Graphite sheets and graphite gap pads used as thermal interface materials

A thermal and mechanical evaluation

Love Fältström
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<tr>
<th>Approved</th>
<th>Examiner</th>
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<tr>
<td>2014-06-13</td>
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<td>Ericsson AB</td>
<td>Christofer Markou</td>
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</table>
Abstract

The electronic market is continually moving towards higher power densities. As a result, the demand on the cooling is increasing. Focus has to be put on the whole thermal management chain, from the component to be cooled to the ambient. Thermal interface materials are used to efficiently transfer heat between two mating surfaces or in some cases across larger gaps. There are several different thermal interface materials with various application areas, advantages and disadvantages. This study aimed to evaluate thermal and mechanical properties of graphite sheets and graphite gap pads. The work was done in cooperation with Ericsson AB. A test rig based on the ASTM D5470 standard was used to measure the thermal resistance and thermal conductivity of the materials at different pressures. It was found that several graphite sheets and gap pads performed better than the materials used in Ericsson’s products today. According to the tests, the thermal resistance could be reduced by about 50 % for the graphite sheets and 90 % for the graphite gap pads. That was also verified by placing the materials in a radio unit and comparing the results with a reference test. Both thermal values and mechanical values were better than for the reference materials. However, the long term reliability of graphite gap pads could be an issue and needs to be examined further.
Sammanfattning

Elektronikbranschen rör sig mot högre elektriska effekterättheter, det vill säga högre effekt per volymenhet. Som en följd av detta ökar också efterfrågan på god kylning. Kylningen måste hanteras på alla nivåer, från komponenten som ska kylas, ända ut till omgivningen. Termiska interface material (TIM) används för att förbättra värmöverföringen mellan två ytor i kontakt med varandra eller för att leda värmen över större gap. Det finns flera olika TIM med olika tillämpningsområden, fördelar och nackdelar.

Denna studie gick ut på att utvärdera termiska och mekaniska egenskaper hos grafitfilmer och så kallade ”graphite gap pads” då de används som TIM. Projektet gjordes i samarbete med Ericsson AB. En testuppsättning baserat på ASTM D5470-standarden användes för att utvärdera värmeldningsförmågan och den termiska resistansen hos de olika materialen vid olika trycknivåer. Resultaten visade att flera grafitfilmer och ”gap pads” presterade bättre än materialen som används Ericssons produkter idag. Enligt testerna skulle den termiska resistansen kunna minskas med 50 % för grafitfilmerna och 90 % för ”gap padsen”. Materialens fördelaktiga egenskaper verifierades i en radioenhet där temperaturerna kunde sänkas i jämförelse med ett referentest med standard-TIM. De nya materialen var mjukare än referensmaterialen och skulle därför inte orsaka några mekaniska problem vid användning. Den långsiktiga tillförlitligheten för grafitbaserade ”gap pads” måste dock undersökas vidare eftersom de elektriskt ledande materialen skulle kunna skapa kortslutningar på kretskorten.
Acknowledgement

First of all, I would like to thank Ericsson for giving me the opportunity to perform this Master Thesis at the company. I would also like to thank my supervisor Hans Havtun, at the Royal Institute of Technology, and my local supervisors at Ericsson, Christofer Markou and Bojan Stojanovic, for giving me support whenever it was needed. Finally, I am also grateful for the assistance from Elisabet Aldurén at Ericsson when performing the tests in the radio unit. Without you all, this study would not have been possible to conduct.
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<th>Character</th>
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<tr>
<td>Area</td>
<td>( A )</td>
<td>m(^2)</td>
</tr>
<tr>
<td>Area of the upper copper bar in the TTV</td>
<td>( A_{c,1} )</td>
<td>m(^2)</td>
</tr>
<tr>
<td>Area of the lower copper bar in the TTV</td>
<td>( A_{c,2} )</td>
<td>m(^2)</td>
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<tr>
<td>Test sample area</td>
<td>( A_{\text{sample}} )</td>
<td>m(^2)</td>
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<tr>
<td>Capacitance</td>
<td>( C )</td>
<td>F</td>
</tr>
<tr>
<td>Specific heat capacity</td>
<td>( C_p )</td>
<td>J/(kg(\cdot)K)</td>
</tr>
<tr>
<td>Distance between copper bar surface and closest measurement point in the TTV</td>
<td>( d )</td>
<td>m</td>
</tr>
<tr>
<td>Frequency</td>
<td>( f )</td>
<td>Hz</td>
</tr>
<tr>
<td>Applied Force</td>
<td>( F )</td>
<td>N</td>
</tr>
<tr>
<td>The function used in an uncertainty evaluation</td>
<td>( f )</td>
<td>-</td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>( k )</td>
<td>W/(m(\cdot)K)</td>
</tr>
<tr>
<td>Thermal conductivity of copper</td>
<td>( k_{\text{copper}} )</td>
<td>W/(m(\cdot)K)</td>
</tr>
<tr>
<td>Bulk thermal conductivity of the TIM</td>
<td>( k_{\text{TIM,\text{bulk}}} )</td>
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</tr>
<tr>
<td>Thickness</td>
<td>( l )</td>
<td>m</td>
</tr>
<tr>
<td>Number of devices</td>
<td>( N )</td>
<td>-</td>
</tr>
<tr>
<td>Electrical Power</td>
<td>( P )</td>
<td>W</td>
</tr>
<tr>
<td>Heat power</td>
<td>( Q )</td>
<td>W</td>
</tr>
<tr>
<td>The thermal resistance between sample and surface of upper copper bar</td>
<td>( R_{c,1} )</td>
<td>mm(^2)(\cdot)K/W</td>
</tr>
<tr>
<td>The thermal resistance between sample and surface of lower copper bar</td>
<td>( R_{c,2} )</td>
<td>mm(^2)(\cdot)K/W</td>
</tr>
<tr>
<td>Thermal resistance of a thermal contact</td>
<td>( R_{\text{contact}} )</td>
<td>K/W</td>
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<td>Thermal resistance within a material</td>
<td>( R_{\text{material}} )</td>
<td>K/W</td>
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<td>Absolute thermal resistance</td>
<td>( R_{b} )</td>
<td>K/W</td>
</tr>
<tr>
<td>Total thermal resistance across the TIM (impedance)</td>
<td>( R_{\text{TIM}} )</td>
<td>mm(^2)(\cdot)K/W</td>
</tr>
<tr>
<td>Term</td>
<td>Symbol</td>
<td>Unit</td>
</tr>
<tr>
<td>----------------------------------------------------------------------</td>
<td>---------</td>
<td>---------</td>
</tr>
<tr>
<td>Standard deviation of measured quantity</td>
<td>( s_\xi )</td>
<td></td>
</tr>
<tr>
<td>Thickness of the test sample</td>
<td>( t )</td>
<td>m</td>
</tr>
<tr>
<td>Temperature measurement of the electrical resistor in the TTV</td>
<td>( T_1 )</td>
<td>K or °C</td>
</tr>
<tr>
<td>Initial temperature of the electrical resistor</td>
<td>( T_{1,0} )</td>
<td>K or °C</td>
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<tr>
<td>Temperature measurement of thermocouple 2 in the TTV</td>
<td>( T_2 )</td>
<td>K or °C</td>
</tr>
<tr>
<td>Temperature at surface close to thermocouple 2</td>
<td>( T_{2,\text{surface}} )</td>
<td>K or °C</td>
</tr>
<tr>
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<td>( T_3 )</td>
<td>K or °C</td>
</tr>
<tr>
<td>Temperature at surface close to thermocouple 3</td>
<td>( T_{3,\text{surface}} )</td>
<td>K or °C</td>
</tr>
<tr>
<td>Temperature measurement of thermocouple 4 in the TTV</td>
<td>( T_4 )</td>
<td>K or °C</td>
</tr>
<tr>
<td>Temperature measurement of thermocouple 5 in the TTV</td>
<td>( T_5 )</td>
<td>K or °C</td>
</tr>
<tr>
<td>Error stated by manufacturer</td>
<td>( u_\xi )</td>
<td></td>
</tr>
<tr>
<td>The overall probable uncertainty</td>
<td>( u_\psi )</td>
<td></td>
</tr>
<tr>
<td>Voltage</td>
<td>( V )</td>
<td>V</td>
</tr>
<tr>
<td>Thermal diffusivity</td>
<td>( \alpha )</td>
<td>m²/s</td>
</tr>
<tr>
<td>Distance between ( T_4 ) and ( T_5 ) in the TTV</td>
<td>( \Delta L )</td>
<td>m</td>
</tr>
<tr>
<td>Thermal expansion of the TTV</td>
<td>( \Delta L_{\text{thermal expansion}} )</td>
<td>( \mu \text{m} )</td>
</tr>
<tr>
<td>Temperature difference</td>
<td>( \Delta T )</td>
<td>K or °C</td>
</tr>
<tr>
<td>Temperature difference between ( T_4 ) and ( T_5 )</td>
<td>( \Delta T_{\text{copper}} )</td>
<td>K or °C</td>
</tr>
<tr>
<td>Temperature difference across the TIM</td>
<td>( \Delta T_{\text{TIM}} )</td>
<td>K or °C</td>
</tr>
<tr>
<td>Temperature difference between ( T_2 ) and ( T_3 )</td>
<td>( \Delta T_{\text{TIM,2-3}} )</td>
<td>K or °C</td>
</tr>
<tr>
<td>Maximum error for input quantity</td>
<td>( \Delta \xi_i )</td>
<td></td>
</tr>
<tr>
<td>Thermal impedance</td>
<td>( \Theta )</td>
<td>K/W</td>
</tr>
<tr>
<td>The measured quantities in the function for maximum error</td>
<td>( \xi )</td>
<td></td>
</tr>
<tr>
<td>Density</td>
<td>( \rho )</td>
<td>kg/m³</td>
</tr>
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## Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>AFG</td>
<td>Advance Force Gauge</td>
</tr>
<tr>
<td>CMOS</td>
<td>Complementary Metal–Oxide–Semiconductor</td>
</tr>
<tr>
<td>CNT</td>
<td>Carbon Nano Tubes</td>
</tr>
<tr>
<td>CTE</td>
<td>Coefficient of Thermal Expansion</td>
</tr>
<tr>
<td>CVD</td>
<td>Chemical Vapour Deposition</td>
</tr>
<tr>
<td>GNF</td>
<td>Graphite Nano Fibre</td>
</tr>
<tr>
<td>HOPG</td>
<td>Highly Ordered Pyrolytic Graphite</td>
</tr>
<tr>
<td>MWNT</td>
<td>Multi Wall Nano Tubes</td>
</tr>
<tr>
<td>PA</td>
<td>Photo Acoustic</td>
</tr>
<tr>
<td>PA</td>
<td>Power Amplifier</td>
</tr>
<tr>
<td>PCB</td>
<td>Printed Circuit Board</td>
</tr>
<tr>
<td>PCM</td>
<td>Phase Change Material</td>
</tr>
<tr>
<td>PSA</td>
<td>Pressure Sensitive Adhesive tape</td>
</tr>
<tr>
<td>RoHS</td>
<td>Restriction of the Use of Certain Hazardous Substances in Electrical and Electronic Equipment</td>
</tr>
<tr>
<td>SWNT</td>
<td>Single Wall Nano Tubes</td>
</tr>
<tr>
<td>TIM</td>
<td>Thermal Interface Material</td>
</tr>
<tr>
<td>TTV</td>
<td>Thermal Test Vehicle</td>
</tr>
<tr>
<td>WEEE</td>
<td>Waste Electrical and Electronic Equipment</td>
</tr>
<tr>
<td>xGnP</td>
<td>Graphitic nano Platelets</td>
</tr>
</tbody>
</table>
1 Introduction

This section contains a brief background of the areas relevant to this project. The background is followed by the aims, the relevance of the work and the limitations of the study.

1.1 Background

Along with the increasing power of electronic devices, the demand on the thermal management has also increased. One important part of the thermal management chain is the heat conduction from the hot component to the heat sink or similar. Due to micro level imperfections in the mating surfaces, air with low thermal conductivity is trapped in the voids formed between the component and the heat sink. In order to mitigate this problem, a thermal interface material (TIM) can be used. Several different categories of TIMs exist, all with their own advantages and disadvantages. Graphite is a material which consists of several layers of hexagonal covalent bonded carbon atoms. Weak van der Vaals bindings are acting in between the layers. This structure makes the graphite highly anisotropic. The thermal conductivity in the plane is in the order of 1 500 W/(m∙K), but much lower through the thickness (around 5 W/(m∙K)). The graphite can be fabricated as thin sheets or for example be used as highly conductive fillers in polymer matrix composites such as gap pads (Gwinn and Webb, 2003; Prasher, 2006; Burrows et al., 2009; Tong, 2011).

In general, manufacturers are giving the in-plane thermal conductivity of graphite sheets in their datasheets. It is reasonable since most customers are looking for heat spreading materials. However, as the materials are used as TIMs in Ericsson's products, the through thickness conductivity is of higher importance. Due to the lack of information given by the suppliers, characterisation of this property from various manufacturers is needed in order to compare the performance of their graphite sheets. To have the best practical use of the tests, the measurements should be performed in a close-to-application test rig.

Gap pads are used to transfer heat across larger gaps. One important factor regarding them is their compressibility. When the electronic product is manufactured, all the parts are produced with certain tolerances. These tolerances can be added up, creating tolerance chains making the gap between a component and heat sink vary in size depending on the specific unit of the same product. The idea is to compensate for this problem by having a compressible TIM (Viswanath, Wakharkar, Watwe and Lebonheur, 2000). However, during the assembly of the product (compression of the gap pad) a pressure will act on the component to be cooled (for example a microprocessor). Since the component only can handle a specific maximum pressure without being damaged, it is vital to know what pressures will occur during the product assembly when using different gap pads. To investigate that, the gap pads have to be compressed to a certain extent at the same time as the pressure is measured. Since the pressure is time dependent with an initial peak before the gap pad relaxes, the measurement needs to be transient (Abadi, 2009).

1.2 Aim and objectives

The aim of this study is to get a better understanding of what characterise a good thermal interface material (TIM) and to find materials that are better than the TIMs used in Ericsson's products today. In order to accomplish this, the thermal performance and the mechanical properties of graphite sheets and gap pads used as TIMs will be evaluated. For the graphite sheets, this translates into two objectives. The main objective is to benchmark the thermal performance of the products from different manufacturers against each other. In addition to this, the compressibility of the graphite sheets will be evaluated.

Concerning the gap pads, the thermal performance is assessed in similar tests as for the graphite sheets. However, the gap pads are used in a different way compared to the graphite sheets and an additional
objective in relation to the mechanical properties is therefore to evaluate the pressures that will occur during the assembly process of a real product.

### 1.3 Relevance

There is a knowledge gap of how TIMs are acting during the compression phase when a product is assembled. A part of this gap can be filled by this Master Thesis work. The thermal and mechanical tests would also be a way to benchmark the materials against each other and the TIMs currently used in Ericsson’s products. Moreover, the thermal conductivity of graphite sheets are most often stated in the plane, whereas the through plane conductivity is more important. The tests bring more knowledge to the through plane conductivity.

### 1.4 Limitations

The project is limited to tests of 21 graphite sheets and two graphite gap pads. In the used measurement set up, it is not possible to measure the thickness of thin materials with high enough accuracy. The material thickness for the graphite sheet thermal conductivity calculations had to be estimated by a separate plastic deformation curve, instead of a more adequate real time thickness measurement. Finally, the thermal contact resistance could not be separated from the thermal results. All the results do thereby also include the thermal contact resistance of the intersection between the TIM and the test equipment.
2 Literature review

This literature review aims to briefly describe where the electronic market is heading today and how this affects the demands on thermal management. The main focus is however on TIMs; why and how they are used and some advantages and disadvantages with the different kinds. More focus is on carbon based TIMs as they are the main subject of this study. Different methods of thermal and mechanical characterisation of TIMs are described in the last section.

2.1 Electronic cooling

The electronic market is moving towards higher and higher power densities (more power in less space) and by that more heat need to be dissipated to keep the electronic components at sufficiently low temperatures. The power of complementary metal–oxide–semiconductor (CMOS) chips (for example many microprocessors) can according to Hannemann (2003) be estimated by

\[ P \sim NCV^2f, \]

where \( P \) is the power dissipation (W), \( N \) is the number of devices per chip, \( C \) is the capacitance (F) of the logical elements, \( V \) is the voltage (V) and \( f \) is the operating frequency (Hz). The capacitance has been reduced with smaller sizes of chips and the voltage has been lowered as well. The increase of power is instead due to the higher frequencies and an increasing number of devices per chip (Hannemann, 2003). In 2020 the power density is expected to reach 200 W/cm² (Pranoto, Leong and Jin, 2012). Higher power densities mean higher temperature of the electronic components if the cooling system remains the same. The failure rate of electronic components is increasing with the junction temperature. As a rule of thumb, the rate is doubled for every 10 °C of temperature increase (Tong, 2011). Hence, the improvement in thermal management becomes important.

The thermal management can be divided into management on different electronic packaging levels. The chip level is to dissipate heat from an actual chip; the board level is the heat transfer from the printed circuit board (PCB) or chip package to the electronic system or chassis; the system level is the management that refers to dissipating the heat from the system or chassis to the system heat exchangers and to the ambient. The heat management can be performed in numerous ways and look different on the various levels. A common method is however to use copper heat-spreaders from the chip, aluminium or copper heat-spreaders from the PCB and natural or forced convection heat exchangers on the system level (Tong, 2011). All modes of heat transfer can be associated with electronic cooling, within the materials it is however the heat conduction that acts. The basic equation for one-dimensional steady state heat conduction is the Fourier equation (Holman, 2010; Tong, 2011):

\[ Q = k \cdot A \cdot \frac{\Delta T}{l}, \]

where \( Q \) is the rate of heat flow (W), \( k \) is the thermal conductivity (W/(m·K)), \( A \) is the contact area (m²), \( l \) is the distance of heat flow (m) and \( \Delta T \) is the temperature difference (K). To have a good heat transfer, and thereby small temperature difference, it is important to have a high thermal conductivity and large area, whereas the distance (thickness) shall be small.

2.2 Thermal interface materials

In the thermal management chain, thermal interfaces occur when two components meet, for example between a heat sink and the heat spreader. Due to micro level imperfections in the mating surfaces, the actual contact area could be as little as 1 % of what is apparent on a macroscopic level. The rest of the area is consisting of air-filled gaps with very low thermal conductivity (0.026 W/(m·K) at room
temperature) acting as a thermal barrier (Gwinn and Webb, 2003). In order to improve the performance of the thermal management, these air gaps should be filled with a material with higher conductivity; referred to as a thermal interface material (TIM). An ideal TIM will replace all the space that otherwise would be occupied by air (Prasher, 2006). A schematic view of the principle of TIMs can be seen in Figure 1.

![Figure 1. In the left picture is a schematic view of a thermal interface between two materials. The thermal conductivity is very low in the air gaps formed at the interface (indicated by dotted arrows). In the right picture an ideal TIM has fully taken the place of the air and the overall thermal conductivity is consequently higher.](image)

In some applications the distance between the surfaces is larger due to the construction of the system. In those cases there will be no contact at all between the materials and a gap filler is needed (Viswanath et al., 2000). An illustration of a gap filler is visible in Figure 2.

![Figure 2. A gap filler is needed if the distance between the surfaces is large.](image)

There are often two TIMs needed in an electronic package. The first TIM (TIM 1) is in the interface between the silicon die and a heat spreader, the second TIM (TIM 2) is between the heat spreader and a heat sink (Prasher, 2006). Some TIMs are constructed to be used as either TIM 1 or TIM 2 while others only can be used in one of the applications (Tong, 2011).

### 2.2.1 Important characteristics of TIMs

There are several important factors to consider when choosing a TIM (Tong, 2011):

- Thermal conductivity within the material
- Conformability and “wetting” of surfaces (low contact resistance)
- Heat spreading capability
- Coefficient of thermal expansion
- Compressibility characteristics
- Density
- Electrical Conductivity
- Compatibility with materials
- Long-term reliability
- Ease of application and replacement
- Environmental sustainability
- Price

When working with thermal interfaces it is common to talk about the thermal resistance, $R_{th}$. The absolute thermal resistance is defined as

$$R_{th} = \frac{l}{k \cdot A},$$

where $R_{th}$ is the thermal resistance (K/W), $k$ is the thermal conductivity (W/(m·K)), $A$ is the contact area (m²) and $l$ is the distance of heat flow (m). The thermal resistance is a material’s (with a specific area and thickness) ability to resist the flow of heat. Thermal resistances can be added in series or in parallels analogue to electrical resistances. A low thermal resistance implies a small temperature difference across the material if the applied heat is the same. When a TIM is considered, there is a bulk resistance within the material (based on the thermal conductivity, area and thickness) and a resistance related to the contact between the TIM and the mating surfaces. If these resistances are added, the thermal impedance, $\Theta$, is achieved (Tong, 2011):

$$\Theta = R_{material} + R_{contact},$$

where $\Theta$ is the thermal impedance (K/W), $R_{material}$ and $R_{contact}$ are the bulk material resistance (K/W) and contact resistance (K/W) respectively. To have the best thermal performance the impedance should be as low as possible; thereby the focus on TIMs should not solely be on improving the thermal conductivity and reduce the thickness of the material but also minimising the resistance at the contact. A material that can conform well to the surfaces will have a low rate of trapped air and thus a low contact resistance (Tong, 2011). Other aspects that affect the thermal resistance, however not directly related to the TIM, are the surface roughness and the applied pressure. A surface with a large roughness will have more air trapped and thus a high resistance. A higher pressure would however make the materials conform better and therefore decrease the resistance. Several equations for estimations of the contact resistance between surfaces with and without TIMs can be found in reports from Yovanovich et. al. (1997) and Yovanovich and Marotta (2005). In many cases resistances and impedances are tabulated with the unit m²·K/W (or mm²·K/W) in literature (de Sorgo, 1996; Holman, 2010; Vass-Várnai, Sárkány and Renicz, 2012; Rong, Lin, Zheng and Lu, 2014). It is easier to use in TIM comparisons as it takes away the impact of the contact area which otherwise have to be considered.

Another important aspect is the TIM’s ability to spread heat. Most often there is a non-uniform heat distribution across the electronic chip. A good heat spreading TIM can even out the temperature gradient and thereby keeping the hotspots below a certain design temperature (Prasher, 2006; Tong, 2011). For heat spreading capability the thermal diffusivity, $\alpha$, is important. It is a value which describes the speed of which a temperature disturbance travels from one part of a body to another. The thermal diffusivity is related to the thermal conductivity as

$$k = \alpha \cdot \rho \cdot C_p,$$
Tolerance issues are always present when manufacturing a product; the more exact dimensions needed, the more expensive the product will be. These mechanical issues translate to the use of TIMs. If a gap is to be filled with a TIM, the gap size might vary between different specimens of the same product, yet it is preferred to just have one size of the gap filler in all products. The gap filler then need to be larger than the largest gap possible (including the tolerance offset) to always have good contact, and as the gap is smaller than the TIM, the TIM needs be compressed (Viswanath et al., 2000). During the compression phase a force is applied, creating a pressure which propagates trough the material. For some materials the pressure is time dependent with a peak during the initial phase before the material relaxes (Abadi, 2009). It is important that the pressure does not exceed limits for what the components to be cooled can handle (Markou and Stojanovic, 2014). Furthermore, for a TIM, and all other components in a product, a low density gives easier handling of the final product during for example transport and mounting, which ultimately may lead to lower costs.

The coefficient of thermal expansion (CTE) is a property which tells how much the relative expansion (ppm/K) of the material will be when exposed to a change in temperature. If there is a mismatch between the CTE of two materials joined together, a mechanical stress will be induced when the joint is subjected to a temperature change. In severe cases this phenomena may lead to premature failure of the component; especially when the strain accumulates over several thermal cycles. The CTE of the TIM should be adapted to the surrounding materials do avoid this problem (Tong, 2011).

To avoid shortages if the TIM accidently comes in contact with for example the PCB, an electric insulating TIM is preferable. In other cases, when the risk of shortage is non-existent, an electrical conducting TIM can be used to shield off electromagnetic interference. Furthermore, it is important that the TIM is non-corrosive with the surrounding materials. The long-term reliability of the TIM is vital to give sufficient thermal performance even after long time of operation. In that sense the TIM shall not be the limiting factor for the lifetime of the electronic device. The TIM should also be easy to apply during production and to replace if needed during product maintenance (Tong, 2011).

In the European Union, manufacturers of electronics must follow certain regulations and directives regarding the materials they use. The first directive, the Restriction of the Use of Certain Hazardous Substances in Electrical and Electronic Equipment (RoHS), regulates how much of certain materials that are allowed when used in electronics. For example, lead is only allowed at small ratios while asbestos is totally forbidden. The second directive, Waste Electrical and Electronic Equipment (WEEE), says that the manufacturers must be able to collect and recycle their devices in an ecologically friendly way. If a company fails to comply with either RoHS or WEEE, they will face penalties or possibly be banned from selling their products in the EU. This should be considered when choosing the TIM as well. Finally, the price of the TIM relative to the gain in thermal performance is also worth considering (Tong, 2011).

### 2.2.2 Different types of TIMs

There are several types and variations of TIMs on the market today, each with their own advantages and disadvantages. Some of the common TIMs are thermal greases, graphite sheets, phase change materials (PCM), gap pads, putties and solders. Carbon is a versatile atom that exists in several allotropes such as diamond, graphite and fullerenes (Wunderlich and Jin, 1993). Owing to the good thermal properties, it can be used by itself or as a part of a composite (Tong, 2011). The Carbon based TIMs are elaborated more on in 2.3 Carbon based TIMs.

#### 2.2.2.1 Thermal greases and compounds

Thermal grease (or thermal paste) is a highly conformable material that wets the surfaces well under low pressures. It is often made of silicone or hydrocarbon oils and is commonly found in desktops between the processor chip and the heat sink. In general, the grease itself has very low thermal conductivity but it is enhanced by loading the grease with highly conductive particles (often metals and/or ceramics). The low
viscosity makes it possible to have a thin layer which gives low thermal impedance. A disadvantage is that it is messy during the application and it is not uncommon that the grease pump out after a while (due to the motion caused by the thermal expansion and contraction of the interface surfaces during temperature cycling), losing thermal performance. Using silicone in the grease also introduces a risk of outgassing (de Sorgo, 1996; Viswanath et al., 2000; Prasher, 2006).

Thermally conductive compounds are grease-like from the beginning. However, after they have been applied and conformed to the surface, they are treated with heat to transform into a thin rubber film. In rubber state they bond to the surfaces via adhesion. The thermal performance of the compound is similar to that of the grease, but without the problem of dry out. They are also less messy to work with and easier to remove than the greases, but an extra curing step is needed during the manufacturing process (de Sorgo, 1996).

2.2.2.2 Phase change materials

In order to cope with the problems regarding the grease flowing out of the joint, a PCM can be used. It is solid at room temperature, but changes to liquid state as it heats up. PCMs can be divided into organic and inorganic compounds. Example of organic PCMs are paraffin and fatty acids, while salt hydrates and eutectic materials are inorganic. However, the organic PCMs are most widely used (Liu and Chung, 2001; Tong, 2011). PCMs can also be a part of a composite in combination with highly conductive materials. A suitable melting point (typically between 50 °C and 90 °C), high heat of fusion, good stability during thermal cycling, low viscosity in liquid state and high thermal conductivity are some of the most important characteristics of PCMs (Tong, 2011). The main advantages of PCM over thermal grease are that it is easier to work with and has better stability over time. The disadvantage is that its thermal performance is slightly lower as both the bulk material thermal conductivity is lower and the surface resistance is higher. Finally, a higher contact pressure is needed, increasing the mechanical stresses in the thermal package (Gwinn and Webb, 2003; Prasher, 2006).

2.2.2.3 Gap pads

Gap pads (also sometimes referred to as gap fillers or elastomeric thermal pads) are thicker materials that can be used if the surfaces in the thermal interface are not in direct contact with each other. They are typically 200-3 000 μm thick and consist of polymer matrices (low thermal conductivity) with high thermally conductive particles or fibres embodied (Viswanath et al., 2000; Tavman and Akinci, 2000). Due to their softness, the gap pads can be deformed and are therefore not sensitive to tolerance issues in the assemblies. There is however a trade-off between the ability to deform and the thermal conductivity – the more filler used, the harder the pad will get. Common failure mechanisms are that the surface resistance increases or that the TIM loosens from the surface if the applied pressure is too low (Viswanath et al., 2000).

2.2.2.4 Putties

Putties are used for the same applications as gap pads; as gap fillers. The material is however softer and conform to the surface even better. The main matrix is often silicon based with filler materials such as aluminium or boron nitride. Putties are dispensable which is an advantage as it makes them easier to use in the assembly process. They can be applied in various thicknesses, ranging from a few mm down to 200 μm. Furthermore, they compress at low pressures (good for the components), are reusable and have a thermal conductivity of up to 17 W/(m-K). A thermal resistance of 16 mm²-K/W has been measured at a pressure of 100 kPa with an initial material thickness of 0.2 mm. Putties can show some signs of a pump-out effect and cracking after thermal cycling tests (Khuu, Osterman, Bar-Cohen and Pecht, 2009; Fujipoly, 2012).
2.2.2.5 Metals

Metallic TIMs can consist of solid sheets made of a solder alloy. One common metal used is Indium. The material is soft and has a thermal conductivity of about 80 W/(m·K). The metals can be heated through a process called reflow, which makes the TIM melt and wet the surfaces by surface tension. This method makes the contact resistance low as it has a good contact at the same time as metals have high thermal conductivities. The problems occur when the CTE of the TIM differs a lot from the surrounding faces, creating mechanical stresses which can lead to failure (Lewis et al., 2007). Another problem may arise during the soldering process. The high temperatures needed for reflow can damage the surrounding components. Furthermore, strong metallic bonds can be formed between the TIM and the surrounding faces (Hurley, Rumer, Christner and Renfro, 2008). This will make a disassembly of the product difficult if needed. Metals can also be used as highly conductive fillers to increase the conductivity of greases, gap pads and other TIMs (Tong, 2011).

2.3 Carbon based TIMs

On earth, carbon is one of the most common atoms. The carbon atom has four valence electrons and can create bonds with up to four other atoms. By bonding to other elements or to other carbon atoms, a great variety of materials can be formed. Carbon alone can create allotropes such as diamond, graphite, amorphous carbon, fullerene and nanotubes, all with different mechanical and thermal properties. In diamond, each carbon has a tight covalent bond with four other carbons, forming an isotropic structure giving the hardest known natural material. Diamond is also characterised by very high thermal conductivity in all directions. Graphite however, has highly anisotropic thermal and mechanical properties due to its strong bonding to three neighbouring carbons in the same plane, but relatively weak van der Vaals bonds in-between the planes. As a result of the good properties, carbon is widely used in TIMs (Wunderlich and Jin, 1993; Tong, 2011; Burrows et al., 2009).

2.3.1 Diamond

Diamond consists of carbon atoms, each in a tetrahedral environment, forming strong covalent bonds to four other carbon atoms (see Figure 3). The structure of the carbon makes it one of the hardest materials known. Furthermore, diamond is an electric isolator since its structure do not allow any partially filled conduction bands (Burrows et al., 2009). The unusual combination of electric insulation and a high thermal conductivity of 900-2 500 W/(m·K) (which is one of the highest available in room temperature), makes it a highly attractive material. The lattice vibration (also called phonon conduction) in the diamond crystal enables the high thermal conductivity, in contrast to metals where the heat is conducted by electrons. Moreover, diamonds are inert to chemicals, have a small CTE and have optical qualities often favoured (Tong, 2011; Inagaki, 2014c).

Figure 3. A schematic view of the structure of diamond. (University of Wisconsin-Madison, 2008)
The technique for creating artificial diamonds has been available since the 1950s. By applying high pressure and temperature in an environment containing a catalyst, the process of transforming graphite to diamond through growth or sintering can be accelerated. The sintered diamonds are not 100% pure due to materials remaining from the process, which makes them insufficient for optically demanding applications. However, they are still good enough for thermal applications. In the 1980s, the chemical vapour deposition (CVD) was developed, enabling a more versatile product. The diamond is deposited from gas phase and can coat larger areas and be grown to thicknesses sufficient for free standing parts, which in turn can be cut to various shapes (Bigelow, 1993). The growth process can be accelerated on the behalf of some quality. The best quality industrial diamonds for optical applications need more time, but still, the lower quality diamonds can be used for heat management applications in for example heat sinks.

The diamonds are often used in metal-diamond composites and has as a result of increased conductivity (670 W/(m·K)) received more attention lately. The application areas are mostly heat sinks and heat spreaders, but as with TIMs the thermal contact resistance is important. A way to ensure good contact is to let the diamond form strong carbon-metal bonds at the surface. These carbides can be formed with elements such as Ti, Zr, Ta, Cr or Si. To avoid the potential oxidising of the surfaces the reactive metal could be covered with Au, Ag, Pt, Cu or another protecting metal. The metal-carbon interaction also means that two types of heat conduction interact; the electron heat conduction in the metal and the lattice vibration in the diamond. An advantage with the composites is that there is a possibility to tailor the CTE to match the semiconductor material (Tong, 2011; Battabyal et al., 2008). Thin films of diamond can be used as TIMs. Due to too large surface roughness, the films have to be polished on both sides, increasing the production cost (Jaiswal and Dwivedi, 2011).

### 2.3.2 Graphite

Graphite is formed of a layered structure with strong covalent bonds within the layers, and weak van der Waals bonds connecting the layers (see Figure 4). The bonds between the layers are weakened in the presence of water, letting the layers slide relative to each other, creating the possibility to use graphite as a lubricant or in pencils. In contrast to diamond, graphite has anisotropic physical properties (Burrows et al., 2009). The thermal conductivity is in the magnitude of 1 000 W/(m·K) in the plane but only around 5 W/(m·K) through the thickness, making it a good heat spreader and possibly also an insulator. Another property which differentiates graphite from diamond is its ability to conduct electricity. This is possible due to the structure which creates partially filled electrical conductive bands. The conductivity is however much higher in the plane than through the planes. Graphite can both be found in nature and be produced synthetically, just like diamond (Tong, 2011). The synthesis can be done through carbonisation of polymers or pyrolysis of hydrocarbons (Pierson, 1993).

![Figure 4. A schematic view of the graphite layered structure. The layers are connected with weak van der Waals bonds. (University of Wisconsin-Madison, 2008)](image-url)
2.3.2.1 Natural graphite

Natural graphite of varying crystallinity can be found in mesomorphic rocks in nature and is divided into amorphous, flake and high crystalline graphite. The natural graphite used in thermal management contains up to 98 % crystalline graphite and is a soft material (Tong, 2011). The layered structure gives the anisotropic character of the physical properties mentioned earlier. The electrical conductivity as well as the thermal conductivity and CTE are different in the plane and through the thickness. For thermal management the material is used in heat sinks, heat spreaders and TIMs. The features that make the natural graphite attractive as a TIM, is its high thermal conductivity in combination of the ability to conform well to the surfaces under moderate pressures (Smalc et al., 2005).

The natural graphite can be formed to thin sheets of more ordered graphite structures. This can be done by first inserting ions between the weakly bonded layers in the graphite. The ions decompose and volatilises as the material is heated, creating a high internal pressure between the graphite layers. Due to the overpressure, the layers are pushed aside as the ions escape the structure. Interstitial graphite particles are expanded in an accordion-like way, making the particles look like worms. The material can then be mechanically treated and formed to a thin flexible sheet that can be used as a TIM or a heat spreader. The thermal conductivity of the graphite is 140-500 W/(m·K) in the plane (conductivities of around 320 W/(m·K) are commercially available (Inagaki, 2014)) and 3-10 W/(m·K) through the thickness. Compared to aluminium and copper, the graphite has a large advantage with its low density in comparison. The density is ranging from 1.1-1.7 g/cm³ compared to copper's 8.89 g/cm³ and aluminium's 2.7 g/cm³ (Smalc et al., 2005).

2.3.2.2 Pyrolytic graphite

By using a CVD method the pyrolytic graphite can be created in a similar manner as diamond. The pyrolysis process is based on thermal decomposition of a hydrocarbon in gas phase. The pyrolysis takes place in a temperature range between 300 °C and 1 400 °C depending on what precursors used. One common precursor is methane (pyrolysed above 1 100 °C and pressures 0.001 to 1 atm) and the reaction formula can be simplified to

\[ \text{CH}_4 \rightarrow \text{C} + 2\text{H}_2, \quad (6) \]

whereas in reality more reactions are taking place in the process. The graphite can, as diamond, be used to coat other materials or if grown thick enough create free standing products. If the material to be coated is temperature sensitive, a plasma CVD can be used at temperatures of 300-500 °C (Pierson, 1993).

After the CVD process the graphite is amorphous with impurities in the crystal structure and non-parallel flakes. The distances between the layers are around 0.3440 nm which is large compared to the ideal distance of 0.3354 nm in a graphite crystal. In order to improve the structure, the material can be treated at high temperatures through an annealing process (graphitisisation). Depending on the process, different degrees of oriented graphite can be achieved. If the annealing is performed at temperatures above 2 700 °C and under pressures of several atmospheres, the graphite will be close to perfect; highly oriented pyrolytic graphite (HOPG) is created. Thermal conductivities of above 4 000 W/(m·K) have been achieved in highly crystalline pyrolytic graphite that has been stress annealed (Pierson, 1993). However, commercial graphite has reached around 1 600 W/(m·K) (Inagaki, 2014c). The conductivity decreases with increased temperature and has its minimum at around 1 000-2 000 °C, temperatures which are not relevant in most electronic cooling applications. The CTE of the graphite is close to zero in the plane and 15-25 ppm/K in the direction of the thickness (Pierson, 1993). The HOPG is fragile due to the week bonds between the layers. To cope with that the HOPG can be encapsulate in a shell of another material (Montesano, 2006).
2.3.3 Graphene

Graphene is a two dimensional material consisting of a single layer of a graphite structure. The atoms are arranged in the same hexagonal manner as in graphite (consider one layer in Figure 4). There are several methods available for creating this material: cleavage of graphite mechanically, exfoliation of graphite via intercalation compounds (similar to production of flexible natural graphite sheets described in 2.3.2.1 Natural graphite), CVD process, organic synthesis and more (Inagaki, 2014b). As the graphene has received increasing attention, the word “graphene” have often been used in the wrong context. Graphene shall only refer to the one layer structure but is mistakenly used for thin materials with a few layers as well; multi-layer graphene (MLG). The distinction between multi-layer graphene and thin graphite is merely a matter of the material thickness, but is not well defined (Shahil and Balandin, 2012b; Inagaki, 2014b).

The properties which make graphene an interesting material are its high thermal conductivity, great mechanical strength and small CTE. The thermal conductivity of a suspended high quality CVD graphene was measured to exceed 2500 W/(m·K) at a temperature of 350 K (Cai et al., 2010). As a filler in composites, the graphene show a greater enhancement of the overall conductivity of the composite compared to graphite and CNT, even at lower loading rates. This can be due to a low thermal resistance between the graphene and the matrix material (Shahil and Balandin, 2012b).

2.3.4 Carbon nanotubes

The carbon nanotubes (CNT) are easiest interpreted as graphene sheets rolled into cylinders. Depending on if the tubes consists of one wall (see Figure 5) or several walls, they are referred to as single wall nanotubes (SWNT) or multi wall nanotubes (MWNT). The SWNT show a thermal conductivity of about 3500 W/(m·K) in the axial direction at room temperature and the corresponding value for MWNT is somewhat less (Pop et al., 2006; Tong, 2011). As with many other carbon forms there are numerous ways to synthesise the material. Creating a discharge between carbon electrodes forms a mix of different carbon structures including the CNTs. However, the process is difficult to control. Hence, high purity CNT are created by other means; laser-abrasion, modified arc discharge and various CVD processes are proposed (Inagaki, 2014a). Plasma enhanced CVD processes have been successfully used to grow vertically aligned CNTs on a silicon wafer with good thermal properties (Xu and Fisher, 2006).

Figure 5. Carbon nanotubes can be visualized as rolled graphene layers. They can be either single walled or have multiple walls (eg. tubes inside each other). (University of Wisconsin-Madison, 2008)

The CNTs are often used as filler material to enhance conductivity but can also be “woven” into mats or formed into sheets and sponges. Despite the high thermal conductivity, the performance of the CNT as filler has not been that good in practice. One reason for this could be the low conductance in the interface between the CNT and the matrix material, also referred to as the Kapitza conductance (Huxtable et al., 2003; Warzoha, Zhang, Feng and Fleischer, 2013; Inagaki, 2014a). However, this conductance have been reported to be higher at higher temperatures (Rong et al., 2014).

2.3.5 Carbon nanofibres

Carbon nanofibres have been used since the late 19th century when it first was introduce by Thomas Edison in his early light bulbs. At that time, they were produced by pyrolysis of cellulose-based
materials, but since then several other methods have been developed. The fibres can for example be fabricated from tar or petroleum oil through a mesophase-pitch method or be produced in a vapour growing process. Owing to good thermal (thermal conductivity of up to 1 950 W/(m∙K)) and mechanical properties, the carbon fibres have been used in composites for the space and aircraft industry and for advanced thermal management in electronic packaging (Arai, 1993). In TIM applications, the carbon fibres have for example been used on so called backypapers that can range from 300 μm to 50 μm thicknesses (Memon, Haillot and Lafdi, 2011).

2.3.6 Carbon in composites

By adding MLG and graphene to a Al and ZnO₂ enhanced thermal grease, the thermal conductivity could be increased from 5.8 W/(m∙K) to 14 W/(m∙K) with a loading fraction of 2 %. Such a low fraction of fillers keep the viscosity and conformability properties of the grease almost the same, while minimising the contact resistance. A reason for the good results using graphene and MLG as a filler is the low thermal resistance between the graphene and the matrix material (Shahil and Balandin, 2012b).

Studies have been performed on how to enhance the thermal performance of mats “woven” by CNTs and graphite nanofibres (GNF). By adding graphene nanoplatelets (xGnP) to the nanostructure, the contact area between the structures is larger, giving better possibilities to transfer heat via lattice vibration. The performance was readily enhanced as the interfacial resistance could be lowered with 31-86 % depending on if the mats were made of GNF, SWCNT or MWCNT. For the SWCNT mats, the thermal resistance in the contact between the TIM and the copper heat sink surface was very low. The best TIM shoved to be a MWCNT mat enhanced with graphene nanoplatelets and a PCM. The thermal resistance across the interface was 0.7 mm²-K/W under an applied pressure of 0.56 MPa, 81 % lower than for the commercial Arctic Silver 5 thermal grease (Warzoha et al., 2013).

By applying carbon black paste on flexible graphite sheets, the thermal resistance at the interfaces could be reduced. Compared with silver enhanced grease, the black paste was a lot better and enhanced the conductivity across the surface with more than 100 % (Leong, Aoyagi and Chung, 2006).

2.4 TIMs in Ericsson’s products

55 % of Ericsson’s net sales are within the area “networks”. Ericsson excels in the area mobile network (and particular mobile broadband networks), where the company is the world’s largest supplier. Ericsson provides voice, data and mobile broadband services through the systems LTE, GSM, WCDMA and CDMA (Ericsson, 2014c). Mobile phones and alike need a network of base stations to function. The base stations receives and transmits signals through radio waves to communicate with the mobile phones (Ericsson, 2014b). The base stations exist in several different versions for use in different applications and environments (Ericsson, 2014a). With an increased demand of serving more customers at increasing speeds, the power of the electronic in the base station have also increased. Typical components that need cooling are power amplifiers (PA) and microprocessors.

In older products, individual heat sinks are commonly used (see Figure 6). The TIM is placed between the component to be cooled and the heat sink. TIMs that have been used in this application is PCM and Pressure Sensitive Adhesive tape (PSA). Springs are used to maintain the pressure when the thickness of the PCM reduces during phase change.
The newer products do however have a heat management system in which all heat from the PCB is conducted to a large common aluminium heat sink, where the heat is dissipated by natural or forced convection to the ambient. The TIMs are needed to ensure good conduction from the hot components to the heat sink. The PA unit is cooled through the PCB by copper vias. The aluminium heat sink is firmly connected to the backside of the PCB where a thin TIM is needed to ensure good contact. Either thermal grease or 100 μm thick graphite sheets are used today. The other components are cooled from the top of the PCB, through the TIMs, to the heat sink. The gap between the components and the heat sink is designed to be 2 mm. Hence, a gap filler is needed (gap pad or thermal putty). To ensure the same gap distance for all the components on the PCB, the heat sink have heels to match the different component heights on the PCB (Markou and Stojanovic, 2014). The principal of how the cooling is performed can be seen in Figure 7.

The TIMs that are used shall follow the general guidelines described in 2.2.1 *Important characteristics of TIMs* but with extra focus on the assembly process. Due to tolerance issues in the production of the PCB, the gap between the heat sink and the component to cool varies somewhat. In most products today the nominal gap is 2.0 mm ± 0.3 mm (including tolerances for heat sink, PCB and component) and the gap
pads are 2.54 mm ± 10 %. In the worst case the gap is 1.7 mm while the pad is 2.8 mm. Hence, the pad has to be compressed 40 %. Ericsson is now moving from those gap sizes and gap pads (3 W/(m-K)). In the upcoming products the nominal gap is 1 ± 0.3 mm, the gap pads are 1.25 mm ± 10 % and of 7 W/(m-K) material. This gives a maximum needed compression of 50 %. In future generation products, gap pads with thermal conductivities of up to 25 W/(m-K) might be used.

During the compression phase of the gap pad, a pressure is applied which propagates to the PA or microprocessors. The pressure will vary with time and the characteristics of the TIM, with an initial peak in the beginning of the compression before the relaxation phase. During the assembly, product failure shall be avoided by not letting the pressure on the components exceed the limits of what they can handle (Markou and Stojanovic, 2014).

### 2.5 Methods for characterisation of TIMs

Most literature is only treating the thermal characterisation of TIMs even though there are other characteristics, such as CTE and hardness, that are also interesting when choosing a TIM. There are several test methods available for thermal characterisation of TIMs due to the great variations of TIMs. The demand on the equipment testing the in-plane thermal conductivity of graphene is totally different from the equipment for testing through thickness bulk conductivity of gap pads. Both steady state and transient methods can be used for thermal evaluation. In general the steady state measurements are performed to obtain the thermal conductivity, whereas the transient methods measure the thermal diffusivity. However, the conductivity can be calculated from the diffusivity using equation (5) or vice versa. The disadvantage of using these indirect calculations is that both the density and the specific heat capacity are needed. When using transient methods, the tests can be quicker since there is no need to wait for steady state to be reached. However, the mathematical calculations used to analyse the data in the transient methods are more difficult to perform (Tong, 2011; McNamara, Joshi and Zhang, 2012).

One standardised method for steady state thermal tests of thin TIMs is the ASTM D5470 tester. A variant of this set up was used for the thermal tests in this work (see section 3.1.1 The thermal test setup). It is built of two co-planar cylinders in between which the test sample is placed (see Figure 8). Heat is applied at the top of the structure by an electrical heater and to ensure a uniform heat flux the ASTM D5470 is cooled from below. Some equipment also has the possibility to control the applied pressure in order to better simulate the environment for the TIM in a real application. Temperatures are measured and recorded at strategic points between the heater and the cooler. The temperature differences are then used to calculate the overall thermal conductivity across the sample by the Fourier equation (2). The resistances between the measurement points and the TIM sample have to be taken into account as well as the thermal losses to the surrounding (McNamara, Joshi and Zhang, 2012). In some cases it is possible to differentiate the thermal resistance associated with the contact from the total thermal resistance. If the total thermal resistance (or impedance) of at least three samples of different thicknesses with the same contact resistance are measured, a plot of the resistance as a function of thickness can be made. The intersection of the straight line (that can be drawn through the points) and the y-axis, gives an estimation of the contact resistance (Francois and Bosch, 2001; Hu and Chung, 2011). Nevertheless, the methods based on the ASTM D5470 are often associated with large measurement uncertainties; 10-50 % with the largest error for measurements of low thermal resistances (McNamara, Joshi and Zhang, 2012) (see Table 1). The temperatures are commonly measured with thermocouples which introduce an error that can be minimised by a proper measurement set up and calibration. Using resistance temperature detectors instead would give higher accuracy (Narumanchi, Mihalic and Kelly, 2008). Furthermore, it is important to keep track on the surface roughness of the cylinders as well as the applied pressures since they affect the results (Yovanovich, Culham and Teertstra, 1997) and are good to have if material comparisons are to be made.

Another method is the so called laser flash method that can be used to measure the diffusivity of a material without physically touching the test sample. A flash lamp is directed towards one side of the sample while the temperature of the backside is monitored by an infrared detector. The transient...
measurements are fitted to curves to obtain the thermal diffusivity of the material. The error is in the range ± 3 % (McNamara, Joshi and Zhang, 2012). The through thickness conductivity can be effectively be measured by this method (Shahil and Balandin, 2012a).

Photoacoustic (PA) techniques uses a laser to heat the TIM. The TIM heats the surrounding gas in the PA cell, creating a pressure change which gives an acoustic response measured by a microphone. The signal is translated to a thermal resistance value through a set of equations (McNamara, Joshi and Zhang, 2012).

The 3ω method utilises a strip heater which is in contact with the TIM and is heated by an alternating current with the frequency ω. A temperature variation with the frequency 2ω is induced in the TIM at the same time as the voltage drop over the heater has the frequency 3ω. The temperature oscillations are dependent on the thermal characteristics of the TIM (McNamara, Joshi and Zhang, 2012).

Thermoreflectance is based on a high powered laser that is directed towards the TIM causing oscillating temperatures in the material. A low powered beam is directed on the back of the TIM and the reflection of the high powered beam is measured. The thermal characteristics of the TIM is creating variations in the intensity and phase of the reflected beam (McNamara, Joshi and Zhang, 2012).

Infrared microscopy have proved to be able to accurately measure both the bulk resistance and the contact resistances of the TIMs with no need of thermocouples. This steady state method utilises the hot and cold sides of the TIM to determine a thermal gradient and the resistance is calculated with the known applied heat flux (McNamara, Joshi and Zhang, 2012). Several other methods are also available, such as: hot wire, Raman and electrical, pump and probe, hot disk and transient absorption (Shahil and Balandin, 2012b).

Table 1. Some of the characterisation methods with their reported range and approximated uncertainty (McNamara, Joshi and Zhang, 2012).

<table>
<thead>
<tr>
<th>Method</th>
<th>Reported range</th>
<th>Approximated uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steady state (ex. ASTM)</td>
<td>20-200</td>
<td>10</td>
</tr>
<tr>
<td>Photoacoustic</td>
<td>1-20</td>
<td>0.5</td>
</tr>
<tr>
<td>Thermoreflectance</td>
<td>1-20</td>
<td>0.1</td>
</tr>
<tr>
<td>Infrared microscopy</td>
<td>5-50</td>
<td>1</td>
</tr>
<tr>
<td>Laser flash</td>
<td>0.01-1 000 mm²/s</td>
<td>± 3 %</td>
</tr>
</tbody>
</table>

2.6 List of carbon based TIMs

Several TIMs from the literature have been found to have very good thermal performance. In Table 8 in Appendix A some of the carbon based TIMs are presented along with their test methods. The results of those tests should be reasonably comparable with the results presented in this report.
3 Method

In this study both thermal and mechanical properties of graphite sheets and gap pads were evaluated. A description of the test equipment and the test procedures together with an uncertainty analysis of the methods is presented here. The uncertainty estimations of each parameter used for calculations are described in the last section.

3.1 The test equipment

To evaluate the thermal performance of the TIM, a thermal test vehicle (TTV) based on the ASTM D5470 standard was used. The mechanical properties were measured with MultiTest 2.5-d. These two appliances can be combined into a single set up in order to have control over the applied pressure, the compression of the TIM and the thermal performance at the same time.

3.1.1 The thermal test setup

The thermal test set up (also referred to as the TTV) is heated by a resistive electrical heater at the top (see Figure 8). The heat is conducted down the structure consisting of copper bars, through the TIM and down to the bottom block which is cooled by running water and can be seen in Figure 9. The whole TTV is placed in the MultiTest 2.5-d which enables control over the applied pressure. The MultiTest 2.5-d is further described in 3.1.2 MultiTest 2.5-d. Temperatures are measured with type K thermocouples (from Pentronics) at five points indicated by $T_1$-$T_5$ in Figure 8. Important dimensions of the equipment are summarised in Table 4. The body of the TTV is made of PTFE and PEEK plastic to give a good insulation and a solid structure. The data acquisition is performed with a 20 channel Fluke NetDAQ 2645A. The average surface roughness of the upper and lower copper bar was measured to Ra 0.33 µm and Ra 0.20 µm respectively.
Table 2. The important dimensions of the TTV. The manufacturing procedure was according to ISO 2768-m.

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Dimension</th>
<th>Assigned variable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper bar height</td>
<td>32 mm</td>
<td>-</td>
</tr>
<tr>
<td>Copper bar cross sectional area</td>
<td>24 mm x 24 mm*</td>
<td>$A_{c1}$ and $A_{c2}$ for upper and lower bar resp.</td>
</tr>
<tr>
<td>Centre of $T_2$ to surface</td>
<td>1 mm</td>
<td>$d$</td>
</tr>
<tr>
<td>Centre of $T_3$ to surface</td>
<td>1 mm</td>
<td>$d$</td>
</tr>
<tr>
<td>Centre of $T_3$ to centre of $T_4$</td>
<td>9 mm</td>
<td>-</td>
</tr>
<tr>
<td>Centre of $T_4$ to centre of $T_5$</td>
<td>20 mm</td>
<td>$\Delta L$</td>
</tr>
</tbody>
</table>

* For higher accuracy the sides of the copper bars were manufactured with a tolerance of $\pm 0.05$ mm.

Figure 9. The TTV when incorporated with the MultiTest 2.5-d. A cold plate cooled by water is placed under the TTV to give a uniform heat flux during the tests.

The total resistance (referred to as thermal impedance in 2.1 Electronic cooling) across the TIM is defined by

$$R_{TIM} = \frac{t}{k_{TIM, bulk}} + R_{c1} + R_{c2},$$

(7)

where $R_{TIM}$ is the total thermal resistance (m²⋅K/W) across the TIM, $k_{TIM, bulk}$ is the bulk thermal conductivity (W/(m⋅K)) of the TIM, $t$ is the TIM thickness (m), $R_{c1}$ and $R_{c2}$ are the thermal contact resistances (m²⋅K/W) on the two sides of the TIM. The $R_{TIM}$ value can be calculated from the data measured in the TTV. The equation is

$$R_{TIM} = \frac{\Delta T_{TIM} \cdot A_{sample}}{Q},$$

(8)
where \( \Delta T_{\text{TIM}} \) is the temperature drop (K) across the TIM, \( A_{\text{sample}} \) is the area of the tested TIM sample and \( Q \) is the heat (W) conducted through the TIM. The heat flow through the TIM was estimated by the calculated heat flow through the lower copper bar:

\[
Q = \frac{k_{\text{copper}} \cdot A_{c,2} \cdot (T_4 - T_5)}{\Delta L},
\]

(9)

where \( k_{\text{copper}} \) is the thermal conductivity (W/(m∙K)) of the copper, \( A_{c,2} \) is the cross sectional area (m\(^2\)) of the lower copper bar, \( T_1 - T_5 \) are the measured temperatures (K) and \( \Delta L \) is the distance (m) between temperature measurement point 4 and 5. When calculating the TIM resistance, the temperature difference across the TIM is needed. For practical reasons there are no measurement points directly at the surface of the copper-TIM intersections; those temperatures had to be estimated. By using equation (9) and two more equations for the heat balance over the TTV, it was possible to estimate those temperatures. The two additional equations are:

\[
Q = \frac{k_{\text{copper}} \cdot A_{c,1} \cdot (T_2 - T_{2,\text{surface}})}{d},
\]

(10)

where \( A_{c,1} \) is the cross sectional area (m\(^2\)) of the upper copper bar, \( T_{2,\text{surface}} \) is the temperature (K) of the copper surface closest to point 2 and \( d \) is the distance (m) between measurement point 2 and the copper surface (or point 3 and the copper surface),

\[
Q = \frac{k_{\text{copper}} \cdot A_{c,2} \cdot (T_{3,\text{surface}} - T_3)}{d},
\]

(11)

where \( T_{3,\text{surface}} \) is the temperature (K) of the copper surface closest to point 3. Since \( \Delta T_{\text{TIM}} \) in equation (8) is the temperature difference between \( T_{2,\text{surface}} \) and \( T_{3,\text{surface}} \) it is possible to combine equation (8)-(11) to express the thermal resistance of the TIM as

\[
R_{\text{TIM}} = \frac{A_{\text{sample}}}{A_{c,2} \cdot k_{\text{copper}} \cdot \Delta T_{\text{copper}}} \cdot \left( \frac{\Delta T_{\text{TIM}, 2-3} \cdot \Delta L - \Delta T_{\text{copper}} \cdot d \left( 1 + \frac{A_{c,2}}{A_{c,1}} \right)}{1} \right),
\]

(12)

where

\[
\Delta T_{\text{TIM}, 2-3} = T_2 - T_3
\]

(13)

and

\[
\Delta T_{\text{copper}} = T_4 - T_5.
\]

(14)

If the thermal conductivity is sought instead, it can be calculated as

\[
k_{\text{copper}} = \frac{t}{R_{\text{TIM}}} = \frac{t \cdot A_{c,2} \cdot k_{\text{copper}} \cdot \Delta T_{\text{copper}}}{A_{\text{sample}} \cdot \left( \frac{\Delta T_{\text{TIM}, 2-3} \cdot \Delta L - \Delta T_{\text{copper}} \cdot d \left( 1 + \frac{A_{c,2}}{A_{c,1}} \right)}{1} \right)},
\]

(15)

where \( k_{\text{copper}} \) is the thermal conductivity (W/(m∙K)) of the TIM (including contact resistance) and \( t \) is the thickness (m) of the TIM.

### 3.1.2 MultiTest 2.5-d

The MultiTest 2.5-d is an equipment capable of applying axial loads of up to 2,500 N (tensile or compressive). The Advanced Force Gauge (AFG) can measure the force and the MultiTest can keep track on the travelled distance of the arm. The apparatus is controlled from the control panel on the front, where different speeds can be set as well as various control modes. The manual mode let the user control
the upward or downward motion with the arrow buttons. There are also two modes for automatic cycling movement where the travelling distance is fixed by mechanical pins on the back of the apparatus. The equipment can be connected to a computer recording the distance, time and force. Figure 10 show the MultiTest 2.5-d.

According to the manual and the manufacturers, the positioning uncertainty is ± 250 μm, whereas the display has a resolution of 10 μm (Mechmesin, 2014). Since the ± 250 μm uncertainty would make the equipment almost useless in TIM evaluation applications, the uncertainty was controlled by tests. For larger forces it was found that the arm of the AFG was flexing, introducing a need for a calibration curve in order to maintain reasonable accuracies.

The uncertainty test was performed by first measuring a gauge block with micrometers and then with the MultiTest equipment. The two larger blocks were placed as foundation to ensure good flatness; the smaller block was used for the actual measurements (see Figure 10). First, the small block was measured ten times in the middle with a digital and analogue micrometer screw gauge. The second step included the measurements in the MultiTest. The three blocks were placed on top of each other with the smallest bar at the top. The MultiTest arm was lowered until the first indication of contact was visible (a force was measured with the AFG). After that the distance was set to zero, the small bar was removed, and the arm lowered until it touched the plate below. The distance travelled indicated by the display is the measured thickness of the gauge block. The procedure was repeated ten times.

![Figure 10. The whole MultiTester 2.5-d can be seen in the left picture, while a close-up of the control panel and AFG can be seen to the right. The gauge blocks are stacked on top of each other to control the uncertainty of the thickness measurements.](image)

The tests results (see Table 3) show that there are strong reasons to believe that the display resolution of 10 μm can be used as the uncertainty instead of the ± 250 μm proposed by the manufacturers.
Table 3. The average measurement values of the thickness of the small gauge block for three different test methods. The difference compared to the MultiTest 2.5-d is also presented.

<table>
<thead>
<tr>
<th></th>
<th>Small gauge block thickness (mm)</th>
<th>Difference compared to MultiTest 2.5-d (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Digital micrometer</td>
<td>6.384</td>
<td>6.5</td>
</tr>
<tr>
<td>Analogue micrometer</td>
<td>6.387</td>
<td>3.0</td>
</tr>
<tr>
<td>Average micrometer</td>
<td>6.385</td>
<td>4.8</td>
</tr>
<tr>
<td>(digital+analogue)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MultiTest 2.5-d</td>
<td>6.390</td>
<td>-</td>
</tr>
</tbody>
</table>

At larger forces though, the arm at which the AFG is sitting on, is flexing, which makes the measurements more difficult (see Figure 11). The flex is in the range of about 500 µm when the force is 500 N. This is very significant since the thickness of the graphite sheets and gap pads are around 100 µm and 2500 µm respectively. Furthermore, the flex of the arm is not a linear function of the force. Hence, it is not sufficient to use a constant multiplier to cope with the error. A calibration curve had to be created. There is also a difference in the curve as the arm is pushed downwards and as it moves upwards.

Figure 11. The MultiTest 2.5-d seen from the side. The red arrow indicates in a schematic way the bending of the arm.

Since the MultiTest is also used combined with the TTV (as showed in Figure 9), a separate calibration curve must be created when the TTV is in place. A few factors make it more difficult to maintain the accuracy in these measurements. First of all, the TTV itself is somewhat compressible, making the curve look different as the displacement is a function of both the flex of the arm and the compression of the
TTV. Additionally, the plastic in the TTV expands as it heats up during the thermal tests, making the force increase. The curve is also sensitive to minor differences; such as if the thermal grease between the TTV and the cold plate has been distributed evenly.

In order to create a calibration curve the arm was pressed against the bottom plate (or TTV) without a test sample in between. The force was measured along with the distance to see the magnitude of the flex as a function of time. For example, if the display indicates -0.5 mm and a force of 500 N, the flex is 500 μm at 500 N as the baseplate is incompressible at such small forces (pressures). To create a curve, the distance and force were recorded for three separate tests, starting at 3 N and finishing at about 2 100 N. For each test the distance was reset to zero at 3 N contact force. As mentioned earlier, the TTV is somewhat compressible, hence a separate compression curve is needed. To ensure a fair accuracy through the whole range from 3 N to 2 000 N, the calibration data was fitted with six interpolating curves, all adopted to separate ranges. The calibration curves both with and without the TTV can be seen in Figure 12.

![Figure 12. A comparison of the calibration curves with and without the TTV included.](image)

The TTV is also expanding as the temperature goes up. To estimate the expansion, the TTV was compressed with a fixed force, and the increase in force was measured as the temperature of the resistor was gradually increased by altering the electrical power. The electrical power was changed every 10 min to simulate a thermal test in the TTV. The force decrease during a gradual cool down was also measured. The expansion of the TTV as a function of the temperature could be estimated by using the blue calibration curve in see Figure 12 together with the force readings. Several temperatures across the TTV was measured (including one in the plastic) in order to find the most suitable to correlate to the thermal expansion. The plastic temperature was intuitively the most convenient to use, but the thermal time constant turned out to not match the one of the thermal expansion. The temperature of the resistor was used instead. The correlation between the temperature difference (compared to the starting temperature) and the thermal expansion at fixed pressures of 25 N, 100 N and 500 N was tested. In Figure 13 a calculation of the estimated expansion at an initial force of 100 N is showed. The reason for the non-linear curve is that the electrical resistor, at which the thermocouple is placed, heats up faster than the expanding plastic. To cope with that, only the steady state points (before the electrical power is altered) were used to create the curves presented in Figure 14. There is also a difference in the expansion when the
material heats up and when it cools down. In the TIM tests the pressure is gradually increased and thus the temperature will go down. Hence, the cool down line is more convenient to use. In Figure 14 the cool down lines at the steady state points for 25 N, 100 N and 500 N tests can be seen.

![Cool down lines](image13.png)

**Figure 13.** An estimation of the thermal expansion along with increasing temperature of the electrical resistor at an initial applied pressure of 100 N. The power is increased in 10 min intervals and thus the temperature and thermal expansion goes up. The red arrows indicate the direction (in time) of the test and the red squares show the four measurement points used in Figure 14.

![Cool down linear approximations](image14.png)

**Figure 14.** Linear approximations of the cool down phase for initial forces of 25 N, 100 N and 500 N. The inclinations of the curves are depending on the initial force. A smaller force gives a higher inclination.

The thermal expansion is dependent on the force; the inclination of the curves in Figure 14 were assumed to follow a logarithmic curve visible in Figure 15.
The thermal expansion of the TTV is estimated by:

\[ \Delta L_{\text{thermal expansion}} = \left( -0.072 \cdot \ln(F) + 1.2784 \right) \cdot \left( T_i - T_{i,0} \right), \]  

where \( \Delta L_{\text{thermal expansion}} \) is the estimated thermal expansion (μm), \( F \) is the applied force (N), \( T_i \) is the temperature (K) given by the resistor and \( T_{i,0} \) is the initial temperature (K) of the resistor before the test is started. \( T_{i,0} \) was approximated with 24 °C (297 K) without introducing a significant error.

### 3.1.3 Other test equipment

Apart from the main test equipment, thickness and mass measurements were performed. A digital micrometer of an unknown brand was used. Through testing, an uncertainty of ± 5 μm for hard materials and ± 10 μm for soft materials was established within one standard deviation. For sample weighing, a Satorius TE64 scale was used. It has a resolution of 0.1 mg, a repeatability of ± 0.1 mg and a linearity of ± 0.2 mg (Satorius AG, 2014).

### 3.2 Test procedures in TTV and MultiTest 2.5-d

In total, five different tests were performed to evaluate graphite sheets and gap pads in the TTV and MultiTest 2.5-d. Moreover, two tests were also done in real Ericsson products. Those are described in 3.3 Test in products.

### 3.2.1 Preparations

In order to ensure a high repeatability of the tests it is important to maintain the same testing environment for all tests. The measures used for this purpose are described below and consist of cleaning of test surfaces, a consistent sample treatment and the use of an isolating box around the TTV.

#### 3.2.1.1 Preparation of test surfaces

1. Clean test surfaces with saturated vinegar and salt solution to remove oxide from surface.
2. Remove vinegar/salt solution with water-soaked paper towel.
3. Finish the cleaning by wiping the surface with alcohol-soaked paper.
### 3.2.1.2 Sample treatment

1. Cut a 24x24 mm piece of the sample.
2. Measure the thickness of the sample at five spots (the four corners and in the middle), the average is used as the thickness.
3. Weigh the sample.
4. (If possible, repeat the thickness measurements at the end of the test to compare the thickness.)

### 3.2.2 Tests of graphite sheets

The graphite sheets are very thin. Since the thermal conductivity is based on the thickness of the sheets, a high accuracy in thickness measurements is needed. As the MultiTest 2.5-d cannot give higher accuracies than ±70 µm when performing real time measurements (described more in 3.4 Uncertainty analysis), the thermal conductivity had to be based on another thickness. A higher accuracy was reached using the plastic deformation curve for each graphite sheet (see 3.2.2.2 Mechanical test procedure, plastic deformation).

#### 3.2.2.1 Thermal test procedure for graphite sheets

1. (If the TTV has been removed in between the tests: push with 2000 N on empty TTV to compress the thermal grease.)
2. Unload and lift the upper part of the TTV. Put it back and reset displacement measurement at 3 N force.
3. Place the sample in the TTV, press gently by hand to even out the TIM.
4. Press the TTV with the arm and stop at 3 N.
5. Start the power supply and the cooling device (the force will increase as the TTV material expands). The general applied heat is 50 W. If the temperature of the heater goes above 110 °C the power has to be reduced.
6. Wait 20 min before first measurement.
7. Note the figures of force and displacement in the dedicated Excel sheet.
8. Export temperature file from the NetDAQ logger and open it in the Excel sheet. Temperature measurements are taken every two seconds and an average from the last ten measurements is used.
9. Increase force and wait 10 min until performing next measurement. Perform measurements at 3 N (increases with expansion), 25 N, 50 N, 100 N, 200 N, 300 N, 500 N, 1000 N and 2000 N.

#### 3.2.2.2 Mechanical test procedure, plastic deformation

1. Measure the thickness (five points) after each compression phase with increasing forces of 25 N, 50 N, 100 N, 200 N, 300 N, 500 N, 1000 N and 2000 N. A plastic deformation curve as a function of the pressure can then be generated.

### 3.2.3 Tests of gap pads

The gap pads are about 20 times thicker than the graphite sheets. Therefore the MultiTest 2.5-d can be used for thickness measurements without losing accuracy in the thermal conductivity calculations. The thermal tests are similar to the graphite sheets while the mechanical tests are divided in two tests, one alternating pressure-relaxation test and one shock test. The purpose of the shock test is to test the peak pressure of the gap pads as they are compressed to around 50% at a compression speed of 450 mm/min, which shall correspond well to the speed in the assembly of the product in factories.
3.2.3.1 **Thermal test procedure for gap pads**

1. (If the TTV has been removed in between the tests: push with 2 000 N on empty TTV to compress the thermal grease.)
2. Unload and lift the upper part of the TTV. Put it back and reset displacement measurement at 3 N force.
3. Place the sample in the TTV, press gently by hand to even out the TIM.
4. Press the TTV with the arm and stop at 3 N.
5. Start the power supply and the cooling device (the force will increase as the TTV material expands). The general applied heat is 50 W. If the temperature of the heater goes above 110 °C the power has to be reduced.
6. Wait 20 min before first measurement.
7. Note the figures of force and displacement in the dedicated Excel sheet.
8. Export temperature file from the NetDAQ logger and open it in the Excel sheet. Temperature measurements are taken every 2 s and an average from the last ten measurements is used.
9. Increase force and wait 10 min until performing next measurement. Perform measurements at relevant compression rates (for example 0 %, 10 %, 20 %... 60 %).

3.2.3.2 **Mechanical test procedure, pressure-relaxation**

1. Reset the displacement measurement at 3 N force against the bottom plate.
2. Place the sample under the pressure arm.
3. Press the sample with the arm and stop at 3 N.
4. Set the compression speed to 5 mm/min.
5. Start the data acquisition software.
6. Compress the material until 50 N is reached.
7. Wait 2 min for the gap pad to relax.
8. Compress the gap pad until it reaches 100 N.
9. Relax again.
10. Repeat the process for 200 N, 300 N, 400 N, 500 N and 600 N.

3.2.3.3 **Mechanical test procedure, shock**

1. (In the MultiTest 2.5-d the mechanical stop must be set at a position that would give a 50 % compression of the gap pad.)
2. Reset the displacement measurement at 3 N force against the bottom plate.
3. Place the sample under the pressure arm.
4. Press the sample with the arm and stop at 3 N.
5. Set the compression speed to 450 mm/min.
6. Move the arm up to 10 mm displacement and stop (to have some distance from the arm to the sample).
7. Start the data acquisition software.
8. Compress the gap pad at constant speed until it stops by the mechanical stop.
9. Wait 2 min for the gap pad to relax.

3.3 **Test in products**

In order to investigate how the best TIMs would perform in practice, tests in a real radio unit were performed. The first step was to do a reference test with standard TIM materials at a specific power. In the second test, the gap pads were replaced with best performing gap pad from the thermal tests in the TTV. For the third test the “new” gap pads were kept and the thermal grease was replaced by the best graphite sheet.
3.3.1 Reference test

Before the new TIMs were tested, a reference test was performed. The TIMs used were 3 W/(m·K) standard gap pads and silicone free thermal grease (for test results of the TIMs see Figure 38 and Figure 46). The radio unit, which is cooled by natural convection, was placed on a pole behind walls to minimize air disturbance (see Figure 16). The radio was connected to a test equipment capable of creating signals matching different load models which simulate real life use. As the unit have a built in back-off system the signal power to the PA will be restricted if the temperatures in the PA get too high. Hence, either lower temperatures (at a constant power) or higher signal power (at a constant temperature) would indicate a better cooling. Temperatures were measured at several points with thermocouples and built in sensors. The ambient temperature was also measured and is subtracted from the results to get the “above ambient” temperatures.

![Figure 16](image.png)

Figure 16. The radio unit used for testing was placed on a pole behind covering walls to minimise air disturbance.

3.3.2 Replacement of thermal gap pads

Five gap pads were considered suitable for replacement. They were located on important components on the TRX board. The gap pads are used to transfer the heat from the components to the heat sink through the principle showed in Figure 7. Dedicated heels on the aluminium heat sink enables thinner gap pads. The gap pads used in this test were the best performing graphite gap pads from the thermal tests (denoted J1 and J1(2) in Figure 46). The thickness was 1.5 mm for four of the components and 2.54 mm for the last. A picture of gap pad J1(2) can be seen in Figure 17.
3.3.3 Replacement of thermal grease

The PA units are cooled through the PCB and thermal grease is used in the same way as in Figure 7. Thermal grease is messy and hard to work with during assembly and repair. Therefore thermal graphite sheets were evaluated as a replacement. For this test, the graphite gap pads from the previous test were left on the TRX components. The thermal grease on the backside of the PA boards was exchanged for the 200 µm thick graphite sheet (B1), which was one of the best performing sheets according to the results in Figure 38. There are two identical PA boards placed beside each other in the unit. The thermal grease as well as the pieces of graphite sheets used can be seen in Figure 18. In total, there are eight PAs and as many drivers. To avoid short circuits on the PCB, the graphite sheets were cut into pieces, not touching the sensitive thermal vias. The graphite sheets were placed on the heat sink side before the assembly. In order to prevent the sheets from slipping out of position, a small drop of thermal grease was applied in the corner of each sheet. The torque used to tighten the screws on the PA board was 1 Nm.

Figure 18. The upper picture show some thermal grease before it had been wiped off. In the lower picture the pieces of graphite sheets used for the replacement can be seen. The two larger pieces are for the PAs and the smaller ones are for the PA drivers.
3.4 Uncertainty analysis

During the TIM evaluations several parameters are measured. All parameters are burdened with some uncertainties. The different uncertainties are assumed independent and contribute to an overall probable uncertainty. This section shows the methods used to estimate the overall uncertainty and each parameter’s contribution to that uncertainty. The governing equations come from the National Institute of Standards and Technology (Taylor and Kuyatt, 1994).

3.4.1 Uncertainty analysis of the TTV

In order to assess the uncertainty of the thermal tests in the TTV the overall maximum error and overall probable uncertainty were calculated. The overall maximum error can be calculated with

$$\delta f = \sum_{i=1}^{n} \left| \frac{\partial f}{\partial \xi_i} \right| \Delta \xi_i,$$  \hspace{1cm} (17)

where \( f \) is the function that is evaluated, \( \xi \) are the measured quantities in the function and \( \Delta \xi \) is the maximum error for the input quantities. To estimate the probable overall uncertainty at an approximate 95 % confidence interval, two standard deviations are used (giving a 95.4 % confidence interval). The overall probable uncertainty is calculated by

$$u_y = 2 \cdot \sqrt{\sum_{i=1}^{n} \left( \frac{\partial f}{\partial \xi_i} \right)^2 \cdot s_i^2},$$  \hspace{1cm} (18)

where \( s \) is the standard deviations for the input quantities. If the maximum error of a quantity is known, the standard deviation can be estimated as

$$s_i = \sqrt{\frac{\Delta \xi_i^2}{3}},$$  \hspace{1cm} (19)

Many manufacturers state the measurement uncertainty for their instruments. If it is true or assumed that the stated uncertainty is within a 95 % confidence interval the standard deviation can be calculated as

$$s_i = \frac{u_x}{2},$$  \hspace{1cm} (20)

where \( u_x \) is the stated uncertainty. In these cases the maximum error can be estimated as

$$\Delta \xi_i = u_x.$$

Applying equation (17) and (18) to equation (12) yields the two expressions

$$\delta R_{TIM} = \frac{\partial R_{TIM}}{\partial \Delta T_{copper}} \delta \Delta T_{copper} + \frac{\partial R_{TIM}}{\partial \Delta T_{TIM,2-3}} \delta \Delta T_{TIM,2-3} + \frac{\partial R_{TIM}}{\partial d} \delta d + \frac{\partial R_{TIM}}{\partial \delta L} \delta \delta L + \frac{\partial R_{TIM}}{\partial A_{c1}} \delta A_{c1} + \frac{\partial R_{TIM}}{\partial A_{c2}} \delta A_{c2} + \frac{\partial R_{TIM}}{\partial A_{sample}} \delta A_{sample} + \frac{\partial R_{TIM}}{\partial k_{copper}} \delta k_{copper},$$  \hspace{1cm} (22)

and

$$u_{R_{TIM}} = 2 \cdot \sqrt{\left( \frac{\partial R_{TIM}}{\partial \Delta T_{copper}} s_{\Delta T_{copper}} \right)^2 + \left( \frac{\partial R_{TIM}}{\partial \Delta T_{TIM,2-3}} s_{\Delta T_{TIM,2-3}} \right)^2 + \left( \frac{\partial R_{TIM}}{\partial d} s_d \right)^2 + \left( \frac{\partial R_{TIM}}{\partial \delta L} s_{\delta L} \right)^2 + \left( \frac{\partial R_{TIM}}{\partial A_{c1}} s_{A_{c1}} \right)^2 + \left( \frac{\partial R_{TIM}}{\partial A_{c2}} s_{A_{c2}} \right)^2 + \left( \frac{\partial R_{TIM}}{\partial A_{sample}} s_{A_{sample}} \right)^2 + \left( \frac{\partial R_{TIM}}{\partial k_{copper}} s_{k_{copper}} \right)^2}.$$

29
The maximum error and standard deviations for all the inherent quantities are presented in Table 4. The uncertainties for $k_{\text{TIM}}$ are treated the same way as for $R_{\text{TIM}}$. The only difference from equation (22) and (23) is that the thickness $t$ is added to the calculations. All the partial derivatives from equation (22) and (23) together with the corresponding equations for $k_{\text{TIM}}$ can be seen in Appendix B.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Measured value</th>
<th>Maximum uncertainty</th>
<th>Standard deviation (68 %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta T_{\text{copper}}$</td>
<td>Varies</td>
<td>0.1 K</td>
<td>0.05 K</td>
</tr>
<tr>
<td>$\Delta T_{\text{TIM,2-3}}$</td>
<td>Varies</td>
<td>0.2 K</td>
<td>0.1 K</td>
</tr>
<tr>
<td>$d$</td>
<td>1 mm</td>
<td>0.5 mm</td>
<td>0.29 mm</td>
</tr>
<tr>
<td>$\Delta L$</td>
<td>20 mm</td>
<td>1.3 mm</td>
<td>0.73 mm</td>
</tr>
<tr>
<td>$k_{\text{copper}}$</td>
<td>391 W/(m·K)</td>
<td>18 W/(m·K)</td>
<td>9 W/(m·K)</td>
</tr>
<tr>
<td>$A_{c,1}$</td>
<td>576 mm$^2$</td>
<td>2.4 mm$^2$</td>
<td>1.2 mm$^2$</td>
</tr>
<tr>
<td>$A_{c,2}$</td>
<td>576 mm$^2$</td>
<td>2.4 mm$^2$</td>
<td>1.2 mm$^2$</td>
</tr>
<tr>
<td>$A_{\text{sample}}$</td>
<td>576 mm$^2$</td>
<td>47 mm$^2$</td>
<td>27.4 mm$^2$</td>
</tr>
<tr>
<td>$t$</td>
<td>Varies</td>
<td>0.07 mm</td>
<td>0.035 mm</td>
</tr>
</tbody>
</table>

Two graphs (Figure 19 and Figure 20) were created to further highlight the importance of the thickness measurements in the TTV. The overall probable relative uncertainty was calculated for various thicknesses of a TIM. These two graphs are created from a measurement of graphite sheet B1 and the results would not be the same if other samples were used. However, the overall curve shape would look quite the same. At large thicknesses the uncertainty is fairly constant at about 20 %. When zooming in to the area that is important for the graphite sheet evaluations (Figure 20) it becomes evident that the accuracy of the thickness measurement need to be about ± 10 µm to have a reasonable overall uncertainty for samples thicknesses down to 50 µm.
Figure 19. A graph showing the overall probable relative uncertainty (95%) of $k_{TIM}$ as a function of sample thickness. The three curves represent different accuracies when measuring the thickness of a test sample. The areas most used for graphite sheet and gap pad measurements are highlighted in blue and pink respectively.

Figure 20. A zoom in on Figure 19 focusing on the areas where most of the graphite sheet measurements are performed.

If the focus is taken away from the thickness problem, in favour for the thickness-independent $R_{TIM}$ uncertainty, it is possible to see which other parts of the TTV that can be improved. According to Table 5, where the uncertainty contributions of the measured parameters are presented, the temperature difference in the copper bar, the distance between the measurement points and the sample area are the most crucial.
Table 5. The part of the overall probable uncertainty for $R_{TIM}$ that comes from each variable.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Relative part of the probable uncertainty*</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta T_{copper}$</td>
<td>19 %</td>
</tr>
<tr>
<td>$\Delta T_{TIM}$</td>
<td>6 %</td>
</tr>
<tr>
<td>$d$</td>
<td>23 %</td>
</tr>
<tr>
<td>$\Delta L$</td>
<td>20 %</td>
</tr>
<tr>
<td>$k_{copper}$</td>
<td>9 %</td>
</tr>
<tr>
<td>$A_{copper,1}$</td>
<td>0 %</td>
</tr>
<tr>
<td>$A_{copper,2}$</td>
<td>1 %</td>
</tr>
<tr>
<td>$A_{sample}$</td>
<td>22 %</td>
</tr>
</tbody>
</table>

*values from a specific test of graphite sheet B1.

The results of the overall probable relative uncertainties can be seen in 4.4 Uncertainty tests.

3.4.2 Uncertainties of the measured quantities

The various parameters that are measured in order to calculate the thermal resistance and conductivity have uncertainties. These uncertainties give the overall uncertainty presented in 3.4.1 Uncertainty analysis of the TTV. In this section, the procedures of determining the uncertainty of the parameters are described.

3.4.2.1 Evaluation of the thickness measurements

To evaluate how good the accuracy of the thickness measurements is using the MultTest 2.5-d (including the calibration curves) a series of reference tests, closely related to the tests performed on the TIMs, were used. In the first test, the thickness of a reference feeler gauge was measured at various forces using the arm alone. In Figure 11 both the arm and two feeler gauges can be seen. The feeler gauge used was measured to 1.01 mm by a micrometer and is considered incompressible at the relevant pressures. The deviation from that value was interpreted as the error. Three main tests were done to study the error, one with the feeler gauge placed in the front of the test surface, one in the middle and one at the back. According to Figure 21 the deviation was within 45 $\mu$m for the mid and back tests while the front test showed a maximum deviation of about 70 $\mu$m. It is likely that the reason the front measurement is worse, is due to the bending or tilting of the arm (see Figure 11). Placing the feeler gauge in the front would enhance the tilting as the torque would increase. As tests are going to be performed at larger samples covering the whole test surface, the mid test is more convenient to use. The estimated maximum error was therefore determined to be $\pm$ 70 $\mu$m. A fourth test with the feeler gauge placed in the middle was made. During the test, the arm was manually pushed or pulled to see if the arm would start to deviate from its calibrated curve. The peaks in Figure 11 can be ignored as they are a result of the disturbance. The overall curve shows no significant difference from the first mid-test.
Figure 21. The uncertainty in thickness measurements as a function of applied force using only the arm. Tests were performed putting the feeler gauge in the back end, front end and in the middle (if the arm is seen from the front). One disturbed test was also made to see if the curve would start to deviate if the arm was pushed or pulled by hand. The peaks in the blue curve represent those disturbances and can be ignored regarding the error.

Similar tests were performed in the TTV as well. The calibration curve including the TTV from Figure 12 and the estimation of the thermal expansion in equation (16) were used. A feeler gauge of 0.8 mm together with small pieces of graphite gap pads were used both to have an incompressible reference and to have a decently low thermal resistance (see Figure 22). In a second test the TTV was completely empty.

Figure 22. A feeler gauge with 0.8 mm thickness put in the TTV together with pieces of graphite gap pads.

The tests were done as if a TIM was tested according to 3.2.2.1 Thermal test procedure. In Figure 23 the results of the tests as a function of the applied pressure can be seen. From this, a maximum uncertainty of
70 μm was established to also have some margin if (for example) the thermal grease below the TTV is not completely compressed.

![Figure 23](image)

Figure 23. The deviation of the thickness measurement for two tests, one with a 0.8 mm feeler gauge and one with an empty TTV.

### 3.4.2.2 Pressure measurement

The applied force was measured by Mechmesin Advanced Force Gauge 2500 (AFG 2500 N). The maximum allowable force was 2 500 N and the accuracy is stated to be ± 2.5 N (Mechmesin, 2014). The pressure was then calculated by division of the area of the test probe (576 mm²).

### 3.4.2.3 Temperature measurements

The temperatures were measured with type K thermocouples by the company Pentronic. They are manufactured according to the class 1 IEC 60584-2 standard (Pentronic, 2014) with a corresponding uncertainty of ± 1.5 °C (Inor, 2014). The data acquisition was performed with Fluke NetDAQ 2645A. The system has the possibility to measure temperatures with 20 channels simultaneously. The reference junction is placed in the well-insulated connector shell at the back of the unit. Several layers of copper are used in between the boards to ensure thermal equilibrium. The measurement uncertainty for the Fluke unit is ± 0.8 °C if type K thermocouples are used. According to the manufacturer this uncertainty should be added to the thermocouple uncertainty (Fluke Calibration, 2014), giving ± 2.3 °C in this case. This figure might be valid for absolute temperature measurements as it is depending heavily on the reference junction accuracy. In the experiments in this report however, temperature differences were used. As the reference junction is placed in an isothermal box and only differences are measured, the offset error for a poor calibrated reference junction disappear (Jonsson, 2001). In order to further investigate this, the uncertainty was determined experimentally.

Two experiments were conducted. In the first one, the three thermocouples placed in the lower copper bar of the TTV \((T_3 - T_5)\) were measuring ambient temperature for three straight hours. Since the thermocouples are in the same copper block, placed in an insulated box, it was assumed that they measured the same temperature. The standard deviation of the three thermocouples versus the time in seconds can be seen in Figure 24. The highest standard deviation was about 0.03 °C.
To test the thermocouples over a wider range of temperatures, three thermocouples were taped together and immersed into a cup of water heated to about 75 °C. The cup was then placed under an insulated box to be slowly cooled down. The standard deviation of the three thermocouples were measured over time and is plotted together with a curve of the average measured temperature in Figure 25. It can be seen that the standard deviation is larger at higher temperatures and as the temperature goes down it approaches the result in Figure 24. The reason for this is most likely due to that there are larger temperature gradients in the water as the temperature is high, making the small distance between the three thermocouples important. However, to be on the safe side a maximum uncertainty of ±0.2 °C (within a 95 % confidence interval) was used for the thermocouples measuring the difference between $T_2$ and $T_3$ as they are placed in separate copper bars. For the $T_4$ and $T_5$ thermocouples the maximum uncertainty was determined to be ±0.1 °C. Additionally, the linearity of thermocouples were checked to see if a poor calibrated reference junction could affect a temperature difference as well. From a type K thermocouple table (Omega Engineering inc., n.d.) it was estimated that the largest possible error, if the reference junction was 2 °C off, would be 0.05 °C for a 20 °C temperature difference. The results of the calculations can be seen in Figure 63 in Appendix C.
Figure 25: The standard deviation of the temperature measurement in a cup of water cooling down. The absolute temperature of the water is also shown to highlight the correlation between standard deviation and absolute temperature.

3.4.2.4 **The distance and area measurements**

The copper bars were manufactured according to ISO 2768-m (Ramo Material AB, 2014). The uncertainty of the important dimensions are either 0.1 mm or 0.3 mm depending on if the distance is shorter or longer than 30 mm. The \( \Delta L \) and \( d \) parameters are distances between thermocouple holes. Since the thermocouples are glued in the hole and have a smaller junction than the diameter of the hole (1 mm), the actual measurement point could be anywhere around the perimeter of the hole (or in the middle as there is a bottom of the hole), resulting in a maximum uncertainty of ± 0.5 mm. This uncertainty was combined with the ISO standard uncertainty to get the total uncertainty of the distances.

The sides of the copper bars had a lower tolerance (+0 –0.05 mm). The maximum uncertainty of the copper bar cross sectional area was therefore determined to be ± 2.4 mm\(^2\) which is small compared to the area of 576 mm\(^2\). It is difficult to make test samples with an exact size of 24 mm \( x \) 24 mm. Therefore the maximum error of the samples is assumed to be ± 0.5 mm on each side. That is also to account for the possibility that the copper bars are not completely centred above each other during the measurements.

Figure 26: A principle of the problem not knowing at what point the thermocouple junction is placed. The maximum error is ± 0.5 mm as the junction can be anywhere in the cross section of the hole.
The gap pads will however be compressed and cover the whole surface. The error was thereby reduced by one fourth.

Measuring the thickness of graphite sheets and gap pads with a micrometer also introduces an error. The greatest problem is that it is difficult to control the torque at which micrometer is tightened. In order not to damage or compress soft materials, a gentle touch is needed. The uncertainty when measuring soft materials was determined to be ± 10 µm within one standard deviation, while for harder materials the corresponding value was ± 5 µm.

3.4.2.5 Weighing of samples
As mentioned in 3.1.3 Other test equipment the Satorius TE64 scale have an uncertainty of ± 0.1 mg.

3.4.2.6 The thermal conductivity of copper
The stated thermal conductivity of copper varies between different sources. As an average, the value 391 W/(m·K) was obtained with a standard deviation of ± 9 W/(m·K) (Young and Freedman, 2008; Granryd, 2009; Holman, 2010).

3.4.2.7 The steady state error
In order to estimate the error deriving from not reaching steady state before taking the measurement, some long tests were conducted. In Figure 27 two prolonged tests for about 1 100 min (18 h) are shown. The temperature difference over the TIM from the beginning of the tests were compared to the final value. As the thermal resistance and thermal conductivity is proportional to the temperature difference, that value can be used to estimate the uncertainty. Two tests were performed, one where graphite sheet B6 was tested from when the equipment was turned on, and one where A1 was tested from when the first measurement point was taken (after 20 min, when the pressure is increased for the first time). By calculating the relative difference over time, the error from taking the measurement after 20 minutes for B6 was established to be about 8 % with a one-sided confidence interval. Waiting 10 min for A1 gave slightly less than 5 % error. A more detailed view can be seen in Figure 28. Since the first measurement (after 20 min) is not used in the results as the pressure varies depending on sample, the uncertainty within one standard deviation was determined to be 5 %. Since the temperature difference decrease along with time, this error contributes to an underestimation of the thermal performance (a higher thermal resistance or a lower thermal conductivity).

![Figure 27. The relative difference of the current and final temperature difference over the TIM as a function of time.](image)

After a few measurements the changes in temperatures are quite small when the pressure is increased (In for example Figure 34, the thermal resistance does not change that much). At that point, the steady state can be reached within 10 minutes. To possibly save time it was investigated if there are other conditions
that can determine if steady state (or rather semi-steady state) has been reached. One indication that can be easily monitored from the software is the range of which the temperature have been in for a specified time. It was found that a suitable condition could be when temperature $T_2$ has been within $\pm 0.05 \, ^\circ$C during a consecutive time of three minutes. In that case the error would be slightly less than 4 % for both cases shown in Figure 28. Therefore it can be safe to take the measurements when that condition is satisfied without introducing a larger error than for the first measurements. Doing so would make the last measurements take about 5 minutes each, instead of 10 minutes.

Figure 28. A zoomed in version of Figure 27 focusing on the first 60 min. The vertical lines represents the time at which temperature $T_2$ has been within $\pm 0.05 \, ^\circ$C for three consecutive minutes. Taking the measurements at that point would give an error slightly below 4 % in both cases.
4 Results

The following section contains the thermal and mechanical test results for the graphite sheets and the graphite gap pads. The results of the sheets and gap pads are presented in separate paragraphs since the TIMs serve different purposes. In most of the diagrams the names of the test samples are presented in the legend in accordance with the description in Figure 29.

![Graphite Sheet Image](image1)

**Figure 29.** Example of how to interpret the legend in the result diagrams.

4.1 Graphite sheets

A total of 21 graphite sheets are included in the test results presented in this section. A graphite sheet sample (E3) is shown to the left in Figure 30. The material to the right, C1, was tested but excluded from some of the results since it is not considered to be a comparable graphite sheet. C1 is built of several graphite sheets vertically aligned and laminated together, creating a 2 mm thick material. The idea is to take advantage of the high in-plane thermal conductivity of each sheet. Furthermore, E2 is coated with an adhesive polymer and is not directly comparable with the other graphite sheets. The manufacturers are often keen to keep their production method a secret; hence some of the other samples might not be pure graphite sheets either. C1 and E2 are included in the main results but none of them perform well as TIMs.

![Graphite Sheets Image](image2)

**Figure 30.** To the left is a piece of graphite sheet E3. To the right is a close up of C1. In C1, thin graphite sheets are vertically aligned and laminated together in order to take advantage of the high in-plane thermal conductivity of the graphite. The structure is brittle and three large cracks are visible across the material.
4.1.1 Thermal tests

The thermal resistance and thermal conductivity as functions of the applied pressures are presented in Figure 31 and Figure 32 respectively. All the results are also available in tabulated form in Table 9 and Table 10 in Appendix D. When the thermal resistance of the materials are compared, the difference is the largest at low pressures, while at higher pressures the values approach each other. The 2 mm thick special C1 sample excels in thermal conductivity. At pressure of about 3.7 kPa it exceeds 50 W/(m·K), while the best graphite sheet reaches about 8 W/(m·K). In Figure 33 that sample is excluded to enable an easier overview of the other samples. All results are based on one test except from A1 which served as a reference and is therefore an average of four separate tests.

![Figure 31. The thermal resistance of graphite sheets as a function of applied pressure. C1 and E2 are not considered pure graphite sheets.](image)
Figure 32. The thermal conductivity of graphite sheets as a function of applied pressure. The special vertically aligned C1 excel in this perspective.

Figure 33. A version of Figure 32 without C1. Due to lack of samples, F1 is not based on the plastic deformation curve, instead the initial thickness.

In Figure 34 and Figure 35 the best performing graphite sheets suitable to be used as 100 μm TIM in Ericsson’s products can be seen. B1 is 200 μm thick but it is highly compressible (see Figure 40 in section 4.1.2 Mechanical tests) and therefore still considered suitable. E4 is currently used by Ericsson.
Figure 34. The thermal resistance of the best performing graphite sheets suitable for 100 μm applications.

Figure 35. The thermal conductivity of the best performing graphite sheets suitable for 100 μm applications. Due to lack of samples, F1 is not based on the plastic deformation curve, instead the initial thickness.

The parts of the diagram in Figure 34 that are most relevant in applications are shown in Figure 36. Eight different samples have lower thermal resistance at most measurement points compared to the reference E4. The thermal resistance of the same samples at a fixed pressure of about 350 kPa can be seen in Figure 37. The reference sample is highlighted with a red frame. At this specific pressure, the best performing samples have one third the resistance of the reference sample.
The two best performing graphite sheets are compared with the reference sheet and reference thermal grease in Figure 38. At the lowest pressures, B1 is the better performer of the graphite sheets, while at pressures higher than about 350 kPa, D2 is the better. However, over the whole range of pressures, both B1 and D2 have a significantly lower thermal resistance than the reference test sample indicated by a blue line. The red line represents the thermal grease used in most of Ericsson’s products. At the lowest pressure, the thermal grease is twice as good as the best graphite sheet, but from about 90 kPa the grease have a higher thermal resistance. The relative reduction in thermal resistance for B1 and D2 compared to
E4 is shown in Figure 39. The reduction in thermal resistance varies between about 75 % and 35 % depending on the pressure level and the sample. The difference is the largest at low pressures.

![Figure 38. A comparison of the two graphite sheets most suitable to replace the existing sheet, E4. The blue line is the reference line.](image)

![Figure 39. The relative reduction in thermal resistance compared to E4 as a function of pressure.](image)

### 4.1.2 Mechanical tests

The results of the plastic deformation tests are presented in Figure 40. Two materials from manufacturer B (B1 and B2) stand out from the rest as they are highly compressible even at low pressures. At about
500 kPa both materials have plastically deformed almost 50%. The third most compressible material is D2. Common for these samples are that most of their plastic deformation takes place at low pressures and that the rate of increased deformation gradually declines with increasing pressure. Notable is also that these three graphite sheets show the lowest thermal resistance at a pressure of 350 kPa (see Figure 37) and have the lowest initial densities (see Table 11 in Appendix D). A picture of how the test sample of B1 looked like in a compressed state can be seen in Figure 41.

Figure 40. The relative plastic deformation as a function of applied pressure. Due to lack of samples F1 could not be tested.
Figure 41. A picture of the B1 test sample after the thermal tests. As the sample was slightly larger than the copper bars in the TTV it is possible to see a distinct imprint. The thickness of the sheet at the edges is thereby around 200 μm while the average thickness at the center is around 40 μm.

To more easily distinguish the other materials, the three most compressible sheets were removed from Figure 40 in order to create Figure 42. The general trend is that the materials do not deform significantly until pressures above 1 500 kPa are reached.

Figure 42. The relative plastic deformation as a function of applied pressure without the top three most compressible materials. Due to lack of samples F1 could not be tested.
The result of the plastic deformation after the sample has been exposed to a pressure of 3 470 kPa can be seen in Figure 43 together with each specimen’s initial density. The trendline indicate that samples with low initial density are in general easier to deform. Table 11 in Appendix D show the initial thickness and density for all tested graphite sheets.

![Graph showing relative plastic deformation as a function of initial density.](image)

Figure 43. The relative plastic deformation of each test sample at a pressure of 3 470 kPa as a function of their initial density.

### 4.1.3 Thermal and mechanical tests combined

The thermal resistance and thermal conductivity of the graphite sheets as functions of each sample’s initial density can be seen in Figure 44 and Figure 45 respectively. According to the trendlines the lower the initial density is, the better the thermal performance will be. The pressures in the figures are around 350 kPa. However, the same trend can be seen at all pressure levels.
Figure 44. The thermal resistance of all graphite sheets except B4, B6, C1, C2, E2 and G1 as functions of their initial density. Those samples were removed since they were not considered to be in the same thickness range. The results are at an applied pressure of approximately 350 kPa.

Figure 45. The thermal conductivity of all graphite sheets except C1 and E2 as functions of their initial density. The results are at an applied pressure of approximately 350 kPa.

4.2 Gap pads

Two graphite based gap pads were tested, H1 and J1, both thermally and mechanically. A thinner version of J1 was also evaluated and is called J1(2). Additionally, two reference pads were tested, one gap pad named K1, which is sold as a 3 W/(m·K) pad, and one 7 W/(m·K) pad entitled L1. They do not contain graphite but are currently used in some of Ericsson’s products.
4.2.1 Thermal tests

As the hardness of the gap pads differs a lot and the pads are designed to be compressed, it is more convenient to present the thermal performance as a function of the relative compression than the applied pressure. Furthermore, the applied pressure is affected by the gap pad touching the walls of the TTV during the compression. Therefore, the pressure is not comparable to what would occur in a real product for the same compression rate. The result presented in Figure 46 show that the reference pads K1 and L1 reach a maximum thermal conductivity of 2.8 W/(m·K) and 6.0 W/(m·K) respectively. H1 have a maximum thermal conductivity of about 12 W/(m·K), while the corresponding values for J1 and J1(2) are 23 W/(m·K) and 19 W/(m·K) respectively. H1, J1 and J1(2) have peaks at low relative compression rates and the conductivity gradually gets lower as the materials are compressed. All the results from the thermal tests are tabulated in Table 12 in Appendix D.

![Graph showing thermal conductivity vs. relative compression](image)

Figure 46. The thermal conductivity of the carbon-based gap pads as a function of relative compression. Gap pad K1 and L1 are not based on graphite and K1 is used in Ericsson’s products today.

The thermal resistance of the gap pads are visible in Figure 47 and Figure 48. The resistance of the graphite-based pads (H1, J1 and J1(2)) is fairly constant as the relative compression increases. This is due to the decreasing thermal conductivity. The K1 and L1 pads do however have a steady decrease in thermal resistance as the material gets thinner while the thermal conductivity is almost constant.
Figure 47. The thermal resistance of the carbon-based gap pads as a function of relative compression. Gap pad K1 and L1 are not based on graphite and K1 is used in Ericsson's products today.

Figure 48. The thermal resistance of the carbon-based gap pads and the 7 W/(m·K) gap pad as a function of the relative compression. Gap pad K1 is not included in the graph.
In Figure 49 a visual comparison of the three gap pads from before and after the thermal tests can be seen. H1 was plastically deformed and cracked when it was removed from the TTV. J1 did not recover to its original form either, whereas K1 looks almost the same as from the beginning.

![Figure 49](image)

Figure 49. A picture showing the difference in visual appearance before and after the thermal tests. The original sample sizes was 24 mm x 24 mm. From the left is H1, J1 and K1. The test sample H1 cracked when it was removed from the TTV after the test.

### 4.2.2 Mechanical tests

The results of two kinds of mechanical tests are presented in this section. The first one is a gradually increasing force with a 2 min relaxation time between each new force. The second one is a shock test at 50 % relative compression with a speed of 450 mm/min. Due to lack of samples L1 could not be tested mechanically.

In Figure 50 the whole test sequence can be seen. The zigzag pattern of the curves represents the alternating load and relaxation phase. After each peak the material relaxes and consequently it compresses more as the materials flows out. The curves of material K1, J1 and J1(2) get steeper as the relative compression goes up and the materials become stiffer. For gap pad H1 it is the other way around. The pad gets softer after the peak at about 15 % relative compression. To study the peaks (after the compression phase) and valleys (after the relaxation phase) of the gap pads in Figure 50, two additional plots were created in Figure 51 and Figure 52, showing the “peak curves” and “valley curves” separately. In Figure 52 it is possible to see that gap pad H1 relaxes more (percentage wise) during each relaxation phase than the other gap pads. Figure 53 show H1 before and after the mechanical tests. The test sample cracked along the border of the laminated layers.
Figure 50. The relative compression of the gap pads as the materials are cycled with gradually increasing force at a compression speed of 5 mm/min with a 2 min relaxation phase after each peak point is reached. The test forces are 50 N, 100 N, 200 N, 300 N, 400 N, and 500 N.

Figure 51. The relative compression at the peak points from Figure 50. The unit on the y-axis is in kPa instead of N as in the previous figure. The more the curve is to the left, the higher the pressure needs be in order to reach a specific relative compression rate.
Figure 52. The relative compression at the valleys from Figure 50 (after 2 min relaxation). The more the curve is to the left, the higher the pressure is for a specific relative compression rate after 2 min relaxation time.

Figure 53. A picture of gap pad H1 before and after a compression test. The test sample tend to crack between the laminated layers.

To study how the gap pads would possibly behave during a product assembly in the factory a 450 mm/min shock test was performed. Figure 54 show that at an approximate relative compression of 50 %, the reference gap pad peaks at about 1 800 kPa, J1 reaches 900 kPa and H1 1 800 kPa. The thinner version of J1 peaked at almost 1900 kPa but at slightly higher compression rates.
Figure 54. The peak pressure of the three gap pads when compressed to about 50 % at a compression speed of 450 mm/min. The reached compression rate is within parenthesis for each material. The initial thicknesses of the gap pads are indicated in each column.

4.3 Test in products

In Figure 55 the results of three temperature measurements are shown. In the reference measurements, the power input was 923 W. In the second measurement, where only the gap pads were exchanged, the power reached 908 W. In the final measurement, where the thermal grease was exchanged as well, the power amounted to 929 W. The results are corrected for the ambient temperature. Both tests with improved TIMs show better thermal performance. In Table 6 the temperature improvements from the two tests are shown for the PA and components on the TRX board respectively. All the temperatures were lowered when the graphite gap pads were introduced; about 3 °C for the PA and 5 °C for the TRX components. Exchanging the thermal grease for graphite sheets could lower the temperature with another 0.2 °C on the PA despite higher power compared to the reference test.

Figure 55. Temperature measurements (above ambient) at different points in the radio unit. The applied power is shown within parenthesis.
Table 6. The test results of each unit category as the temperature difference compared to the reference test.

<table>
<thead>
<tr>
<th>Test</th>
<th>PA</th>
<th>Components on TRX board</th>
</tr>
</thead>
<tbody>
<tr>
<td>Graphite pad (908 W)</td>
<td>- 2.8 °C</td>
<td>- 4.8 °C</td>
</tr>
<tr>
<td>Graphite pad + sheet (929 W)</td>
<td>- 3.0 °C</td>
<td>± 0.0 °C</td>
</tr>
</tbody>
</table>

In Figure 56, the temperature measurements including the absolute values are presented. The back-off is controlled by the PA which has an almost constant absolute temperature.

![Graph showing temperature measurements at different points in the radio unit. The three lines at the top indicate the absolute temperature measurements. The lines below are corrected for the ambient temperature.](image)

Figure 56. Temperature measurements at different points in the radio unit. The three lines at the top indicate the absolute temperature measurements. The lines below are corrected for the ambient temperature.

The thickness of the graphite sheets were measured after the test as well. It is assumed that the initial thickness of the sheet was 200 μm. In Figure 57, it can be seen that the thickness of the graphite sheet varies. The uneven thickness indicates an uneven pressure distribution over the TIM. The thinnest part of 26 μm was found close to a screw. From the results in Figure 40 the pressure is estimated to have surpassed 4 MPa at that point. According to Figure 58 the graphite at the PAs were exposed to an average pressure between 400 kPa and 1 200 kPa. For the PA drivers the corresponding values are between 800 kPa and 1 900 kPa. The average estimated pressure for the PAs, regardless of the left or right board, is 700 kPa. The average pressure for the PA drivers is 1 150 kPa.
Figure 57. The upper picture shows the thickness (μm) of the graphite sheet measured on the left PA board, the right board is in the lower picture. The original thickness was about 200 μm.

Figure 58. The upper picture shows the average thickness (μm) of the graphite sheet (divided into 8x2 areas) on the left and right side PA board. The corresponding pressure estimations in kPa are shown below. Combined, the average pressure is 700 kPa and 1150 kPa for the PA and their drivers respectively.

4.4 Uncertainty tests

The overall probable relative uncertainty varies between all the samples tested. The average uncertainty for graphite sheets and gap pads are divided into separate categories in Table 7. For gap pads the average uncertainty was around 10% while for graphite sheets the uncertainty ranged from about 20% to 30%.
Table 7. A table showing the average probable overall uncertainty for all graphite sheets and gap pads tested. The uncertainty is larger for the thermal conductivity calculations as the material thickness is included there as well. The -5 % steady state error is not included in this table.

<table>
<thead>
<tr>
<th></th>
<th>Overall maximum relative error</th>
<th>Overall probable relative uncertainty (95 %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Graphite Sheets</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$R_{TIM}$</td>
<td>34 %</td>
<td>17 %</td>
</tr>
<tr>
<td>$k_{TIM}$</td>
<td>57 %</td>
<td>29 %</td>
</tr>
<tr>
<td>Gap pads</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$R_{TIM}$</td>
<td>20 %</td>
<td>10 %</td>
</tr>
<tr>
<td>$k_{TIM}$</td>
<td>22 %</td>
<td>11 %</td>
</tr>
</tbody>
</table>

The effect of the uncertainties on the results for graphite sheets and gap pads can be seen in Figure 59 and Figure 60 respectively.

Figure 59. The results from Figure 38 with included error bars. The error bars are longer on the negative side as the steady state error is included.
The relative uncertainty increased with the pressure since the uncertainties in for example the temperature measurements become more significant as the temperature difference goes down. In Figure 61 that phenomena can be seen. At the highest pressures the average overall relative uncertainty approaches 45% for the thermal conductivity.

Figure 60. The results from Figure 46 with included error bars. The error bars are longer on the positive side as the steady state error is included.

Figure 61. The overall probable relative uncertainty for the graphite sheets as a function of pressure. The uncertainty is larger for the thermal conductivity as the thickness is also a part of the uncertainty. In these graphs the steady state error of -5% is not included.
The repeatability of the tests in the TTV was also considered. Four reference tests using four different samples of A1 was tested at four separate occasions (with other tests performed in between). The curves in Figure 62 show just a small deviation between the results. The same trend is seen for the empty TTV tests.

![Figure 62. A graph showing the results of repeated tests. Two tests with and empty TTV and four tests with sample A1. The repeatability was within the estimated uncertainty range.](image)
5 Discussion

This section contains a discussion about how the results should be interpreted and how graphite sheets and gap pads would possibly perform in practice. Some of the advantages and disadvantages using the best performing TIMs are also mentioned. There is a separate section in the end, discussing what future work could be focused at.

5.1 Interpretation of the results

The test setup used did not give the possibility to measure the bulk thermal conductivity (or resistance) of the TIMs as the surface resistances were always present. In real life applications though, there is always an interface resistance between the TIM and the mating surfaces. Hence, it is more convenient to use this method. However, the results are highly dependent on the roughness and material of the surfaces in contact with the TIM (in this case polished copper). The thermal values given in this report should therefore not be considered as the real values since different environments (surfaces are most crucial) would give other results. It is more reasonable to look at the results as a way to benchmark the different materials against each other. The best performing TIM here would probably (but not certainly) be the best performing one in a real application.

The thickness is needed when calculating the thermal conductivity of a material. If the conductivity is based on the initial thickness, a thick and soft material that can easily be compressed, would have high values (for example B1). The most convenient way would thereby be to measure the thickness at the same time as the TIM is compressed in order to not favour certain materials. However, during the thermal tests it was not possible to measure the thickness of thin materials in real time and still keep a high accuracy. Instead, the thermal conductivity of the materials was based on the plastic deformation curves measured in a separate test. This was considered to be the fairest option to not, in the largest extent, favour certain materials. Still, a material that is not plastically deformable but have a high elastic deformation would be treated as it was as thick as in the beginning and by that get a high value of thermal conductivity. Nevertheless, the method is repeatable and serves as the best compromise.

By measuring the thickness of the graphite sheets used in the radio unit, the pressure was estimated. The estimations are however very sensitive since a difference of about 5 μm in thickness could give a difference in estimated pressure of 500 kPa when the compression rate is high. Therefore the results are best treated as a hint of the magnitudes and as an indication that the pressure distribution is not even. The most reasonable values to use are the averages of 700 kPa for the PAs and 1150 kPa for the PA drivers.

Regarding the uncertainties of the tests, the estimated values from the TTV seem to be in the same range as for the ASTM D5470 showed in Table 1. Uncertainties of up to 100 % for the thinnest materials with the smallest temperature drops are however high. Nevertheless, it has to be remembered that some of the parameters (for example the thermal conductivity of the copper and the distances between the measurement points) are unknown systematic errors. The good repeatability shown in Figure 62 can be explained by these errors. The test done in this study would work well as benchmarking tests.

5.2 The graphite sheets in practice

Several graphite sheets were tested as thermal interface materials. A few of them were physically considered suitable (regarding thickness and compressibility) to replace the 100 μm graphite sheet E4, currently used in some of Ericsson’s products. The two best materials regarding thermal resistance (B1 and D2) were studied more deeply. Graphite sheet B1 had a lower resistance at low pressures while D2 was better at higher pressures. Depending on the pressures in the real applications, either B1 or D2 could be the best choice. Furthermore, in most products Ericsson is using thermal grease. The test showed that the grease would be preferable at really low pressures while the best graphite sheets show a much lower
thermal resistance at higher pressures. As the thermal grease is messier, have a shorter expected lifetime and worse thermal performance compared to these sheets, there are not many reasons to keep using it. One of the strongest reasons however, is mechanical. On the one hand the thermal grease can be compressed to a very narrow thickness and flows out at a very low pressure. In that sense the mechanical stress on the components to be cooled will be minimal. On the other hand the thermal grease would not be able to fill any larger gaps as the surfaces have to be very flat. Those gaps can occur during the assembly as the surfaces may bend when the screws are tightened.

Another factor that has to be considered is the relation between the benchmarking tests and the real applications. As mentioned earlier the different environments will give different results. There are some problems with bending of the components in the applications today. At some places the grease will create a good contact just close to the screws, not using the whole available surface for good thermal transport. In those cases it is possible that a soft graphite sheet can capture these tolerance issues and have a good contact over the whole surface, significantly decreasing the thermal resistance. With that said, it is not certain that a material that shows 50 % less thermal resistance in the TTV would give a 50 % decrease in temperature drop compared to the original material, it could be more and it could be less.

The tests in the radio unit showed that replacing the thermal grease with graphite sheet B1 would lower the temperature of the PA even though the applied power was higher. There would therefore not be any thermal problems with such exchange. However, the pressure estimations indicate that a probable pressure range would be around 400 kPa to 1 900 kPa which makes sheet D2 more favourable according to Figure 38. It is not certain that the pressure would be as high if an 80 μm thin D2 sheet was used. Choosing between the two requires a corresponding test in the radio with D2 instead. Nevertheless, it is possible to see that the thermal grease has about twice the thermal resistance of the two graphite sheets at those pressures.

When reading product specifications for graphite sheets it is common to first look at the thermal conductivity (as high as possible) and a thickness to match the application. This study shows that other parameters are more important. Instead of choosing the best in-plane thermal conductivity, the density could be a better indication of how a material would perform as a TIM.

Figure 43 and Figure 44 show that there are correlations between the thermal performance and the initial density of the graphite sheets; in general a low density gives a good thermal performance. The low density materials are also easier to compress and it is likely that they can conform better to the surfaces, decreasing the interface resistance. Furthermore, the top three samples regarding low thermal resistance are the same samples that are the most compressible and also have the lowest initial densities. On the high density side is for example B6. That graphite sheet has a stated in-plane thermal conductivity of 1 500 W/(mK), a thickness of 45 μm and a density of 1.7 g/cm³. Even though it could look like a good material at a first glance (concerning the thermal conductivity), the poor ability to conform to the surface makes it one of the worst performing materials regarding the thermal conductivity. Despite the thin nature of the material the thermal resistance is average, just about matching the much thicker reference E4.

From these results it can be concluded that looking at the specified thickness and stated thermal conductivity is not enough to determine if a graphite sheet would suit an application or not. In fact, if a graphite sheet is to be used as a TIM, the density could give a better indication of how the material will perform. Moreover, a thick but highly compressible material as B1, could be used in an application dimensioned for a thinner graphite sheet. The general recommendation is that graphite sheets may advantageously replace the thermal grease at places where its electrical conductivity do not cause any problems.

5.3 The gap pads in practice

The results of the thermal tests show that both H1 and J1 outperform the reference gap pads when it comes to thermal conductivity and thermal resistance. One trend, opposed to the original K1 and L1 gap
pads, is that the thermal conductivity goes down as the materials are compressed. The change in conductivity leads to a slight increase in thermal resistance, even though the thickness of the material decreases. It is evident that something happens with the material within the two gap pads, making the thermal transport less beneficial. In H1 the graphite is vertically aligned in the beginning. The compression and the cracking of the material (see Figure 53) do most probably disturb the alignment and thereby also affect the thermal performance. For gap pad J1 no visible structural changes can be seen as the material still look homogenous after it has been compressed. The results do however show that the thermal conductivity decreases. J1(2) show slightly lower thermal conductivities than the thicker J1. It is most probably due to that the contact resistance is higher relative to the total thermal resistances.

In practice, it is only the resistance that determines the temperature of the component to be cooled. Therefore both H1 and J1 would perform quite the same regardless of how much they are compressed. That fact makes it easier to predict the temperature drop over the gap pad as the resistance, using for example J1, would be around 100 mm²·K/W between 10 % and 40 % relative compression. Notable is that these test were performed between two polished copper surfaces that may not give the same contact resistance as in real life applications.

During the mechanical tests it became evident that J1 was the softer material of the three. H1 was harder than K1 during the compression phase but as it relaxed the pressure got below that of K1. However, H1 had a tendency to crack, which ultimately could lead to electrical conducting pieces falling off, creating damaging short circuits on the PCB. The cracks that can be seen in Figure 53 might also be the explanation to why the material becomes softer as it is compressed (see Figure 51). At about 15 % relative compression the curve changes direction, opposed to the other two gap pads. One theory is that the forces holding the laminated structure together become too weak at that point, the cracks are initiated and the material becomes easier to compress. The results for J1(2) show that the thinner materials are harder to compress. That has to be considered when moving towards thinner gap pads.

The peak compression results shown in Figure 54 were supposed to serve as indications of how large the maximum pressure would be on the components. The sample rate of the data acquisition unit was limited to about 25 Hz, or one sample per 0.04 s. The peak pressure could therefore not be considered as the absolute peak value; the peak could have been higher for a short period of time. What could be said is that the pressure has not been higher than the measured value for longer than 0.08 s.

The first tests in the radio unit showed that the temperatures of the components on the TRX board could be reduced. During the second test the temperature increased again. The reason for the increase is still unknown. It is however possible that after the unit had been disassembled to prepare for the last test, the lowered pressure allowed the gap pads to relax. During the reassembly, the pressure on the gap pads did not reach the same level as before. The lower pressure could therefore give a higher contact resistance and consequently a larger temperature drop over the TIM.

If it was to choose between incorporating gap pad H1 or J1 into Ericsson’s products, J1 would be the preferred one. It has the best thermal properties at the same time as the mechanical properties are more favourable. The tendency to crack is also smaller compared to H1. However, the risks of incorporating an electrical conductive gap pad have to be assessed not to jeopardise the PCB safety.

### 5.4 Future work

First of all, there are a few things that can be done to improve the test rig, both to give more reliable results and to make the testing easier to perform. By increasing the length of the copper bars and introducing two new measurement points in the top bar, the uncertainty can be decreased at the same time as the applied heat can be controlled above the TIM as well. Furthermore, it is important to find a way to reduce the uncertainty of the thickness measurements in the test rig to be able to do real time measurements for thin materials as well. Possible solutions could be to introduce magnetic sensors or utilise some kind of optical measurements. Preferable, the whole MultiTest 2.5-d would be replaced with
something that is more suitable for these kinds of tests. If the pressure is applied straight from above, with for example a pneumatic arm, the bending problem could be avoided. If the thickness measurement would be better, it could also be possible to estimate the contact resistance through the method described in the ASTM D5470 description in 2.5 Methods for characterisation of TIMs. Finally, a programmable test rig is advantageous. That would make the control of the test rig easier as the rig can wait for a predefined steady state condition and then automatically increase the pressure.

Regarding the evaluation of the TIMs, there are a few tests that were not done in this study (apart from real time thickness measurements for thin materials) that could increase the understanding of the materials further. As mentioned earlier, the conformation of the TIM to the surfaces is important in order to have a low thermal contact resistance. The tests in this report were focused on the compressibility of the graphite sheets while in reality the properties of the sheet surface might be more important. Therefore it would be useful to study the relationship between the surface hardness and thermal performance.

To get a better understanding of the TIMs behaviour in the real applications it could be interesting to further and more accurately study the pressures and stresses involved when the TIMs are compressed between two surfaces, for example the PCB and heat sink. That could possibly be done by computational structure analysis or tests with pressure sensitive tape or similar. It would for example then be possible to see the mechanical effects of replacing the soft thermal grease with graphite sheets. The increased understanding of the application would also make it easier to find the most crucial characteristics of a TIM. The pressure distribution between the PCB and the heat sink could for example also be used to estimate the variation of the TIM’s thermal resistance over the surface. Additionally, a modified TTV with surfaces that are more similar to the real application could be created; not polished copper to copper as it is today.

Further reliability tests for both graphite sheets and gap pads are also needed to makes sure the TIM can withstand the whole lifetime of the product without inflicting any damage. It has to be studied if the non-rebounding nature of the graphite gap pads (compared to the standard pads) seen in Figure 49, increases the risk of losing the contact at the interfaces in the long run.

New materials are under development and something better is expected to come from for example the CNT or graphene areas. It would be interesting to study the performance of the best materials from Table 8 in Appendix A since they are said to have one twentieth of the thermal resistance of the best graphite sheets tested for this report. Finally, it can also be useful to look at other designs of the cooling system. Maybe the good heat spreading capability of some graphite sheets could be utilised in a totally new concept in future products.
6 Conclusion

The aim of this study was to get a better understanding of what characterise a good thermal interface material (TIM) and to find materials that are better than the TIMs used in Ericsson’s products today. This was done by evaluating thermal and mechanical properties of graphite sheet and graphite gap pads.

Through tests of several graphite sheets from various manufacturers it was found that the materials used in some of Ericsson’s products are performing less good in comparison. By strictly looking at the thermal tests in the TTV, the thermal resistance, and consequently the temperature difference, could be reduced by 50 % or more. Furthermore, it was showed that it is possible to replace the thermal grease in a radio unit with soft graphite sheet (B1) as thick as 200 μm without causing any direct mechanical or thermal problems. The temperatures of the PA decreased with 3 °C compared to the reference test. This makes room for a possible shift from thermal grease and old graphite sheets to new softer graphite sheets. However, depending on the pressure level, D2 might work as well as B1 (or even better). It was also found that the TIMs that are highly compressible tend to have a low thermal resistance and low initial density. Therefore, when studying product specification for graphite sheets, a low initial density could be the best way to find a material that will give a low thermal resistance.

Regarding the gap pads, the thermal conductivity could be three times higher than the best performing 7 W/(m·K) gap pads used in some of Ericsson’s products today. This is possible through the use of a graphite gap pad (J1) with a thermal conductivity of up to 23 W/(m·K). Such a high value could be reached still keeping the gap pad softer than the pads used today. This was showed by the lower pressure at the same relative compression rates. The peak pressure during the simulated assembly test was also lower for the J1 graphite gap pad. Compared to the 3 W/(m·K) standard gap pad, a smaller nominal gap with the gap pad J1(2) could reduce the thermal resistance with 90 %. However, if the gap distances are decreased, the pressures will be higher, increasing the need of a softer gap pad. Applying graphite pads in the radio unit gave a temperature drop of about 5 °C on the relevant parts of the unit. Unfortunately, there is a tendency of cracking which could cause electrical conducting pieces to fall off in the long run, creating devastating short circuits in the electronics. Therefore, this material is not suitable to substitute the old gap pads until the safety aspect has been assessed.
References


**Figures**

*University of Wisconsin-Madison, 2008. Based upon material developed by the Materials Research Science and Engineering Center on Structured Interfaces at the University of Wisconsin-Madison with funding from the National Science Foundation under award numbers DMR-1121288, DMR-0520527, DMR-0079983, and EEC-0908782. Any opinions, findings, and conclusions or recommendations expressed in this report are those of the authors and do not necessarily reflect the views of the Foundation. Available at: <http://education.mrsec.wisc.edu/nanoquest/carbon/> [Accessed 1 Mar. 2014]
## Appendix A – List of TIMs

Table 8. A list of various carbon based TIMs found in literature.

<table>
<thead>
<tr>
<th>TIM</th>
<th>Total thermal resistance (impedance) (mm²K/W)</th>
<th>Bulk thermal conductivity (W/(mK))</th>
<th>Measurement method</th>
<th>Applied pressure (kPa)</th>
<th>Test surface and roughness</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Graphene-MLG-Epoxy (10 vol.%)</td>
<td>-</td>
<td>5.1</td>
<td>Laser Flash</td>
<td>-</td>
<td>Aluminium</td>
<td>(Shahil and Balandin, 2012a)</td>
</tr>
<tr>
<td>Graphite-Epoxy (20 wt.%)</td>
<td>-</td>
<td>4.3</td>
<td>Laser Flash</td>
<td>-</td>
<td>-</td>
<td>(Debelak and Lafdi, 2007)</td>
</tr>
<tr>
<td>Zn-Al-Graphene-MLG (2 vol.%)</td>
<td>-</td>
<td>14</td>
<td>Laser Flash</td>
<td>-</td>
<td>Aluminium</td>
<td>(Shahil and Balandin, 2012a)</td>
</tr>
<tr>
<td>Flexible graphite 130 µm</td>
<td>71.4 ± 4.6</td>
<td>-</td>
<td>ASTM D5470</td>
<td>460</td>
<td>Copper, Ra=15 µm</td>
<td>(Leong, Aoyagi and Chung, 2006)</td>
</tr>
<tr>
<td>Flexible graphite 130 µm-Thixotropic Carbon black paste</td>
<td>34.1 ± 1.0</td>
<td>-</td>
<td>ASTM D5470</td>
<td>460</td>
<td>Copper, Ra=15 µm</td>
<td>(Leong, Aoyagi and Chung, 2006)</td>
</tr>
<tr>
<td>Flexible graphite</td>
<td>42.7 ± 2.9</td>
<td>-</td>
<td>ASTM D5470</td>
<td>460</td>
<td>Copper</td>
<td>(Leong, Aoyagi and Chung, 2006)</td>
</tr>
<tr>
<td>Material Description</td>
<td>Conductivity</td>
<td>Test Method &amp; Measurements</td>
<td>Temperature</td>
<td>Notes</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-----------------------------------------------------------</td>
<td>--------------</td>
<td>------------------------------------------------------------------</td>
<td>-------------</td>
<td>--------------------------------------------</td>
<td></td>
<td></td>
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<tr>
<td>130 µm-Fluidic Carbon black paste</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aligned CNT Array on silicon wafer</td>
<td>19.8</td>
<td>ASTM D5470 with IR-camera for temp. measurement</td>
<td>445</td>
<td>Copper, Ra=15 µm</td>
<td></td>
<td></td>
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<td></td>
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<td></td>
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<tr>
<td>Aligned CNT Array - Honeywell PCM 45F 250 µm</td>
<td>5.2</td>
<td>ASTM D5470 with IR-camera for temp. measurement</td>
<td>350</td>
<td>Copper, Ra=1.4 µm</td>
<td></td>
<td></td>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mats of MWCNT-xGNP</td>
<td>3.5/1.6</td>
<td>ASTM D5470</td>
<td>140/560</td>
<td>Copper, RRMS = 0.877 µm and 1.563 µm resp.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mats of MWCNT-xGNP-PCM</td>
<td>1.3/0.7</td>
<td>ASTM D5470</td>
<td>140/560</td>
<td>Copper, RRMS = 0.877 µm and 1.563 µm resp.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(Xu and Fisher, 2006)
Appendix B – Partial derivatives

\[ u_{\text{TM}, 2-3} = 2 \cdot \left[ \left( \frac{\partial R_{\text{TM}}}{\partial T_{\text{copper}}} s_{r_{\text{TM}}} \right)^2 + \left( \frac{\partial R_{\text{TM}}}{\partial T_{\text{TIM}, 2-3}} s_{r_{\text{TM}, 2-3}} \right)^2 + \left( \frac{\partial R_{\text{TM}}}{\partial d} s_d \right)^2 + \left( \frac{\partial R_{\text{TM}}}{\partial A_{c, 2}} s_{A_{c, 2}} \right)^2 \right]^{\frac{1}{2}} \]  

(24)

\[ \frac{\partial R_{\text{TM}}}{\partial \Delta T_{\text{copper}}} = \frac{R_{\text{TM}}}{\Delta T_{\text{copper}}} + \frac{A_{\text{sample}} \cdot d \cdot \left( 1 + \frac{A_{c, 2}}{A_{c, 3}} \right)}{A_{c, 2} \cdot k_{\text{copper}} \cdot \Delta T_{\text{copper}}} \]  

(25)

\[ \frac{\partial R_{\text{TM}}}{\partial \Delta T_{\text{TIM}, 2-3}} = \frac{A_{\text{sample}} \cdot \Delta L}{A_{c, 2} \cdot k_{\text{copper}} \cdot \Delta T_{\text{copper}}} \]  

(26)

\[ \frac{\partial R_{\text{TM}}}{\partial d} = -\frac{A_{\text{sample}} \cdot \Delta L}{A_{c, 2} \cdot k_{\text{copper}}} \cdot \left( 1 + \frac{A_{c, 2}}{A_{c, 3}} \right) \]  

(27)

\[ \frac{\partial R_{\text{TM}}}{\partial A_{c, 1}} = \frac{A_{\text{sample}} \cdot \Delta L}{A_{c, 2} \cdot k_{\text{copper}}} \]  

(28)

\[ \frac{\partial R_{\text{TM}}}{\partial A_{c, 2}} = \left( \frac{R_{\text{TM}}}{A_{c, 2}} + \frac{A_{\text{sample}} \cdot d}{A_{c, 2} \cdot k_{\text{copper}}} \cdot \frac{A_{c, 3}}{A_{c, 1}} \right) \]  

(29)

\[ \frac{\partial R_{\text{TM}}}{\partial A_{\text{sample}}} = \frac{R_{\text{TM}}}{A_{\text{sample}}} \]  

(30)

\[ \frac{\partial R_{\text{TM}}}{\partial \Delta L} = \frac{A_{\text{sample}} \cdot \Delta T_{\text{TIM}, 2-3}}{A_{c, 2} \cdot k_{\text{copper}} \cdot \Delta T_{\text{copper}}} \]  

(31)

\[ \frac{\partial R_{\text{TM}}}{\partial k_{\text{copper}}} = -\frac{R_{\text{TM}}}{k_{\text{copper}}} \]  

(32)

\[ u_{k_{\text{TM}}} = 2 \cdot \left[ \left( \frac{\partial k_{\text{TM}}}{\partial T_{\text{copper}}} s_{r_{\text{TM}}} \right)^2 + \left( \frac{\partial k_{\text{TM}}}{\partial T_{\text{TIM}, 2-3}} s_{r_{\text{TM}, 2-3}} \right)^2 + \left( \frac{\partial k_{\text{TM}}}{\partial d} s_d \right)^2 + \left( \frac{\partial k_{\text{TM}}}{\partial A_{c, 2}} s_{A_{c, 2}} \right)^2 \right]^{\frac{1}{2}} \]  

(33)
\[ \frac{\partial k_{\text{TIM}}}{\partial \Delta T_{\text{copper}}} = \frac{k_{\text{TIM}}}{\Delta T_{\text{copper}}} + \frac{k_{\text{TIM}} \cdot d \cdot \left(1 + \frac{A_{e,2}}{A_{e,1}}\right)}{\Delta T_{\text{TIM},2-3} \cdot \Delta L - \Delta T_{\text{copper}} \cdot d \cdot \left(1 + \frac{A_{e,2}}{A_{e,1}}\right) \cdot A_{e,1}} \]  
(34)

\[ \frac{\partial k_{\text{TIM}}}{\partial \Delta T_{\text{TIM},2-3}} = -\frac{k_{\text{TIM}} \cdot \Delta L}{\Delta T_{\text{TIM},2-3} \cdot \Delta L - \Delta T_{\text{copper}} \cdot d \cdot \left(1 + \frac{A_{e,2}}{A_{e,1}}\right)} \]  
(35)

\[ \frac{\partial k_{\text{TIM}}}{\partial d} = \frac{k_{\text{TIM}} \cdot \Delta T_{\text{copper}} \cdot d \cdot \left(1 + \frac{A_{e,2}}{A_{e,1}}\right)}{\Delta T_{\text{TIM},2-3} \cdot \Delta L - \Delta T_{\text{copper}} \cdot d \cdot \left(1 + \frac{A_{e,2}}{A_{e,1}}\right) \cdot A_{e,1}} \]  
(36)

\[ \frac{\partial k_{\text{TIM}}}{\partial A_{e,1}} = -\frac{k_{\text{TIM}} \cdot \Delta T_{\text{copper}} \cdot d \cdot A_{e,2}}{\Delta T_{\text{TIM},2-3} \cdot \Delta L - \Delta T_{\text{copper}} \cdot d \cdot \left(1 + \frac{A_{e,2}}{A_{e,1}}\right) \cdot A_{e,1}^2} \]  
(37)

\[ \frac{\partial k_{\text{TIM}}}{\partial A_{e,2}} = \frac{k_{\text{TIM}}}{A_{e,2}} + \frac{k_{\text{TIM}} \cdot \Delta T_{\text{copper}} \cdot d}{\Delta T_{\text{TIM},2-3} \cdot \Delta L - \Delta T_{\text{copper}} \cdot d \cdot \left(1 + \frac{A_{e,2}}{A_{e,1}}\right) \cdot A_{e,1}} \]  
(38)

\[ \frac{\partial k_{\text{TIM}}}{\partial A_{\text{sample}}} = -\frac{k_{\text{TIM}}}{A_{\text{sample}}} \]  
(39)

\[ \frac{\partial k_{\text{TIM}}}{\partial \Delta L} = -\frac{k_{\text{TIM}} \cdot \Delta T_{\text{TIM},2-3}}{\Delta T_{\text{TIM},2-3} \cdot \Delta L - \Delta T_{\text{copper}} \cdot d \cdot \left(1 + \frac{A_{e,2}}{A_{e,1}}\right)} \]  
(40)

\[ \frac{\partial k_{\text{TIM}}}{\partial k_{\text{copper}}} = \frac{k_{\text{TIM}}}{k_{\text{copper}}} \]  
(41)

\[ \frac{\partial k_{\text{TIM}}}{\partial t} = \frac{k_{\text{TIM}}}{t} \]  
(42)
Appendix C – Complementary figures

Figure 63. The blue curve show the voltage per °C for a type K thermocouple as a function of the temperature measured. The red curve indicate the possible error for a 20 °C temperature difference if the reference junction calibration is two degrees off. The highest values are slightly below 0.05 °C.
Appendix D – Complementary tables

Table 9. The thermal resistance of each graphite sheet at different test pressures.

<table>
<thead>
<tr>
<th>Graphite Sheet</th>
<th>Average test pressure (kPa)</th>
<th>45</th>
<th>87</th>
<th>173</th>
<th>347</th>
<th>521</th>
<th>872</th>
<th>1741</th>
<th>3479</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mm²·K/W</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A1</td>
<td></td>
<td>279</td>
<td>199</td>
<td>143</td>
<td>79</td>
<td>48</td>
<td>22</td>
<td>12</td>
<td>9</td>
</tr>
<tr>
<td>A2</td>
<td></td>
<td>257</td>
<td>171</td>
<td>110</td>
<td>54</td>
<td>35</td>
<td>23</td>
<td>16</td>
<td>13</td>
</tr>
<tr>
<td>B1</td>
<td></td>
<td>190</td>
<td>84</td>
<td>44</td>
<td>29</td>
<td>24</td>
<td>18</td>
<td>12</td>
<td>10</td>
</tr>
<tr>
<td>B2</td>
<td></td>
<td>229</td>
<td>126</td>
<td>66</td>
<td>34</td>
<td>26</td>
<td>20</td>
<td>14</td>
<td>12</td>
</tr>
<tr>
<td>B3</td>
<td></td>
<td>520</td>
<td>421</td>
<td>321</td>
<td>233</td>
<td>196</td>
<td>146</td>
<td>96</td>
<td>70</td>
</tr>
<tr>
<td>B4</td>
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<td>264</td>
<td>162</td>
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<td>56</td>
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</tr>
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<td>93</td>
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<td>35</td>
<td>20</td>
<td>14</td>
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<td>264</td>
<td>166</td>
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<td>60</td>
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</table>
Table 10. The thermal conductivity of each graphite sheet at different test pressures.

<table>
<thead>
<tr>
<th>Graphite Sheet</th>
<th>Average test pressure (kPa)</th>
<th>W/(m·K)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>45</td>
<td>87</td>
</tr>
<tr>
<td>A1</td>
<td>0.3</td>
<td>0.4</td>
</tr>
<tr>
<td>A2</td>
<td>0.4</td>
<td>0.7</td>
</tr>
<tr>
<td>B1</td>
<td>1.1</td>
<td>2.4</td>
</tr>
<tr>
<td>B2</td>
<td>0.3</td>
<td>0.5</td>
</tr>
<tr>
<td>B3</td>
<td>0.1</td>
<td>0.2</td>
</tr>
<tr>
<td>B4</td>
<td>0.8</td>
<td>1.0</td>
</tr>
<tr>
<td>B5</td>
<td>0.4</td>
<td>0.6</td>
</tr>
<tr>
<td>B6</td>
<td>0.1</td>
<td>0.2</td>
</tr>
<tr>
<td>C1</td>
<td>3.2</td>
<td>3.9</td>
</tr>
<tr>
<td>C2</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>D1</td>
<td>0.3</td>
<td>0.4</td>
</tr>
<tr>
<td>D2</td>
<td>0.4</td>
<td>0.6</td>
</tr>
<tr>
<td>D3</td>
<td>0.6</td>
<td>0.9</td>
</tr>
<tr>
<td>D4</td>
<td>0.4</td>
<td>0.5</td>
</tr>
<tr>
<td>E1</td>
<td>0.3</td>
<td>0.4</td>
</tr>
<tr>
<td>E2</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>E3</td>
<td>0.4</td>
<td>0.5</td>
</tr>
<tr>
<td>E4</td>
<td>0.3</td>
<td>0.5</td>
</tr>
<tr>
<td>E5</td>
<td>0.2</td>
<td>0.3</td>
</tr>
<tr>
<td>F1</td>
<td>0.3</td>
<td>0.5</td>
</tr>
<tr>
<td>G1</td>
<td>0.5</td>
<td>0.6</td>
</tr>
</tbody>
</table>
Table 11. A table showing each graphite sheet test sample's initial thickness and density.

<table>
<thead>
<tr>
<th>Graphite sheet</th>
<th>Measured thickness (μm)</th>
<th>Thickness from manufacturer (μm)</th>
<th>Density (g/cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>84.5</td>
<td>70</td>
<td>0.71</td>
</tr>
<tr>
<td>A2</td>
<td>112</td>
<td>100</td>
<td>0.74</td>
</tr>
<tr>
<td>B1</td>
<td>202.6</td>
<td>200</td>
<td>0.25</td>
</tr>
<tr>
<td>B2</td>
<td>69.6</td>
<td>76</td>
<td>0.66</td>
</tr>
<tr>
<td>B3</td>
<td>75.2</td>
<td>76</td>
<td>1.72</td>
</tr>
<tr>
<td>B4</td>
<td>268.2</td>
<td>254</td>
<td>0.88</td>
</tr>
<tr>
<td>B5</td>
<td>131.6</td>
<td>127</td>
<td>1.00</td>
</tr>
<tr>
<td>B6</td>
<td>43</td>
<td>45</td>
<td>1.72</td>
</tr>
<tr>
<td>C1</td>
<td>1 889.2</td>
<td>2 000</td>
<td>1.94</td>
</tr>
<tr>
<td>C2</td>
<td>237.8</td>
<td>200</td>
<td>1.86</td>
</tr>
<tr>
<td>D1</td>
<td>73.6</td>
<td>70</td>
<td>1.03</td>
</tr>
<tr>
<td>D2</td>
<td>81.2</td>
<td>70</td>
<td>0.62</td>
</tr>
<tr>
<td>D3</td>
<td>108.8</td>
<td>100</td>
<td>0.75</td>
</tr>
<tr>
<td>D4</td>
<td>68.2</td>
<td>70</td>
<td>1.18</td>
</tr>
<tr>
<td>E1</td>
<td>127.6</td>
<td>-</td>
<td>1.7</td>
</tr>
<tr>
<td>E2</td>
<td>131.8</td>
<td>-</td>
<td>1.15</td>
</tr>
<tr>
<td>E3</td>
<td>92.2</td>
<td>75</td>
<td>0.81</td>
</tr>
<tr>
<td>E4</td>
<td>123.2</td>
<td>100</td>
<td>0.71</td>
</tr>
<tr>
<td>E5</td>
<td>69</td>
<td>70</td>
<td>1.23</td>
</tr>
<tr>
<td>F1</td>
<td>139.8</td>
<td>110-120</td>
<td>0.69</td>
</tr>
<tr>
<td>G1</td>
<td>209.6</td>
<td>200</td>
<td>0.81</td>
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</table>
Table 12. Tabulated results from the thermal evaluation of the gap pads.

<table>
<thead>
<tr>
<th>Gap pads</th>
<th>H1</th>
<th>J1</th>
<th>J1(2)</th>
<th>K1</th>
<th>L1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relative compr.</td>
<td>2 %</td>
<td>5 %</td>
<td>10 %</td>
<td>17 %</td>
<td>32 %</td>
</tr>
<tr>
<td>W/(m·K)</td>
<td>9.1</td>
<td>11.5</td>
<td>12.0</td>
<td>11.5</td>
<td>9.0</td>
</tr>
<tr>
<td>mm²·K/W</td>
<td>215</td>
<td>164</td>
<td>150</td>
<td>144</td>
<td>150</td>
</tr>
<tr>
<td>Relative compr.</td>
<td>3 %</td>
<td>12 %</td>
<td>18 %</td>
<td>30 %</td>
<td>40 %</td>
</tr>
<tr>
<td>W/(m·K)</td>
<td>20.6</td>
<td>22.7</td>
<td>21.7</td>
<td>18.4</td>
<td>15.0</td>
</tr>
<tr>
<td>mm²·K/W</td>
<td>130</td>
<td>107</td>
<td>104</td>
<td>105</td>
<td>110</td>
</tr>
<tr>
<td>Relative compr.</td>
<td>0 %</td>
<td>8 %</td>
<td>12 %</td>
<td>22 %</td>
<td>30 %</td>
</tr>
<tr>
<td>W/(m·K)</td>
<td>12.5</td>
<td>17.1</td>
<td>19.0</td>
<td>17.8</td>
<td>16.1</td>
</tr>
<tr>
<td>mm²·K/W</td>
<td>124</td>
<td>82</td>
<td>71</td>
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<tr>
<td>Relative compr.</td>
<td>3 %</td>
<td>13 %</td>
<td>19 %</td>
<td>25 %</td>
<td>33 %</td>
</tr>
<tr>
<td>W/(m·K)</td>
<td>2.1</td>
<td>2.5</td>
<td>2.6</td>
<td>2.8</td>
<td>2.8</td>
</tr>
<tr>
<td>mm²·K/W</td>
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<tr>
<td>Relative compr.</td>
<td>13 %</td>
<td>20 %</td>
<td>24 %</td>
<td>31 %</td>
<td>37 %</td>
</tr>
<tr>
<td>W/(m·K)</td>
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<td>5.5</td>
<td>6.0</td>
<td>5.9</td>
<td>5.9</td>
</tr>
<tr>
<td>mm²·K/W</td>
<td>238</td>
<td>182</td>
<td>156</td>
<td>146</td>
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