger modules and higher cost [18].

The bond wire is critical for the lifetime even the shape of the bond wire can affect the lifetime. A group of researchers [19] made a test bench to determine how the shape of the bond wire effects the lifetime. In Figure 7 a schematic view of a bond wire can be seen. As the ratio of the height to width of the bond wire increases, the lifetime becomes longer. For a ratio at 0,15 the lifetime is about 100 000 cycles, when the ratio is 0,3 the lifetime increases drastically to 5 000 000 cycles. The difference in lifetime is explained by the fact that the radius at the joint between the bond wire and the chip and the radius at the top of the bond wire is exposed for plastic strains. These stresses of the bond wire results in heel cracks [19].

The shape of the bond wires in Fuji 2MBI300VN-120-50, which is the one used in this report, can be seen in Figure 6, for other modules the width and height of can be different. The ratio of the width to height of the bond wire is a factor that determines how the bond wire suffers from heel cracks.

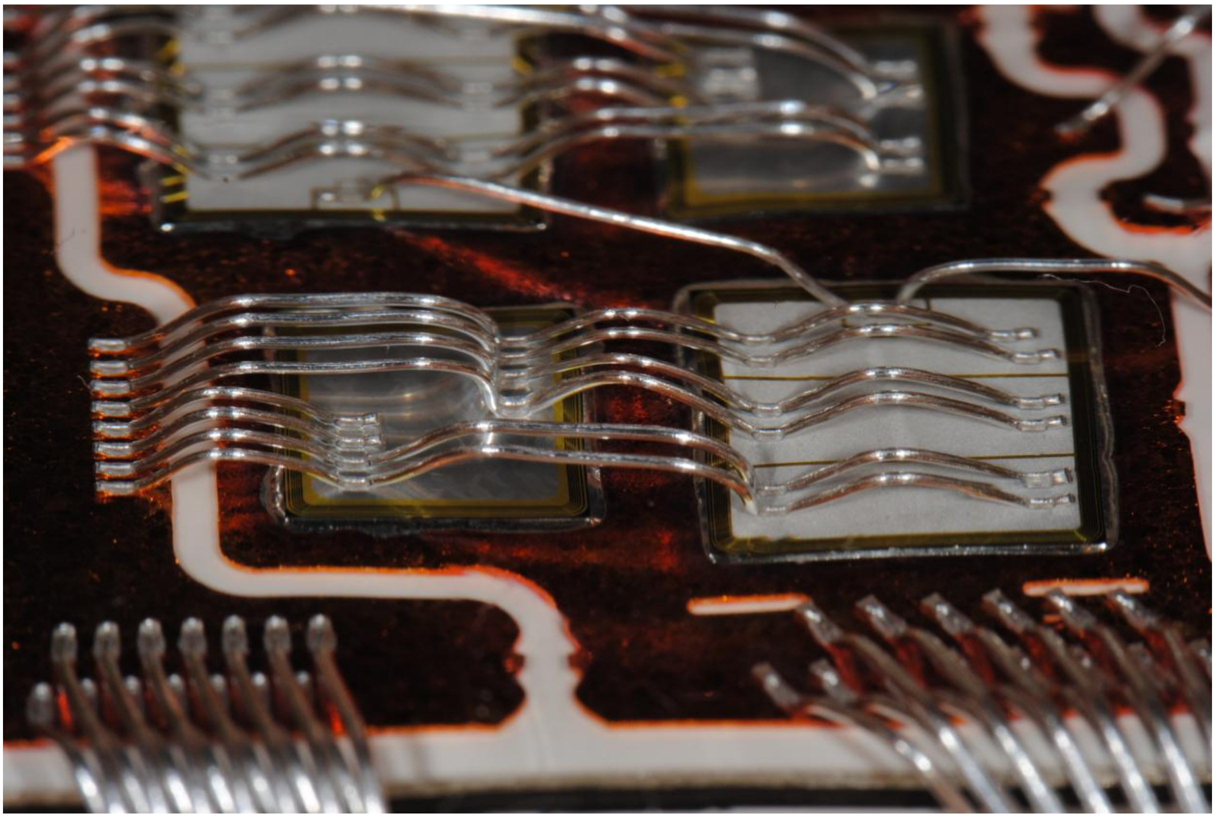


Figure 6: The bond wires to the diode and IGBT of Fuji 2MBI300VN-120-50.

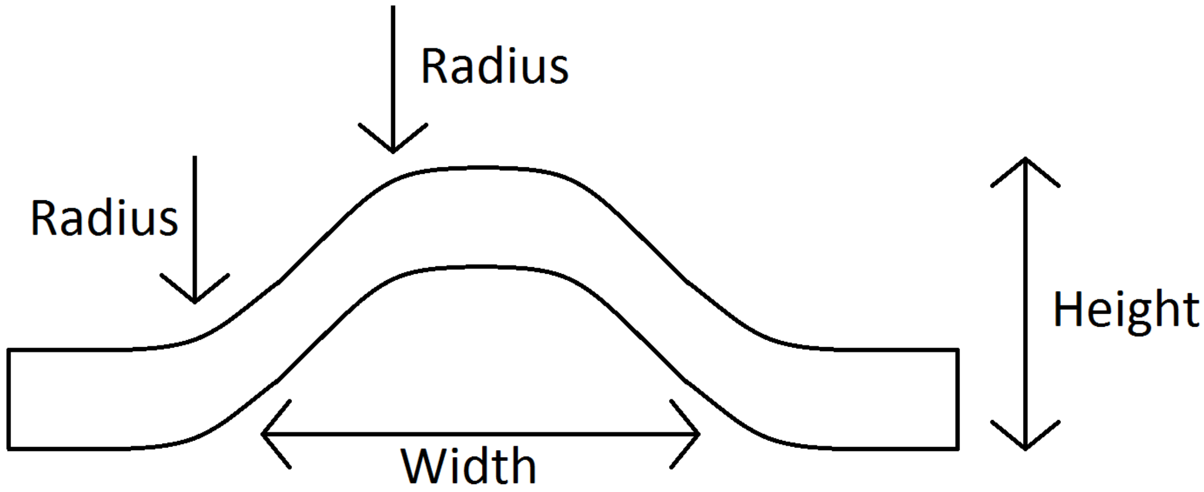


Figure 7: Schematic view of a bond wire.

Furthermore in [20] an Arrhenius equation based on an empirical approach is presented. The result is based on several different PE modules

$$N = K\Delta T^{\beta_1} e^{\frac{\beta_2}{T_{j,max}+273}} {t_{on}}^{\beta_3} I^{\beta_4} V^{\beta_5} D^{\beta_6} \tag{2}$$

the values for β_x, based on empirical results from different modules, are as suggested in Table 4 according to [20].

The physical meaning of the symbols in (2) can be seen in Table 3.

Table 3: Explaining of the abbreviation in Arrhenius equation for the lifetime.

Abbreviation in (2)	The physical meaning of the abbreviation
N	Number of samples before reaching the end of life
K	Constant
ΔT	Temperature difference
$T_{j,max}$	Maximum junction temperature
t_{on}	On time for each cycle
I	Current per bond wire
V	Blocking voltage of the module
D	Diameter of the bond wire

However the factors are not completely independent of each other, especially current and temperature difference is affected by each other, assuming the cooling of the module is not changing [20]. Since the data is collected over the years from different modules it is not sure it will fit the IGBTs today. It is more to be see how important the different parameters are and indicate how the number of cycles change if one parameter is changed, than calculating the actual number of cycles.

Table 4: Parameters for lifetime of IGBT

β_1	β_2	β_3	β_4	β_5	β_6
-3,483	1917	-0,438	-0,717	-0,751	-0,564

The physical reason why t_{on} is effecting the lifetime is due to the way that the temperature profile of the chip is affected by the thermal time cycle. For long t_{on} times the junction temperature spreads out over the chip, thus the temperature gradient becomes higher than for shorter t_{on} times. The current that flows in the chip is a factor, part of it because a higher current results in higher junction temperature but also it gives extra heat in the joint between the bond wire and the metallization on the chip. The chip with high blocking voltage is thicker than a chip with low blocking voltage, regarding the lifetime it is actually an advantage of a thinner chip. The reason for this comes from lower thermal expansion for thin chips because they, to some extent, follow the expansion of the wires and the solder [20].

The wire diameter was found to preferable being small, it may sound strange as a smaller diameter would increase resistance and the stresses in the wire itself might increase by this, but it has to do with the same factor as the thickness of the chip. A thicker bond wire will have bigger area to the chip and this will result in a bigger difference of the thermal expansion. There is a lower limit for how small the bond wire can be, the bond wires to the chip needs to be thick enough to carry the current that the chip is rated for [20].

The dependency on ΔT is strong and it comes from the thermal expansion, since a higher thermal gradient expand more than a small temperature gradient the stresses of the expanding material becomes higher and the lifetime shorter for higher ΔT [20].

In Figure 8 Fuji electric's lifetime curve can be seen for the module that is used in the work done for this report. The manufacturer has tested both diodes and IGBTs at the same time and the failure criteria is when the module becomes open or short. Since both the diode and the IGBT were tested at the same time, the lifetime curve is valid for both types of chips according to the manufacturer [17]. The lifetime curve gives an estimation of how many cycles are needed for each test for any ΔT. For the lifetime test Fuji used 2 s t_{on} and 18 s t_{off} [17].

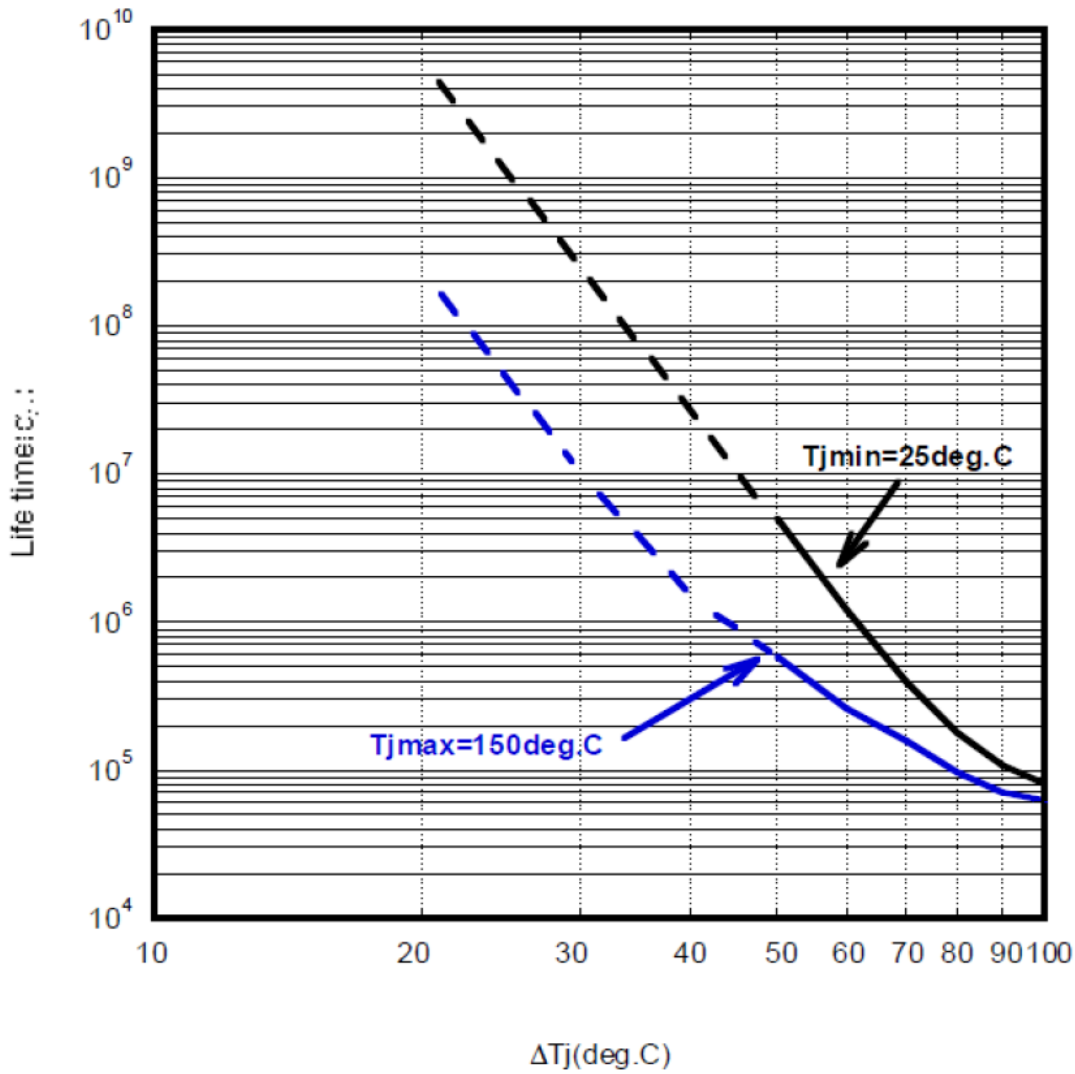


Figure 8: The lifetime for different ΔT_j from datasheet to Fuji 2MBI300VN-120-50 [17].

2.5. Temperature increase of a PE module

Since the lifetime of the IGBT largely depend on the temperature difference it is important to know how much the IGBT-chip is heated up and how well the power is transported to the other layers and eventually out of the module to the heat sink, if the thermal conductivity is high, the temperature does not need to increase much for the power to be transported out. To choose a proper cycling time also the time response of the module must be known.

The thermal conductivity, λ in W/(mK), is used together with the area of the chip, A in m^2, and the thickness of the material, l in m, in (3) to get the thermal resistance $R_{th,i}$ in K/W [7]

$$R_{th,i} = \frac{l}{\lambda A} \qquad (3)$$

Since there is a thermal resistance in each layers, this is calculated for each layer separately and than they are added together,

$$R_{th} = R_{th,1} + R_{th,2} \dots + R_{th,i} \tag{4}$$

to get the total thermal resistance of the system [7]. This value simply tells how much the temperature is increasing for each Watt of losses in the chip.

To choose a proper cycle time, the temperature rise of each layer must be known. The specific thermal capacitance in J/K is given as

$$C_{th,i} = Cm \tag{5}$$

where C is the thermal capacitance in J/(kgK) and m is the weight in kg [7]. The thermal capacitance is a specified value for each material which can be seen in Table 1.

The thermal resistance and the thermal capacitance can be used together to get a result of how much and how fast the temperature increases for a layer,

$$T_i = T_{i-1} + \frac{t_s}{C_{th}}\left(P - \frac{T_{i-1} - T_{a,i-1}}{R_{th}}\right) \tag{6}$$

where t_s is the sample time, T_i is the temperature for this sample, T_{i-1} is the temperature for the previous sample and $T_{a,i-1}$ is the ambient temperature for the previous sample. C_{th} is the thermal capacitance, R_{th} is the thermal resistance and P is the power losses.

Figure 9 shows the thermal capacitances and resistances in the system. The thermal capacitance and resistance for a layer can also be combined to Z_{th}.

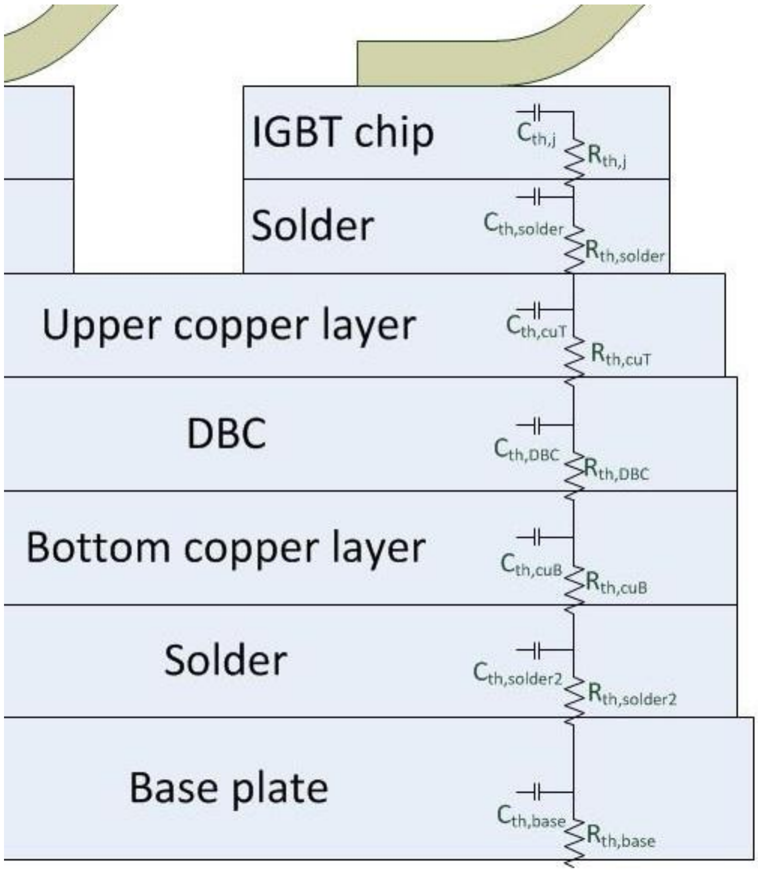
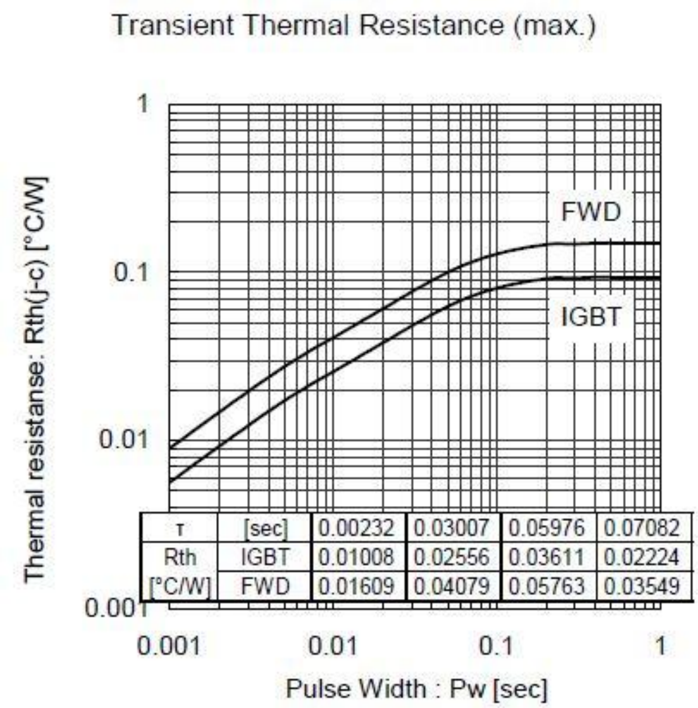


Figure 9: The thermal capacitances and resistances in the system.

Fuji electric have a graph over the transient behaviour for the module tested which can be seen in Figure 10, which is based on real measurements. A time response measurement is done and compared with Fuji's model. The y-axis in Figure 10 is Z_{th}, when it stabilizes after 0,2 s the thermal capacitances have been charged completely and the model reaches steady state which is the thermal resistance.



τ	[sec]	0.00232	0.03007	0.05976	0.07082
Rth	IGBT	0.01008	0.02556	0.03611	0.02224
[°C/W]	FWD	0.01609	0.04079	0.05763	0.03549

Figure 10: Transient thermal resistance for Fuji 2MBI300VN-120-50 [21].

2.6. Failure of IGBT-module

A PE module can reach its end of life in a number of different ways, most of them depend on stresses of the materials as they expand/contract during operation. Different materials have different thermal expansion coefficients, which mean that the materials will expand differently which causes stresses between the different layers. It can be difficult to specify one reason why the IGBT failed since they affect each other, for example if one mechanism occurs it might increase the thermal resistance which will speed up other faults [16].

2.6.1. Definition

Several different definitions for when a PE module have reached its lifetime exists. It can be thermal properties, the thermal resistance increased, or it can be electrical properties, increase of threshold voltage or increase of collector-emitter resistance. How much a parameter can increase depends on the process and what can be tolerated [5].

In this thesis an increase of collector-emitter voltage with 20 % is considered as the end of life limit.

The diode has the same condition as the IGBT for failing and if either a diode or an IGBT chip fails the complete module is considered to have failed.

2.6.2. Bond wire

One way in which the IGBT can fail, is when the bond wires lift off. This happens because of the thermal stresses from the temperature differences. When the temperature differences occur, the materials expands and contracts which causes fatigue on the joint between the bond wire and the chip. With increasing fatigue, the contact in the joint become worse and the collector-emitter voltage increases. As the voltage increases, the power losses in the chip increases and the temperature difference becomes even higher which accelerates the process. The process will accelerate even more if one of the bond wires is lifted off, as the current in the remaining bond wires then increase [16].

The more bond wires that are lifted off, the more current have to go in the remaining bond wires. When the current density is high enough the aluminium metallization will start to melt and arcs between the chip and the bond wire will occur, these arcs will eventually destroy the chip which usually happens before the last bond wire lift off completely [5].

Furtermore at temperatures above 110°C the aluminum metalization between the chip and the bond wire is exposed to stress relaxation which reconstructs the aluminum. The aluminum metalization's cross section area become reduced by the reconstruction and increases the resistance, which, for the same current, leads to an increased collector-emitter voltage. This accelerate the bond wire lift off [16].

The bond wire lift off problem can be avoided to some degree by using coating on the joint between the bond wire and the chip. However this will not solve the problem only moving it, the bond wire still needs to move which will cause heel cracking instead. Heel cracking is stresses in the heel of the bond wire which in time evolves to cracks. Sinter technology can be used between the bond wire and the chip, this will increase the lifetime. The bond wire and metallization on the chip can also be changed from aluminum to other materials, for example copper, this also increase lifetime [16].

As mentioned in 2.4.2 the geometry of the bond wire is a big factor of the lifetime for the bond wire. The failure mechanism caused in a bond wire with improper geometry is heel cracks.

The stresses on the bond wire is concentrated in the edge of the bond wire at the bending close to the joint with the chip. The other area with high stresses is in the bend in the middle of the wire. For a high loop, the stress is low at the edge of the wire and high in the middle. For a low loop the stresses are oppsite compared with high loop. The stresses in the middle of the wire for high loop is almost twice the value of the stresses in the edge of the wire for a wire with low loop. These stresses will in time result in cracks in the wire which will reduce the lifetime of the bond wire. Since the lifetime for the complete module is very dependent on the bond wire it is important that the manufacturer of the PE module constructs the bond wire with low stress [19].

2.6.3. Solder layers

Another common failure of PE modules are delamination of the solder. Like with the bond wire cracks, this failure is related to temperature differences, the temperature differences stresses the solder and cracks in the solder is formed. The solder is not uniform, during the soldering different layers in the solder is formed and the layer closest to the DBC have high concentration of copper, which is the weakest. The cracks are usually formed in the layer with copper, other layers of the solder is richer in tin and lead [16]. The delamination usually start in the outer parts and move inward but it could start from the centre of the chip and move outwards but this usually only happens for large chips, over 100 mm^2. The reason why it can start in the middle of the large chip is because the temperature gradient is largest there [5].

As the solder between the chip and the DBC delaminates, the contact resistance increases. The increasing resistance causes two things, increase of the collector-emitter voltage and increasing thermal resistance. Both of these increase the temperature of the chip even more and accelerate the process [16].

In PE modules with base plates there is also a solder layer between the base plate and the DBC. This solder layer is weaker than between the chip and the top copper layer since it covers a larger area and the difference in thermal expansion is larger [16].

To decrease the problem with solder delamination the modules can be made without base plates, if it does not affect the thermal resistance from the DBC to the heat sink. The delamination issue can be further reduced by changing the material of the DBC from Al_2O_3, which is the most common, to AlN. For AlN the thermal expansion coefficient to Si is closer then between Si and Al_2O_3, thereby stresses are reduce and lifetime increased [5]. If the chip and the top copper layer are joined using sinter technology, the stress can be reduced further [16].

2.6.4. Other failures

Apart from solder layer delamination, bond wire lift off and heel cracks there are several other reasons for the IGBT-module failure. The contacts from the gate driver, which controls the turn on and off of the IGBT, can result in reduced lifetime. If the connection for the gate on the IGBT gets completely disconnected or if the resistance becomes too high, the gate may not be turned on properly. The connections from the voltages and/or temperature measurements may become damaged which could shut down the module. The connections to the IGBT may corrode depending on the environmental affects, like corrosive atmosphere. Further on it may get cracks in the case either by vibration or by passive temperature cycling [5].

Also the chip itself can break, if one chip breaks, the current in the other chips get higher which speeds up the ageing as discussed before and the module will likely fail soon. The chip can fail due to high temperatures or over-voltage. With failure due to high temperature it is meant that the chip itself is damaged, not that it becomes unusable from solder delamination or bond wire lift-off.

2.7. Differences between diode and IGBT chips

The failures for the diode are the same as for the IGBT, the difference is the possible problems with the gate, since a diode does not have a gate to control when they are on or off, they can not have any problems with it. However, since the thermal resistance for the diode is higher it becomes warmer if the same current flows through the chips and the higher delta temperature will result in an earlier failure. The higher thermal resistance in diodes is given from (3), the material and thickness of IGBTs and diodes are the same and the area of diodes are usually smaller then IGBTs, resulting in higher thermal resistance for the diodes. Also, since they are cooled with the same cooling water, the maximum junction temperature will be higher for the diode which also contributes to an earlier failure. Otherwise if the delta temperature and the maximum junction temperature are the same for the diode and the IGBT chips they are expected to fail in about the same time. The failure of the modules are rarely with the chip itself, most of the time it comes for bond wire lift off or solder delamination and they will heated up and cooled down in the same way, regardless if the chip is an IGBT or a diode.

A difference for most PE modules, including the specific module from Fuji electric, is that an IGBT chip is larger than a diode chip, which indicates a longer lifetime for the IGBT can be expected, if all other parameters are the same [18]. Also the number of bond wire are not the same, the diodes have eight bond wires to each chip while the IGBT chips have six bond wires connected to it. But each bond wire to an IGBT chip have contact on two places instead of the one connection between each bond wire and diode chip.

2.8.Statistical analysis

The very basic equation for statistics is the sample mean. It is supposed to be random, but the power electronic to be tested comes from the supplier and it is not known how random the sample is. Since all components are ordered at once, it is likely to come from the same batch which would not be random. In order to decrease this risk, it would be better to purchase the power electronics modules from different sources and at different times, but this would be very impractical due to the long time it would take.

For most statistical equations, different variations exist, for example depending on how high the number of samples is. Since the power electronics modules are mass produces the sample is assumed to be infinite,

$$\hat{\bar{X}} = \frac{1}{n}\sum_{i=1}^{n} x_i \tag{7}$$

is the sample mean equation where n is the number of samples and x_i is the value for each sample. In this case x_i is the lifetime for each power electronic component.

The sample mean is the average value of the sample that is tested, the sample mean should be close to the population mean.

The variance of the sample is a number for how big the spread of the values are. If the samples fail very soon after each other, the variance will become low,

$$\tilde{S}^2 = \frac{1}{n-1}\sum_{i=1}^{n}\left(x_i - \hat{\bar{X}}\right)^2 \tag{8}$$

n is the number of samples and x_i is the value for each sample. $\hat{\bar{X}}$ is the sample mean, hence the variance is basically the difference between each value of the sample and the sample mean. The standard deviation is the square-root of the variance.

When doing lifetime testing it is important to know how confident the result is. With a higher number of samples the result is in general more confident, but with a high number of samples the time to test is extended more than necessary.

The confidence interval can be described as

$$\bar{X} - \frac{k\sigma}{\sqrt{n}} \leq \hat{\bar{X}} \leq \bar{X} + \frac{k\sigma}{\sqrt{n}} \tag{9}$$

where $\overline{X}$ is the sample mean, σ the standard deviation, n number of samples and k is a value depending on the probability density function, the desired confidence. For a student t-distribution the k value is also depending on the degrees of freedom [22].

3. Temperature measurement

Accurate temperature measurement is important to obtain a valid Wöhler curve of the IGBT-module.

The temperature can be measured in several different ways, it can be direct or indirect. A direct measurement is to measure the temperature with a sensor or a heat camera. Measuring with a heat camera is not possible since the chip needs to be visible and it is difficult to dismount the module and remove the protecting gel without potentially harming the module.

Measuring with the NTC element included in the module is very simple but the result is also inaccurate since it is located relatively far from the chip junction and the temperature of the NTC will differ from the chip with up to 40°C [17]. Thermocouples could be connected to the chip and indicate the temperature but it might differ on different places on the surface of the chip.

The temperature can also be measured indirectly, by measuring temperature sensitive parameters, such as the on state voltage drop or the resistance. Depending on the chip temperature the voltage across the chip is different, by measure the voltage, the temperature of the chip can be calculated.

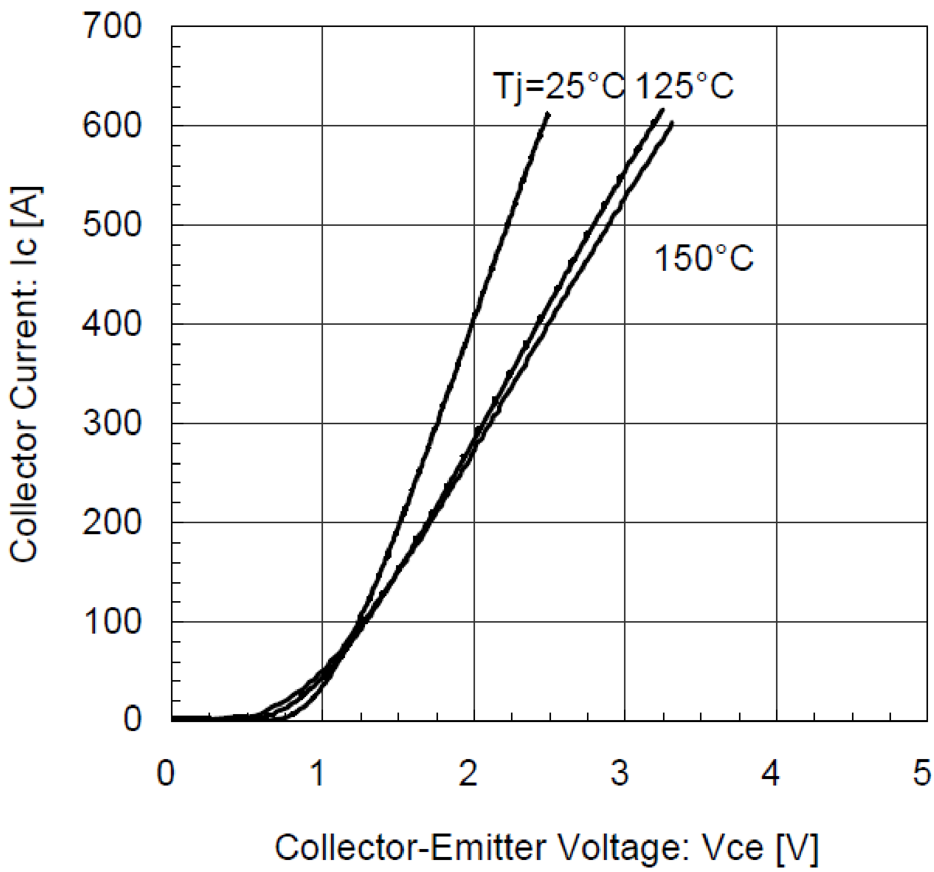


Figure 11: The collector-emitter voltage dependency of the current [21].

Measuring of the voltage is needed to do for determining the lifetime, therefore it is chosen to be the temperature sensitive parameter that is used in the test, in Figure 11 it can be seen how the voltage is depending on the temperature. For 300 A the voltage at T_j=25°C is 1,75 V, when the temperature increases to 150°C the voltage increases to 2,1 V. But there are also a voltage drop over the chip and the terminal where the voltage is measured, this voltage drop is specified to be 0,45 V independent of the temperature of the chip [21].

3.1. Temperature increase

Not all manufacturers are choosing to provide information of the materials that are used and how thick each layer is. Generally, for modules, the different materials, layers and thicknesses are not known. In Table 5 the materials for the Fuji module that have been used in this report are given together with the measured approximate thicknesses of each layer. The thicknesses are not given and had to be measured which creates an uncertainty since there are unknown tolerances of the manufacturing. Also the measurements itself creates uncertainty since the sample might had been slightly tilted and all edges of the layers are not sharp. The area of each layer has been measured. For the upper copper layer and all lower layers the area has been measured and divided with the numbers of active chips. This assumes all available material in the layer is divided equally over the active chips, since it is likely that the thermal energy is focused under the chip this assumption might give too low thermal resistance and too high thermal capacitance. The chips for the IGBT and the diode have the same thickness.

Table 5: Geometric properties for Fuji 2MBI300VN-120-50.

Layer	Material	Area/chip (mm^2)	Thickness (mm)	Volume (mm^3)
Chip (IGBT)	Silicon	100	0,125	12,5
Solder (IGBT)	SnAg base	100	0,12	12
Chip (Diode)	Silicon	64	0,125	12,5
Solder (Diode)	SnAg base	64	0,12	12
Copper top	Copper	320	0,41	131,2
DBC	Al_2O_3	667	0,31	206,7
Copper bottom	Copper	667	0,38	253,3
Solder	SnAg base	667	0,23	153,3
Base plate	Copper	1200	3,05	3660

First an approximation is made where all the power is assumed to be created equally over the chip and transported through the layers only in the vertical direction, which means the power is transported only in the same area as the chip and that the extra area of copper and DBC is not transporting any power at all. In reality the losses in the chip is not created equally over the chip area and in the copper layers and DBC the power is distributed over larger area than the chip. The power is distributed in sideways in each layer as well, for each layer it will cover more and more of the total area.

For the same Fuji module as before, the thermal capacitance for each layer in the module can be seen in Table 6 together with the thermal resistance. The thermal capacitance and resistance comes from the values in Table 1 and Table 5 used in (3), (4) and (5). For the module the total R_{th} for the IGBT chip becomes 0,058 K/W for the case when all the area of the layer is divided on the active chips and 0,204 K/W for the case when it is assumed the heat is only transferred directly under the chip. The R_{th} specified in the data sheet is 0,094 K/W.

Table 6: Thermal resistance and capacitance for Fuji 2MBI300VN-120-50.

Material	R_{th} (K/W) all area is heated up	C_{th} (Ws/K) all area is heated up	R_{th} (K/W) only area under the chip is heated up	C_{th} (Ws/K) only area under the chip is heated up
Silicon (IGBT)	0,0074	0,0218	0,0074	0,0218
Solder (IGBT)	0,0171	0,0232	0,0171	0,0232
Silicon (Diode)	0,0074	0,0218	0,0074	0,0218
Solder (Diode)	0,0171	0,0232	0,0171	0,0232
Copper top	0,0032	0,4585	0,0095	0,1553
DBC	0,0172	0,6519	0,0999	0,1124
Copper bottom	0,0014	0,8851	0,0077	0,1636
Solder	0,0049	0,2962	0,0256	0,0570
Base plate	0,0064	12,7895	0,0369	2,2039
Total R_{th}	0,058	-	0,204	-

In (6) the thermal capacitance and resistance for one layer is used to get the temperature increase for a whole module however it is slightly modified to several equations, one for each layer,

$$T_{j,i} = T_{j,i-1} + \frac{t_s}{C_j}\left(P - \frac{T_{j,i-1} - T_{solder\,,i-1}}{R_j}\right) \tag{10}$$

where T_j is the junction temperature and T_{solder} is the temperature of the solder layer between the chip and the upper copper layer. $T_{j,i-1}$ and $T_{solder,i-1}$ is the temperature for the last sample. Equation (10) gives the temperature increase between the chip and the solder and when combined with the other similar equations it will give the temperature for each layer under one chip. But all chips are assumed to be equal, hence the temperature increase will be the same under each chip.

The thermal resistance and capacitance in Table 6 is used in a Matlab script which calculates the temperature rise and how warm it becomes. The power losses in the chip are assumed to be the only losses and they are calculated from the datasheet using 100 A, the typical voltage at 125°C, which is 2,1 V and during the off time of the cycle there are no losses. The temperature is calculated for one of the chips.

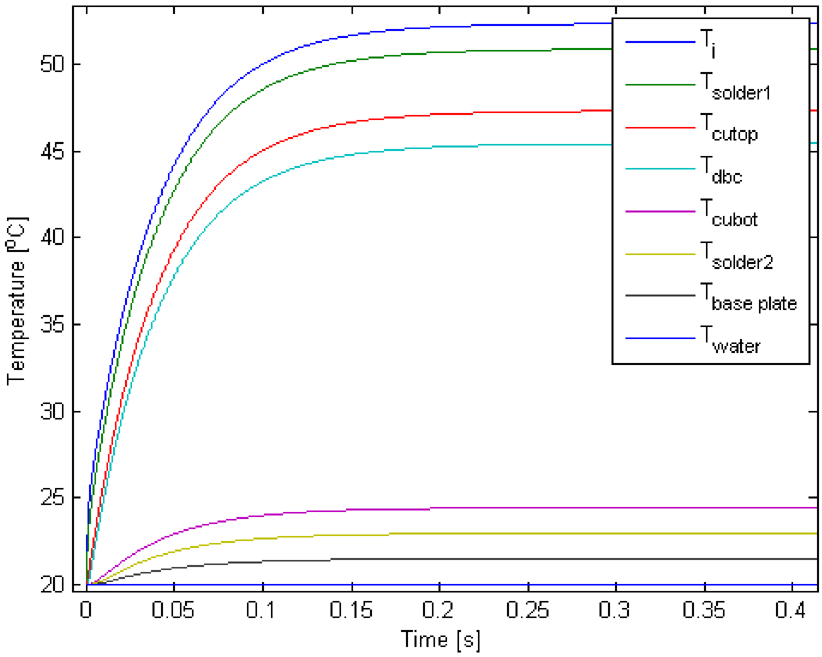


Figure 12: The temperature increase calculations for each layer when heating up.

In Figure 12 the plot of the temperature increase calculations can be seen for the case where all the area of each layer is heated up. It is seen that with the rated current the response of the temperature is fast and reach steady temperature after approximate 0,25 s. The reason why the temperature doesn't reach more than 33°C over the ambient temperature is that the R_{th} is incorrect, it is 0,058 K/W instead of the datasheet value 0,094 K/W. For the case when only the area under the chip is heated up the temperature reached steady state already after 0,1 s. The reason is because the major part of the thermal capacitance is in the base plate which has a very low temperature increase, if it increases slower it is not affecting the rest of the system. However, it is important to remember that these are very simple temperature calculations. Figure 10 in Chapter 2.5 shows the Z_{th} of the module given from the manufacturer, the Z_{th} is approximate 0,2 s which is indicating that the temperature will stabilze after 0,2 s. In Figure 12 the temperature stabilizes after approximate 0,2 s which is similar to the Z_{th} given from Fuji, hence the temperature can be concluded to stabilize after 0,2 s.

4. Test set up

For the test a DC power cycling is made, using two different mean temperatures. The temperature swings, from minimum temperature to maximum temperature, is referred to as delta temperature or ΔT. At one point, a sample of eight diodes or IGBTs are tested.

Figure 13 shows a simple block diagram of how the test setup is done.

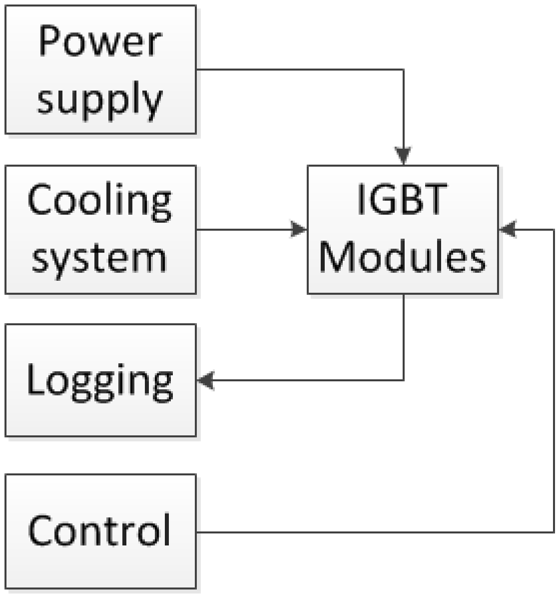


Figure 13: The test setup in a block diagram.

As can be seen in Table 7, Fuji electric 2MBI300VN-120-50 will be tested together with the gate driver Agile switch EconoDual Electrical Master FE0300V112. The equipment used in the test can be seen in the Table 7.

The 2MBI300VN-120-50 module is using solder between the chip and the top copper layer, the module also has a base plate. Expected problem are solder delamination of the base plate and DBC or the chip and DBC connection and bond wire lift off.

Since the PE modules can handle many cycles in a power cycle test, it is important to choose as short cycle times as possible to reduce the time of the test. If one cycle of the power cycle would take 1 minute and the module would last for 100 000 cycles, it would take almost 70 days before it fails which is an unreasonable long time. But if the cycle time is chosen too short the chip might not get a high temperature difference and then the test would take much more than 100 000 cycles before failure and the test time might still be unreasonable long.

To shorter the test time the modules will be run in parallel as well as in series. When the current flows in one set of modules the second set is cooled down and vice versa. In Chapter 3.1, the Z_{th} for the Fuji module is concluded to be around 0.2 s, which indicates that it would be enough if the on cycle is 0,2 s. However, neither the IGBT chip nor diode chip are completely balanced, some layers will be warmer over a larger area faster than others and to make sure that there is enough time for all materials to heat up over a larger area, then just directly under the warmest part of the chip, a longer cycle time is needed. Also cooling down the module will take longer time than heating it up. Therefore it is decided that a factor 10 of difference between the time transient and the on time for the cycle is a good start, eventually it can be even shorter. The on time for each cycle is 2 seconds and the off time is 2 seconds as well, that gives a total cycle time of 4 seconds. During 24 hours approximate 20 000 cycles can be made, for a lifetime of 100 000 cycles it will take 5 days until the components are broken.

Table 7: Components used in the test setup.

Function	Model
IGBT modules	Fuji electric - 2MBI300VN-120-50
Gate driver	Agile switch - EconoDual Electrical Master FE0300V112
Power supply for power cycling	Digatron EVT 300-500-80kW IGBT
Power supply for 24V	Switchbox SB 30-10
Power supply for 24V 2	Sorensen XHR 60-18
Power supply for 15V	Sorensen XHR 60-18
Fan speed control	Escort EGC-2230
Current shunts	0,075 mΩ
Voltage measurement	NI 9221
Voltage measurement 2	NI 9229
Temperature measurement	NI 9219
Module for switching	NI 9485
Cooling plate	Aavid thermalloy – 416601U00000G
Thermal grease	Electrolube HTSP50T

During the test, the voltage over each component, the voltage over the power supply, the voltage over the shunts and the temperature of the NTC element is logged. All parameters are logged with different DAQ-units from National instruments (NI). The switching on/off of the IGBT modules is handled by another DAQ-unit from NI, NI 9485. All software to control the switching and logging are made in Labview.

The temperature is logged directly from the built-in NTC elements. The NTC elements temperature will not match the temperature of the chip since it is placed far from the chip and is changing slower than the chip. However it can be used to protect the chip from getting overheated. When analysing the data, the temperatures of the NTC elements can be used to control that there are no big changes in the temperature. The DAQ-unit to log the resistance from the NTC elements is a NI 9219.

The voltage over the power supply and the voltage over the current shunts are measured with the DAQ-unit NI 9229. The voltage over the power supply is used as a reference and the sum of voltages over all the components should match this voltage, if the difference is large it is indicating a measuring error. To measure the current, two current shunts are used and the voltage over these is logged. Since the resistance of the current shunts are known, Ohm's law is used to get the current.

Also the voltage over each chip and its terminals is logged. The voltage over the chip is correlating with the number of cycles of the component and after the test the ageing of the chip can be seen as the voltage over it increases. Since the voltage of the chip is also depending on the temperature, the temperature can be estimated from the voltage. The voltages for the chips are logged with a NI 9221.

4.1. Electric circuit scheme

In Figure 14 the electrical circuit scheme for the test set up can be seen. When one diode or IGBT have failed a 50mm^2 cable is connected over the failed IGBT/diode to short circuit it. Then the test is continued with the rest of the IGBTs and diodes.

The limiting factor of the number of parallel set of modules is the cost. It would be possible to have more parallel modules but it would require bigger space and more importantly it would require more current from the power supply which is limited to 300 A. The limitation of the number of modules in series is how much energy the cooling system can transport.

Initially, in the test four modules are connected in series. In two of these modules the current flows through the IGBT, in the other two modules the current flows through the diodes. The current is shut off by switching the IGBT chips. In a hybrid application the diodes are an important part of the module as they are required for regeneration of energy and needs to be tested as well. If only the IGBT chips are tested and the lifetime of the diodes are shorter the module smight broke down earlier than expected because a possible shorter lifetime of the diodes had not be noticed.

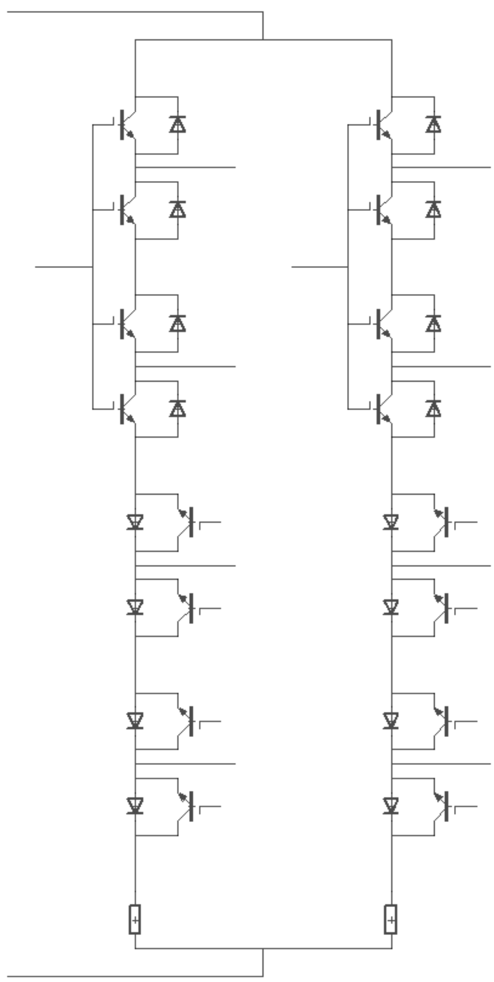


Figure 14: The electrical circuit scheme for the test setup.

4.2.Water cooling

To cool down the PE modules water cooling is used. Air cooling is not able to cool the modules fast enough to be useful.

In Figure 15 the water cooling system can be seen. The radiator, fan and water pump are capable of transport 8kW with a water temperature rise of 30°C compared with the ambient temperature. The valve is used to control which modules that should be cooled. As the chips in the PE modules are heated up very quickly, a small water flow is used parallel to the valve so the modules that are heated still have a small water flow. Later when the modules should be cooled down the valve is switching and a higher water flow is passing by the PE modules which cools them down.

The IGBT modules are mounted on two separated heat sinks, in order to be able to cool half of the modules as the other half is heated up.

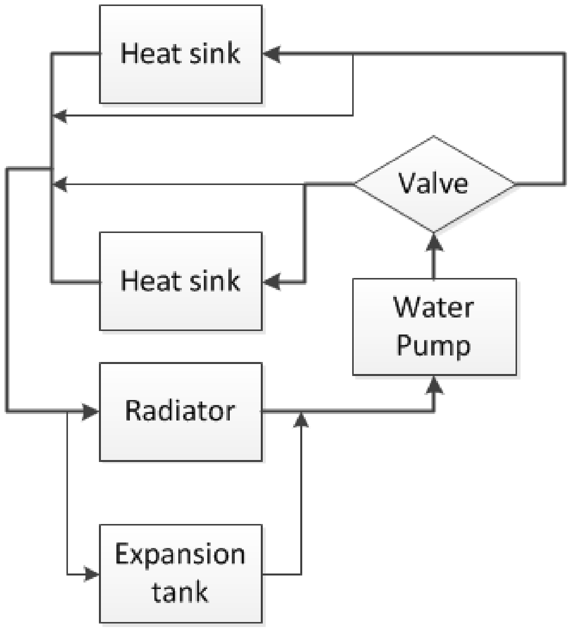


Figure 15: Block diagram of the cooling water system.

4.3.Switching

To switch between the heating up and the cooling down phases, the PE modules is switched on respectively off. The gate driver for the PE modules have been modified, the built in short circuit protection has been removed. The gate signal is 15 V for turning on and 0 V for turning off, the gate signal that is connected through the NI 9485. A counter is implemented which increased for each time the first parallel leg is switched on, the counter is used to compare with the cycles from the log data.

4.4.Test conditions

First test used 300 A and the cooling plate had a water temperature of around 50°C. Since the diodes and IGBTs have different thermal resistance their maximum junction temperature will be different. The NTC element of the PE modules shows a temperature between 56 and 62°C for the chips, slightly cooler for the IGBTs and a bit warmer for the diodes. Since the offset between the NTC element and the junction temperature is roughly 40°C it indicates a mean temperature of 100°C for the chips. For a water temperature of 50°C it is expected for the temperature to vary between 150 and 50°C for the diodes and 130 and 50°C for the IGBTs.

When one of the diodes or IGBTs stops conducting, the test is stopped and the component that stopped conducting is either removed or disconnected and then the test restarts. When a component is broken and disconnected it will be fewer chips left in the test and the total power consumption is decreased. If the fan and pump is operating in the same way as before it will result in lower temperature which might affect the result. Therefore as a component is disconnected and the test is restarted the fan’s operating point is reduced and tuned so the temperature is close to the same during the whole test. Since the water temperature is changed slowly it takes a while to settle in the right temperature range but the difference is small, less than 5°C, thus it have no major impact on the test result.

To determine which component that have failed when the test have stopped, the power source with 300 A is turned off, then a small power source of maximum 18 A, limited to 1 A is connected and the test is restarted. It is noticed which of the parallel legs that is not conducting. After that the power source is connected over a single module, if it is a module where the IGBTs are used the gate signal is turned on to 15 V, if the module conducts the power source is connected to the next module. When the module that is not conducting is found it is measured in a similar way but first between the positive DC and the AC and then between the AC and the negative DC for the modules working as IGBTs and vice versa for the ones working as diodes. After the broken component is disconnected, the test is continued.

The modules are tested at different currents from 300 A to 250 A, this results in different temperature increases. This is planned to be tested for two different mean temperatures, higher mean temperature should, in theory, result in shorter lifetime. The Wöhler curve of the lifetime is expected to be very similar for the higher mean temperature but shifted to shorter lifetime. The fan and/or water pump is adjusted for the mean temperature to become equal for all tests. In Table 8 the different combinations of tests can be seen. T_m is the mean temperature of the semiconductor.

Table 8: The different points where the tests will be conducted.

T_m	ΔT	Type of component	Current
100	100	Diode	300
100	90	Diode	275
100	80	Diode	250
90	80	IGBT	300
90	70	IGBT	275
90	60	IGBT	250

In Figure 16 the test setup can be seen. The valve and the water pump is to the right of the PE modules and the radiator is barely seen in the top of the figure.

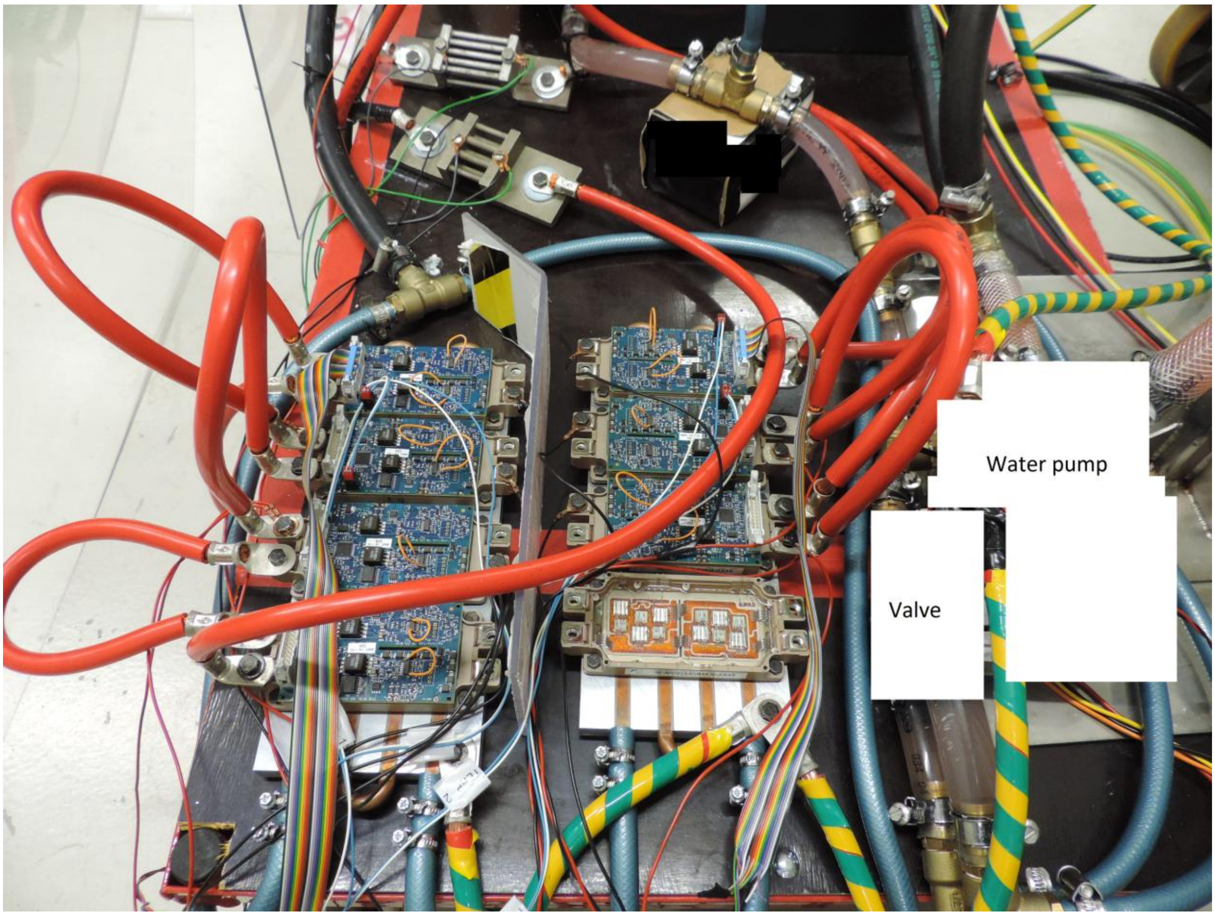


Figure 16: The setup for the tests, the module lacking protection and cover is only in this state for the picture.

5. Result of test

For the diodes in the first test, a maximum junction temperature of 150°C and a temperature swing of 100°C the mean lifetime rated by the supplier is approximate 60 000 cycles. The components tested under this conditions broke down after approximately that number, it ranged from 45 000 to 65 000 and most of them where ±5 000 cycles from 60 000. The supplier defines a broken component as when it becomes a short circuit or an open circuit. The voltage rises very fast in the end of the lifetime so a definition of 20 % of voltage increase or a complete short- or open circuit is not making a big difference of the lifetime.

For the IGBTs that run on the same time as the diodes they reach a junction temperature of 130°C and the temperature swing is 80°C, then the rated lifetime is approximate 150 000 cycles. All the IGBT chips broke down around 140 000 cycles for the case when the temperature swing is 80°C.

Table 9: The sample mean lifetime and the standard deviation during different conditions.

Tm	ΔT	Type of component	Current (A)	Number of cycles, 20 % voltage increase	Standard deviation
100	100	Diode	300	55 900	6 800
100	90	Diode	275	104 300	14 000
100	80	Diode	250	180 800	44 100
90	80	IGBT	300	137 800	600
90	70	IGBT	275	377 900	19 800
90	60	IGBT	250	-	-

In Table 9 the average lifetime for each case is shown. For the IGBT case with 275 A the log data shows 347 900 cycles before a 20 % increase of the voltage occured, but around 30 000 cycles is lost as the program stopped logging during a weekend, the test continued without the log data and the counter is 30 000 cycles higher than the log data showed. For several of the IGBTs they broke completely before the voltage increased 20 %, for these IGBTs the 20 % voltage increase is counted as the same number of cycles as when they broke completely.

For the first diode samples, that is run until they short circuited or did not conduct anymore, it could clearly be seen that there have been damage between the aluminised surface of the diode chips and the bond wires. As can be seen in Figure 17 the surface is dark and some bond wires are completely off from the chip. Since the test run well close to the specified time and how the voltage reacts in the end, it is believed that when one of the bond wires started to lift off, more current flows in the remaining bond wires, which accelerates the ageing. More bond wires starts to lift off and the temperature of the chip increases. In the end the current concentration in the remaining bond wires is much higher then originally and the contact between the chip surface and the bond wires is thin or completely lift off, resulting in an arc which creates the burned silicone around the chips. After the arc, the chip is either too damaged to conduct anymore or the distance between the bond wire and surface of the diode have become too large. Then the same thing happens to the other chips in parallel, but now the current is even higher and that is why they becomes even more burned than the first chip.

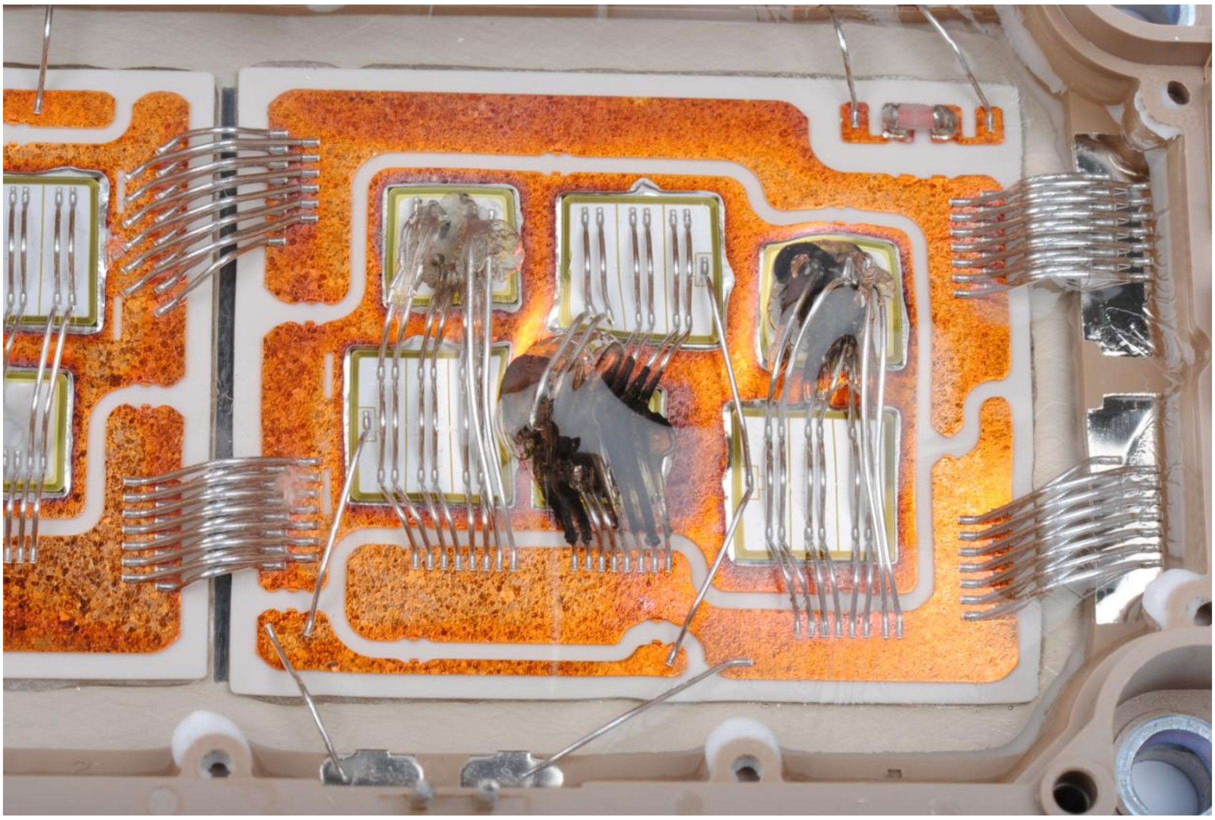


Figure 17: Fuji module sample number 7, this is the first diode to break at 300A.

5.1.Sample preparation

When both the diode or IGBT components in a module have broke down it is opened up for inspection, interesting samples are more detailed analysed, but all are at least inspected with the bare eye. A sample that stands out is first cut in a cutter, these are then cleaned in ethanol and the biggest parts of the silicone are removed by hand. For the silicone around the bond wires and the chips it is too difficult to remove by hand and there is too big risk of damaging the connection between the bond wires and the aluminised surface of the chips.

In Figure 18 the black lines shows where the modules are cut in the case when the IGBT had been cycled, first the outer parts with the case and terminals are removed and the modules are cut in two pieces, one for the upper IGBT and diode and one for the lower. Then the cutting is made and the interesting parts of the module could be inspected without needing to grind for too long. For modules with the diodes cycled the cutting is similar but right next to or on the diodes instead of the IGBTs.

The silicone on the module is removed with Dynasolve 220, it is placed in a sample cup for 48 hours, during the 48 hours it is stirred and replaced continuously. It is supposed to take 24 hours, but after this time there are still silicone left, then the sample are placed back in the sample cup with new Dynasolve 220 for another 24 hours.

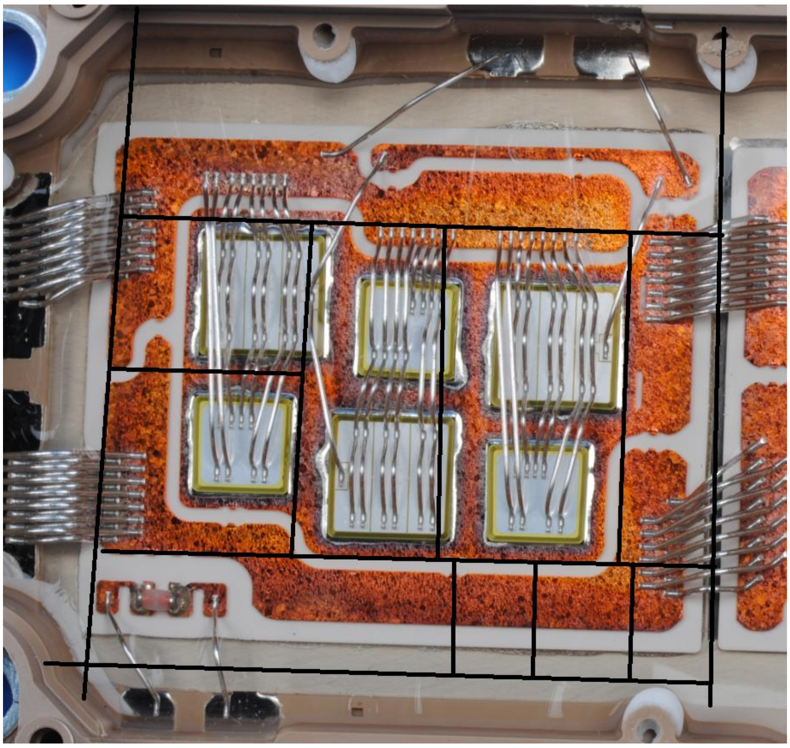


Figure 18: The cutting of the modules that are inspected in epoxy samples.

After the samples have been cleaned from the silicone it is moulded, this mould is then polished and viewed under microscope to see if there are any solder delamination or bond wire lift off.

5.2.Microscope pictures

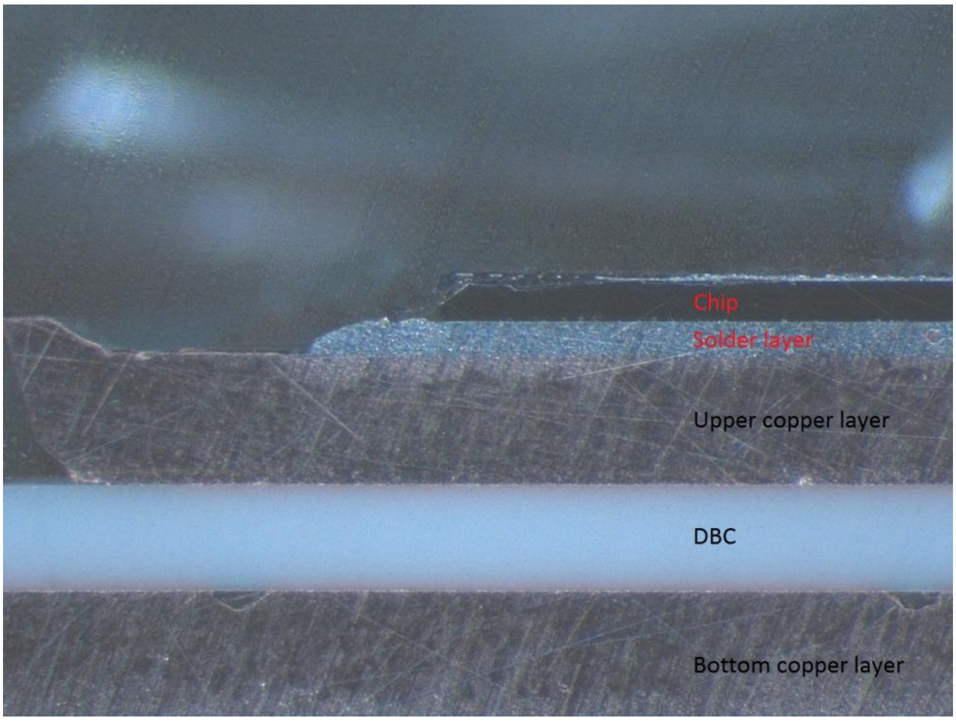


Figure 19: Diode chip for sample number 3, no solder delamination can be seen.

In Figure 19 intersect of a diode chip on sample number 3 can be seen. The scratches come from the grinding and polishing. The sample are grinded and then inspected. If there is no interesting result, such as solder delamination, it is grinded further. The cracks could be unevenly distributed under the chip, therefore, if any exists, it can be difficult to find. For some cases such as in Figure 19 the sample are polished and a picture of it are saved for comparing with other intersections.

The sample from module number 3 is continued to be grinded and inspected, the closest to a crack can be seen in Figure 20, this is after grinding with a rough surface but the unevenness from the inspection is considered to be analysed more thoroughly. After grinding with finer surfaces and polishing the sample the result can be seen in Figure 21. Here it does not look like a crack at all. Either there is a crack but the polishing smoothen it out or there was never a crack but the rough grinding damaged the surface making it look like a crack.

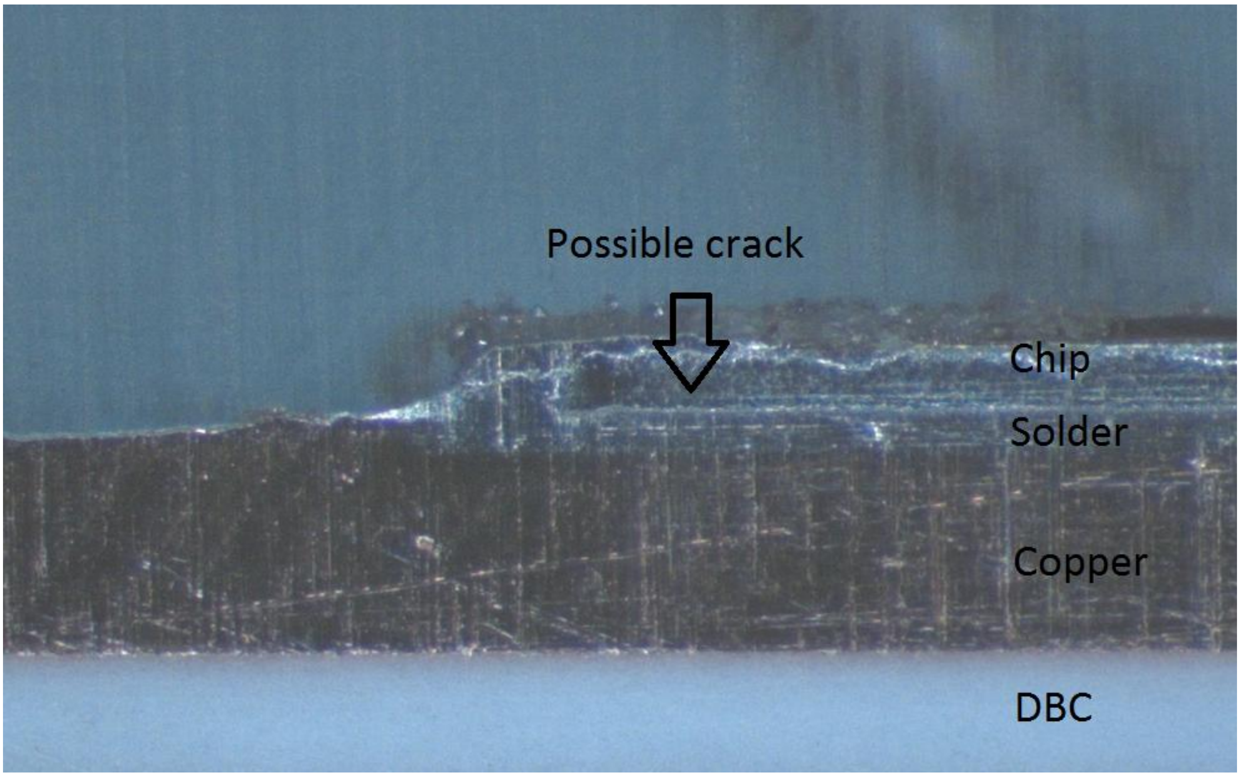


Figure 20: A potential crack between the chip and the solder layer, the sample is only grinded roughly.

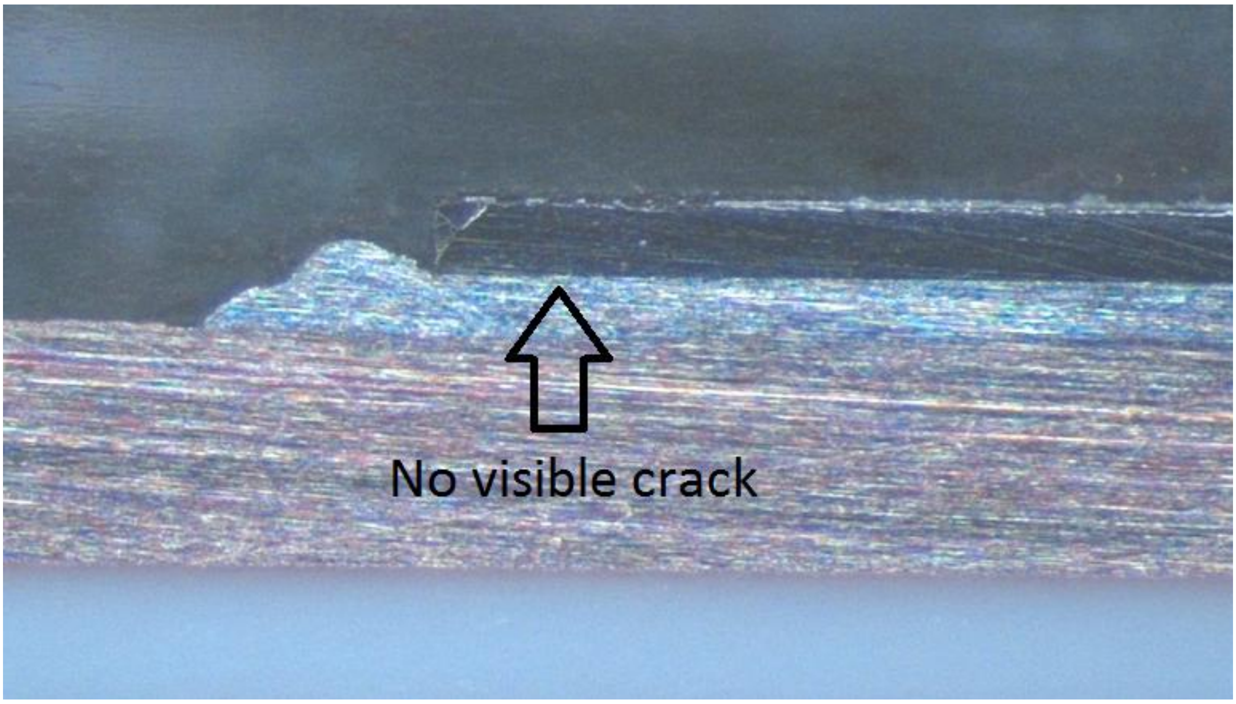


Figure 21: Same chip as in Figure 20 but after polishing.

The limiting factor for the lifetime is expected to be bond wire lift off. In Figure 22 a bond wire with none or little wear. In comparison, Figure 23 shows a bond wire where the module has wear out. The two figures are from the same module but since the IGBT chips are being cycled and the diode chip are only passive warmed up from the heat of the IGBT chips, the bond wire of the diode is more or less unaffected because the passive temperature swing is low. The bond wire can be seen as a bond wire with no wear.

For the bond wire with no wear the joint is strong and no cracks can be seen. For the bond wire with wear on the other hand, the joint has lost connection in the edges and the connection is starting to get cracks in the middle as well.

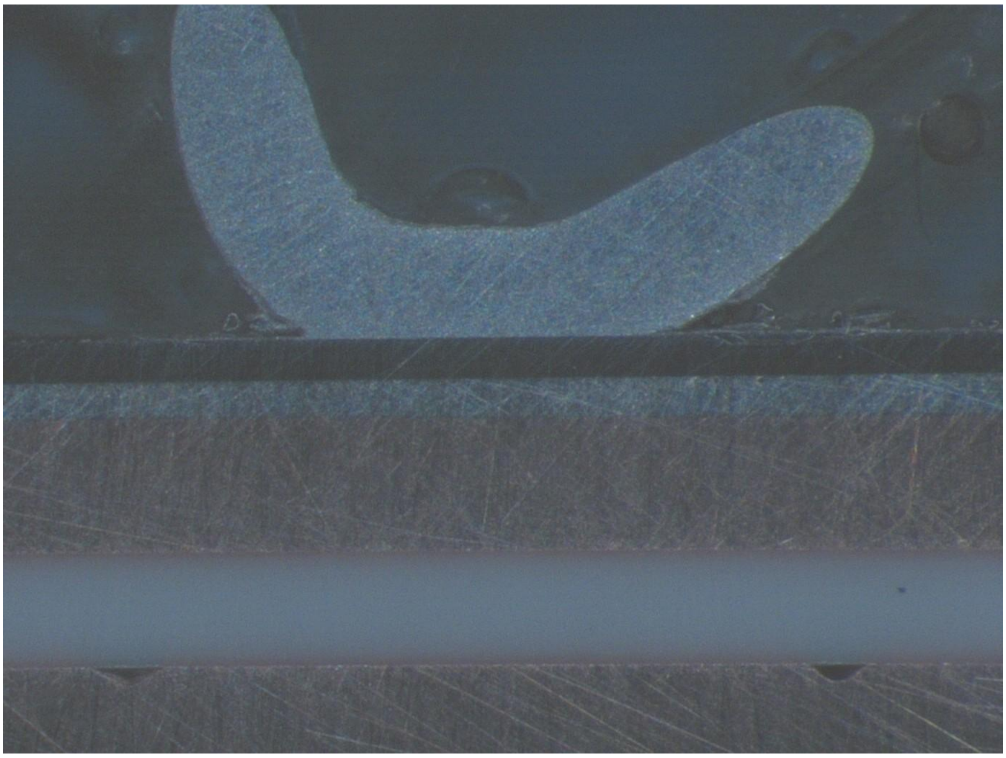


Figure 22: Bond wire to a diode in module number 6.

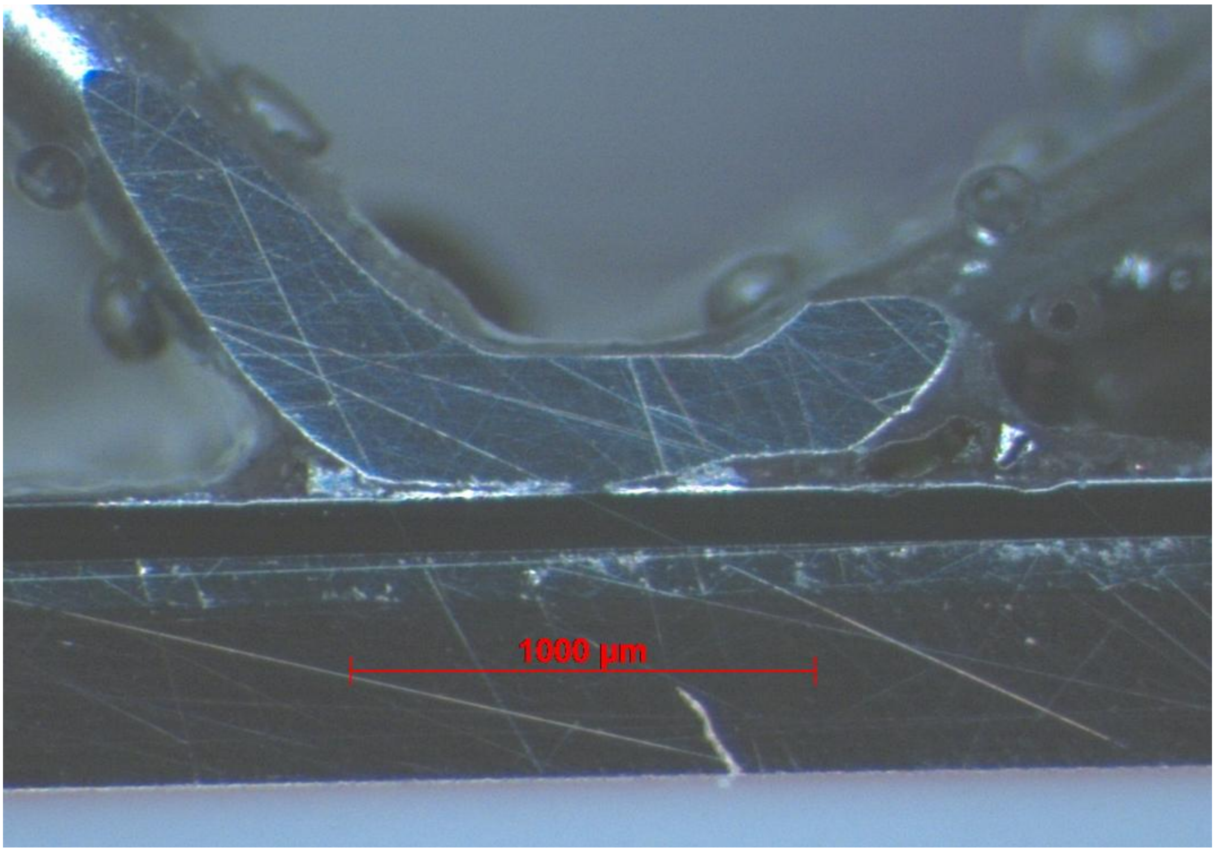


Figure 23: Bond wire to an IGBT in module number 6, cracks can be seen between the bond wire and the chip.

In Figure 24 another bond wire from another module is shown, this picture is taken with a different microscope than previous figures on bond wires, this microscope has a higher zoom level and a crack can be seen between the chip and the bond wire, the crack goes over the whole joint between the wire and the chip.

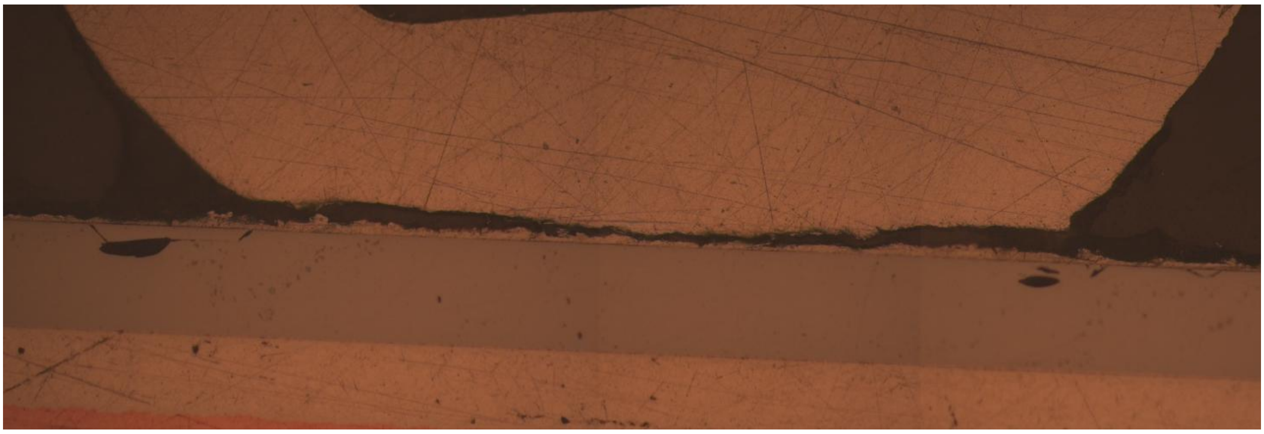


Figure 24: Panorama picture over a bond wire to a diode chip on sample number 3.

Figure 25 shows the same bond wire as Figure 24 but zoomed in on the right side. The distance between the chip and the bond wire is roughly 5 µm at most. There exists a possibility that the sample is in one edge of the bond wire and since the wire is circular it might not be connected to the chip simply because it is too far away from the joint. However, in the left top of Figure 24 one can see the top of the bond wire and it is thinner than the right side which could be because it is pressed down during the ultrasonic welding of it. This could mean that at least the left side is cut in the middle of the bond wire.

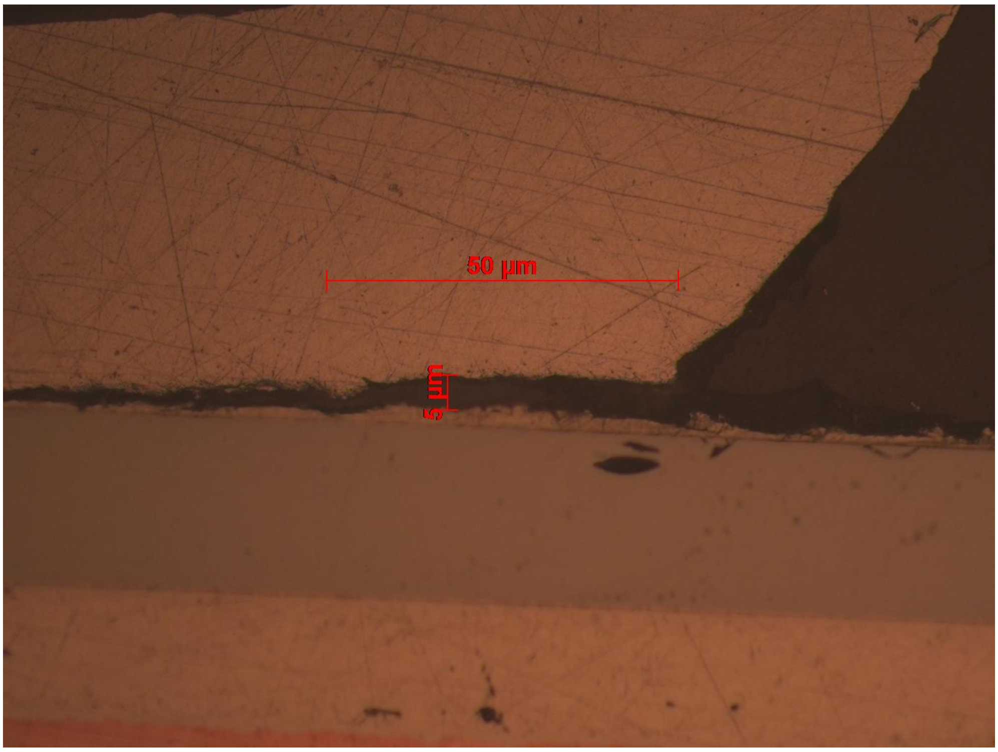


Figure 25: Zoomed in picture on the same bond wire as in Figure 24.

Also the solder layer between the bottom copper layer and the base plate is inspected but no cracks or beginnings of cracks could be seen.

5.3.Number of cycles

When analyzing the result it turned out that the definition of when the component fails affects the result significant. Table 10 shows the number of cycles for different definitions. For the diode 5 % or 20 % voltage increase does not make a big difference but for the IGBT the life time is drastically different if 5 % voltage increased insted of 20 % is used. For the IGBTs, however only a few of the 8 samples reached the 20 % voltage increase before they became open or short. For the diodes all reached a voltage increase of 20 % before they became open or short. As mentioned in Chapter 5 the lifetime of the IGBTs at 275 A are 30 000 cycles higher than the log data shows because the logging stopped over a weekend.

Table 10: Sample mean lifetime for 5 %, 20 % and open or short circuit for the case with 275 A.

Type of component	Current (A)	Number of cycles, 5 % voltage increase	Number of cycles, 20 % voltage increase	Number of cycles, open or short circuit
Diode	275	90 000	104 300	106 400
IGBT	275	185 400	377 900	389 100

The failure is shown in different ways, some of the modules became short circuited and some of the modules became open circuits. After the modules failed they are taken out of the test rig and one of the modules that are tested with the diodes that became open circuit is inspected more closely. A small power supply set to 30 V and 2 A is connected to it and the diodes did not conduct, then the voltage is turned down to 5 V and the positive conductor is connected through the silicone layer and pressed on top of the diode, then the diode is conducting but the voltage across it is 0 V. Also the other set of diode chips in the module are tested like this and all showed 0 V when they conducted. Probably the chips are damaged and short circuited but the bond wires have been lifted off too much to conduct any current. For the modules that are short circuited the bond wires are probably still attached enough for them to conduct.

Figure 26 shows the voltage of a diode chip when it is crossing the 20% voltage increase. It can be seen that there is more or less a jump in the voltage at the time the diode is worn out. The diode is the bottom diode in module number 7. The sudden jump in the voltage comes when a bond wire is lifted off.

Figure 27 shows the voltage over the bottom diode for module number 3. Just like the bottom diode in module number 7 a jump in the voltage is suddenly made. The difference is that for Figure 26 the steady voltage is starting to increase, then makes a jump and continues to increase fast before it dies completely shortly above the 20% voltage increase. For Figure 27 on the other hand, the voltage is quite steady the whole way until the voltage jump and after the 20% voltage increase it continues to work for much longer time then the Figure 26 which could be explained by the fact that the voltage of the diode in module number 7 increases faster than the voltage of the diode in module number 3.

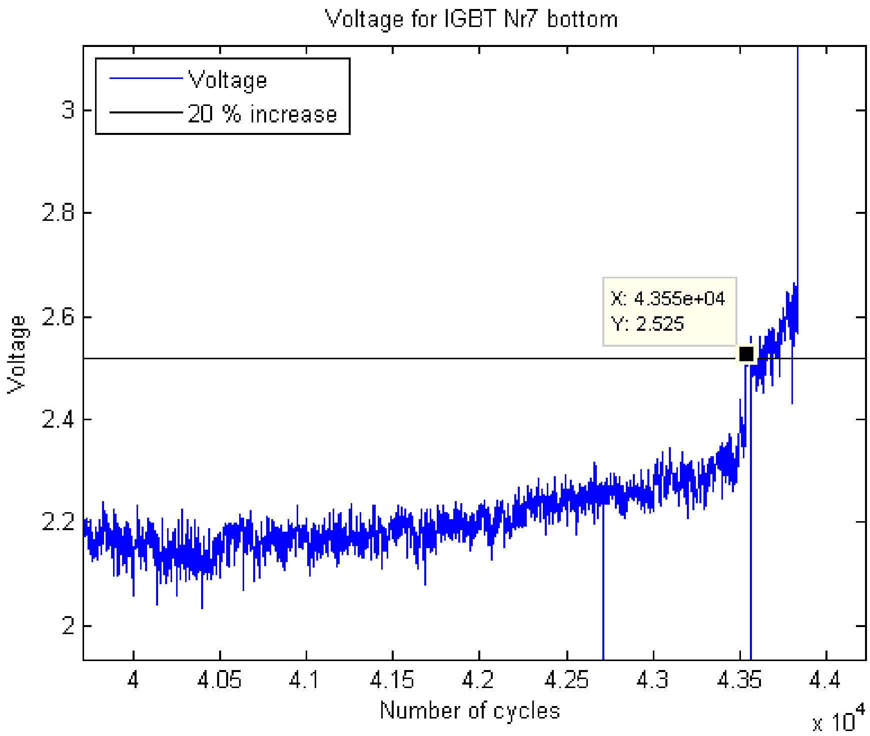


Figure 26: Voltage for the bottom diode in module number 7.

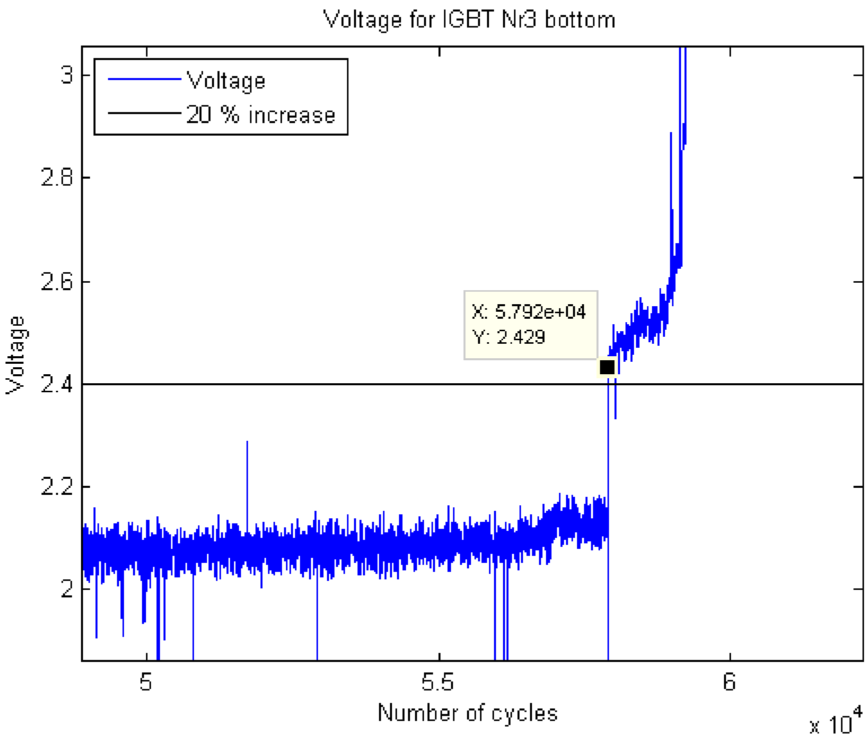


Figure 27: Voltage for the bottom diode in module number 3.

In Figure 28 the voltage for the bottom IGBT in module number 11 is shown, many of the IGBTs showed similar shape of the voltage over the lifetime. The reason why the voltage at the arrow in the figure have made a jump down is that it is cycled during a weekend and the temperature is lower in the lab.

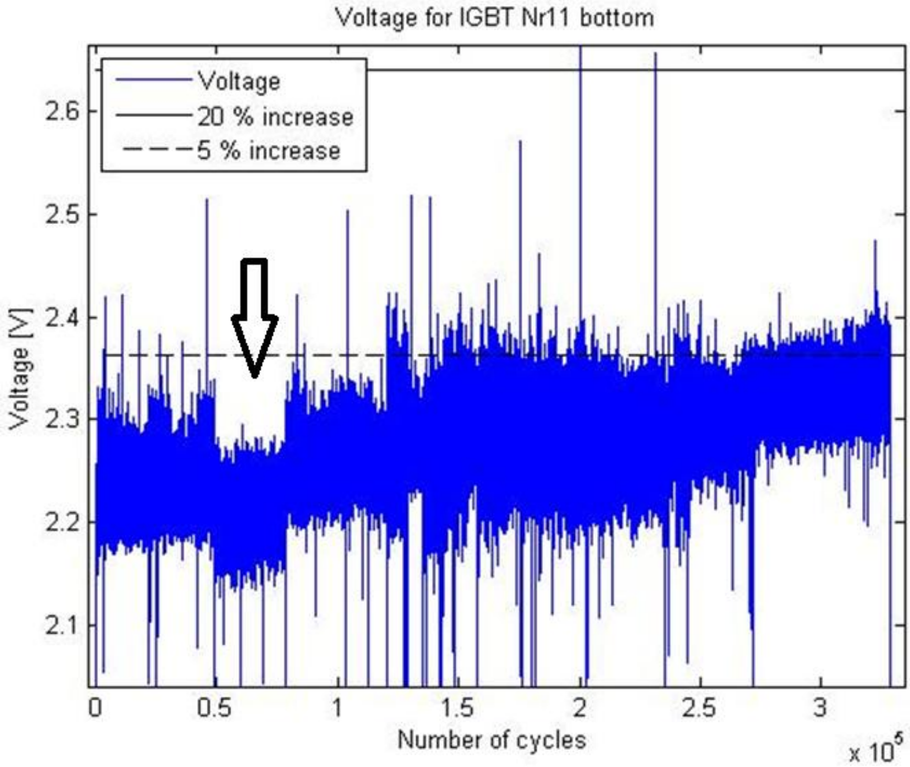


Figure 28: Voltage increase during the whole lifetime for the bottom IGBT in module number 11.

5.4.Statistic

In Figure 29 the result of the test can be seen together with the equation (2), the β parameters uesd are taken from that study and the parameters such as t_{on}, V, ΔT are taken from the specific module and test method in this report. Each point in the figure is a mean value from the measurement, at that ΔT using 20 % voltage increase as definition when it fails. The K value in (2) is fitted for the curves to go through the point at 275 A. The reason for not fitting it to the 300 A test is that often in other reports the lifetime for the maximum temperature have been a bit lower than the Wöhler curve.

For the diodes it seems like both the 80°C case follows the lifetime curve very well and the 100°C case is a bit lower than the curve. For the IGBT there are too few measuring points to get in details about it but at least the higher measuring point is below the lifetime curve. Since the IGBTs had a lower middle temperature it is expected that they should last longer which the two lifetime curve strengthens as the diodes lifetime curve is slightly below the IGBTs lifetime curve at 80°C ΔT.

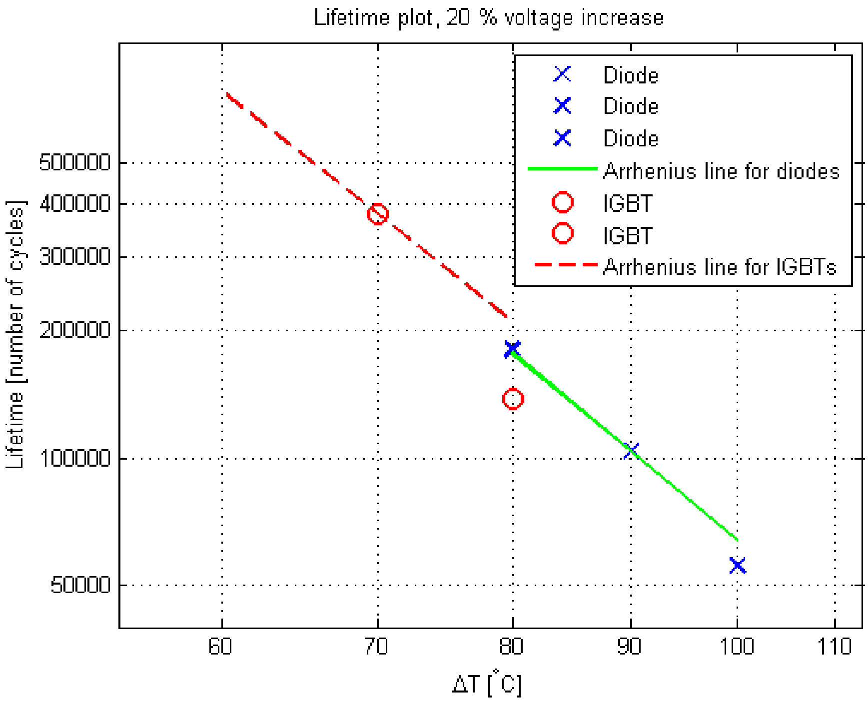


Figure 29: Lifetime of the diodes and the IGBTs together with the lifetime curve from (2).

Compared with Figure 8 that is the lifetime curve Fuji provided, the lifetime is as expected for the highest ΔT for both the diodes and the IGBTs, while the other values have longer lifetime then what is believed from Figure 8. If the K value in (2) is instead changed so the lifetime curve matched the 100°C ΔT for the diodes and 80°C ΔT for the IGBTs then the values on the lifetime curve at 90 and 80°C ΔT for the diodes and 70°C ΔT are very close to the values that Fuji provided.

In Figure 30 all failures from the diodes and the IGBTs have been included. It can be seen that when ΔT decreases, the deviation between the samples increases. Also the deviation between the IGBT samples are less than the diode samples.

The voltage could be seen changing as the temperature of the NTC elements changed during normal conditions. However, during the end of life when the voltage increased drastically no temperature increase could be seen. The NTC element is probably located too far away from the chip.

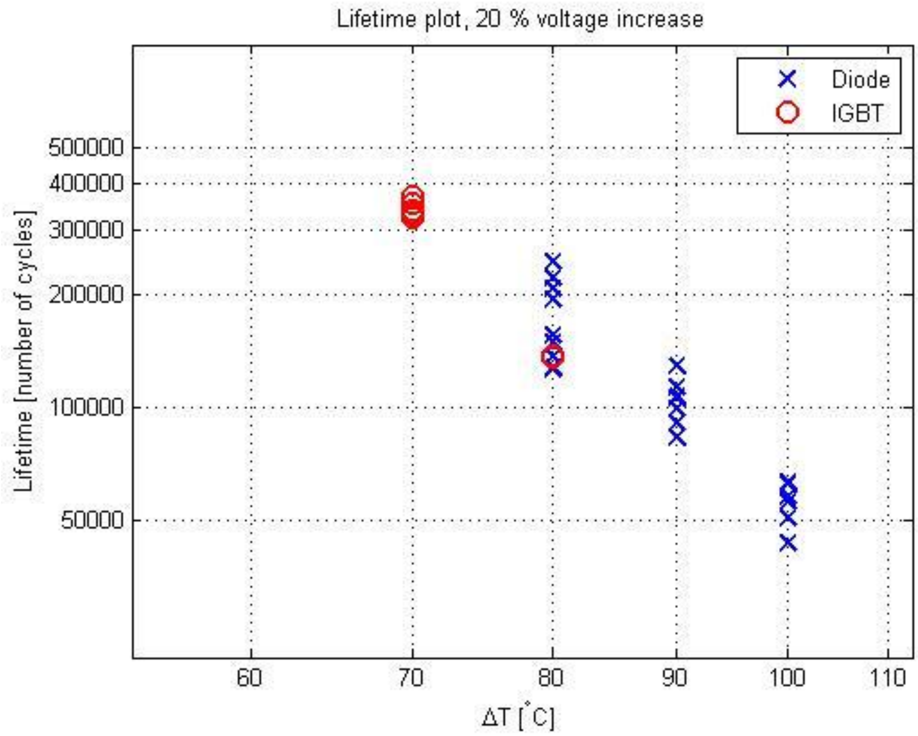


Figure 30: All failures of Diodes and IGBTs.

5.5.Other result

After the tests several burned spots similar to Figure 17 are found on diodes as well as IGBTs. Even more interesting, since the burned spots are believed to be created by arcs between the bond wire and the chip, the result is that sometimes in modules used as diodes the burned spots are found on both diode and IGBT chips.

To investigate if the burned spots could be from over temperature a module is placed in a temperature chamber set to 200°C for 1 hour after reaching the wanted temperature. The modules are specified to 175°C. After the time there is no sign of damage and the PE module is still working, it is placed in the temperature chamber again, now for 250°C during 2 hours. Also after this test the module worked and there are no signs of burned spots on the chips. The module had some discoloration but no burned spots or something that looked as the beginning of burned spots.

During the test on 250 A arcs are noted on the gate driver. Later it is concluded it was on the upper diode in module number 21 that failed that had the arcs, in the control program the voltage started to increase before the arcs and at that time no arcs could be seen. Some damages could be seen on the gate driver over the resistor where the arcs have been. This was the only time arcs are noted in the test but since most of the IGBTs and diodes have broken over night, it is possible that it could be arcs over each gate driver when the IGBT or diode fails.

Module 21 is one of the modules with burned spots on IGBTs even if it is the diodes that are tested. To see if it could be overvoltage on the gate that could be the reason for the burned spots a small test is done. A small power supply set to 30 V and 5 A is connected to a 10 Ω before the gate. Another power supply set to 4 V and 1 A was connected between the positive and the AC connection on the module. The gate voltage is specified to maximum of 20 V. The gate is switched on and off several times but the PE module worked every time and there are no signs off burned spots on the chips. Then the 10 Ω resistor is removed and the test repeated without the resistor. It still worked and the chips looked just as before with no sign of burned spots on neither the IGBT nor the diode.

Also the lid on a module is removed to see if a thermal camera could detect the temperature change on the chips. The current in the module flowed through the diodes because then the gate driver is not needed, hence the connection is easier. The thermal camera is directed to one of the diodes and zoomed in until each chip could be identified. However the camera display did not show temperature variations, even when the t_{on} time is set to 5 s, the temperature is steady 1-2°C under the lowest temperature of the NTC element.

6. Discussion and future work

The main focus during this report has been the lifetime test of PE modules, including both IGBTs and diodes. First a test rig was built and simple temperature calculations were made to determine the test conditions. After the test, the modules were investigated and the failure reasons determined. Simple statistics on the result are made and compared with the manufacturers measured data.

6.1. Discussion of the results

When viewing on different samples in microscope it is very difficult to find potential cracks between the top copper layer of the DBC and the chip. This does not mean that there are no cracks in that solder layer, they could have been missed, but it seems they are not the main reason of failing in the module. Especially when the damages between the bond wires and the chips are considered, it is difficult to believe that the solder delamination would be the reason of failing. However the solder layer between the bottom copper layer and the base plate can be concluded to not be the limiting factor in this case since no cracks were seen and other studies within the area support this statement.

The lifetime of the modules are as expected or better. For the highest temperature of the diode and IGBT the result matched the data Fuji provided. For the other test points however the diodes and IGBTs survived longer than expected.

It turned out that the definition of when the component has reached its end of life was very important. If the definition would be 5 % voltage increases instead of 20 % it would be enough to detect the fault and drive the vehicle to the workshop before it breaks down completely. For the 275 A case the 5 % voltage increase was 90 000 cycles for diodes and 185 400 cycles for IGBTs, 20 % voltage increase was 104 300 cycles for diodes and 377 900 cycles for IGBTs. On the other hand, 5 % increase of the voltage for the IGBT is far before they break down completely and it would require increased cost for the haulage contractor or the manufacturer. However, since most of the IGBTs did not survive long enough for the voltage to increase 20 % the definition needs to be lower to be suitable in field.

6.2. Future work

The test in this report has been active power cycling which is an important part of required testing of PE modules. With that said, there are still several other tests that can be done to ensure the power electronics works well in the field.

The passive cycling are often done with higher temperature swings than active cycling and the whole module is heated up, which result in much lower number of cycles on the other hand the temperature takes much longer time to stabilize and the test time is not needed to be shorter.

Also other power electronics module should be tested with the method in the thesis report and compared with the result from this. It would be extra interesting to test with a module with sintering technique of the bond wire to see if that is improving the lifetime further.

Also the result would benefit from more tests on lower ΔT for both diodes and IGBTs, this would give a better result to determine if the lifetime follows the lifetime curve also on lower temperature swings.

Also the test could be done with longer cycle periods which would give the modules a higher risk of failures from solder delamination.

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