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APPLICATION OF GRAPHITE IN THERMAL MANAGEMENT OF MICROELECTRONICS

APLIKACE GRAFITU V TEPLOTNÍM MANAGEMENTU MIKROELEKTRONIKY

MASTER'S THESIS
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Investigate the topic of thermal management in microelectronics and materials used for cooling electronic components.

Describe carbon-based materials, allotropic and thermal properties. Focus on graphite as a suitable allotropic carbon for thermal management of microelectronic devices.

Using numerical simulation, create 2-3 case models of general structure cooling, which will demonstrate the use of graphite and its comparison with commonly used materials.

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ABSTRACT

This thesis is focused on the enhancement of thermal management of microelectronics by implementing carbon-based materials, exactly graphite foils into the thermal architecture. The thesis starts by explaining current thermal methods and challenges in the field of microelectronics and moves to commonly used materials - aluminum and copper, explaining their capabilities and adding carbon allotropes into the scope. In the second part, this thesis contains several use cases of the pyrolytic graphite sheet in thermal management of microelectronics, proving its usability and analyzing the benefits for heat spreading, thermal conductivity while enabling electrical insulation and the possible use in flexible electronics.

KEYWORDS

thermal management, thermal architecture, carbon, graphite, PGS, heat

ABSTRAKT

Tato práce je zaměřena na zlepšení tepelného managementu mikroelektroniky implementací materiálů na bázi uhlíku, přesněji grafitových fólií, do tepelné architektury mikroelektroniky. Práce začíná vysvětlením současných metod chlazení a výzev v oblasti mikroelektroniky. Poté přechází k běžně používaným materiálům - hliníku a mědi a přidává do výběru i uhlíkové alotropie. Ve druhé části tato práce obsahuje několik příkladů použití pyrolytické grafitové fólie v tepelném managementu mikroelektroniky, prokazuje jeho použitelnost a analyzuje přínosy pro šíření tepla, tepelnou vodivost při dodržení elektrické izolace a možné využití ve flexibilní elektronice.

KLÍČOVÁ SLOVA

teplotní management, teplotní architektura, uhlík, grafit, PGS, teplo

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ROZŠÍŘENÝ ABSTRAKT

Tepelný management v mikroelektronice je dynamický obor poháněný silou inovací s velkým zájmem z různých stran technologického průmyslu. V současné době jsou naše kapesní počítače mnohem efektivnější a výkonnější, než byly naše stolní nebo halové počítače před deseti lety. S tímto trendem ruku v ruce přicházejí i požadavky na správu a odvod tepla. V mnoha případech už dnes techniky, které byly jednou standardem, nemohou dosáhnout požadovaného chladicího výkonu, a pak je potřeba vytvořit specializované řešení, které se později stává novým standardem.

Chlazení může probíhat jak za pomoci vzduchu, tak chladících kapalin, stejně jako existují i možnosti chlazení pomocí Peltierových článků. Mezi největší výzvy současné tepelné architektury v mikroelektronice patří vytváření oblastí s teplotou výrazně vyšší, než je teplota okolí, což je způsobeno zvláště využíváním stále výkonnějších a výkonějších mikročipů. Další výzvou jsou komplikovanější architektury jednotlivých čipů, kdy dochází ke skládání více čipů na sebe, což je velmi náročné pro efektivní chlazení. Poslední výzvou současné doby jsou dotyková a nastupující flexibilní zařízení, která neumožňují používat techniky dříve považované za standard v chlazení.

V posledních letech došlo k velkému vývoji v oblasti tepelného managementu a tepelné architektury, ale i přes to se v této oblasti stále používají dva hlavní materiály - hliník a měď. V této práci je diskutována možnost využití materiálů na bázi uhlíku, zejména pyrolytické grafitové fólie.

Teplu lze přenášet pomocí tří mechanismů: vedení, proudění a záření. Každý z nich pracuje jinak, ale mohou být - a většinou jsou kombinované. Velmi často existují všechny tyto tři mechanismy současně. Na druhé straně, pro simulace nebo odhady přenosu tepla není neobvyklé nezahrnout všechny do „rovnice“, což usnadňuje řešení s žádným nebo velmi malým rozdílem ve výsledku simulace. K vedení dochází v pevných látkách, kapalinách a plynech a je to mechanismus přenosu tepla, ve kterém se teplo přenáší prostřednictvím interakcí mezi atomy, molekulami a hmotou obecně. Přenos tepla, kde dochází k výměně energie mezi pevnou stěnou a sousední pohyblivou tekutinou (kapalinou nebo plynem), se nazývá konvekce. Existují dva prvky konvekce: přenos energie v důsledku náhodného molekulárního pohybu - difúze a druhý je přenos energie hromadným nebo makroskopickým pohybem tekutiny - advekce. Všechna tělesa s teplotou nad absolutní nulou (0°K) mají tepelnou energii, která je emitována ve formě elektromagnetických vln. Tato forma přenosu tepelné energie se nazývá záření. Protože přenos je prováděn elektromagnetickými vlnami, není třeba média, protože elektromagnetické vlny se mohou pohybovat i ve vakuu. Energie může být emitována v ultrafialovém, viditelném a infračerveném spektru, záleží pouze na teplotě samotného těla.

V praktické části je ukázáno několik příkladů použití pyrolytického grafitového listu pomocí simulace metody konečných objemů v softwaru SolidWorks Flow Simulation a pomocí metody konečných prvků v softwaru ANSYS Steady-State Thermal.

Pyrolytická grafitová fólie je skutečný materiál, který lze použít v mikroelektronice. Ale jak a kdy? Pro zodpovězení těchto otázek byly simulovány a analyzovány tři případy použití, aby se ukázaly možnosti tohoto materiálu. Každý z těchto případů použití je vytvořen tak, aby demonstroval různé schopnosti PGS, a ve všech z nich je PGS porovnávána s hliníkem a mědí. Všechny tři případy použití jsou navrženy se zaměřením na jejich vytvoření skutečně blízko realitě, takže mohou sloužit jako základ pro podrobnější studie a simulace.

Jedním z nejnáročnějších problémů je vytváření horkých míst a nerovnoměrné rozložení tepla napříč elektronikou. Řešením pro lepší šíření tepla může být použití materiálu na bázi uhlíku - pyrolytického grafitu, který má vysokou vodivost ve vrstvě roviny a může dobře pomoci s výzvou horkých míst. V kapitole 4 je malá demonstrace použití tohoto materiálu pro eliminaci nerovnoměrného zahřívání. Tato kapitola ukazuje výhody, které pyrolytický grafit může přinést pro tepelný management mikroelektroniky. V této kapitole jsou také uvedeny grafy časově proměnných simulací ukazující, že pyrolytický grafit nejrychlejší jak v růstu teploty, tak v jejím poklesu. To má za následek tepelná vodivost pyrolytického grafitu, která je několikanásobně vyšší, než tepelná vodivost hliníku a mědi. Myšlenka použití pyrolytického grafitu pro šíření tepla je dále rozvíjena a testována na náročnějším a realističtějším designu v prvním příkladu použití (kapitola 7.1).

Tepelný management mikroelektroniky je náročný obor, a jedním z důvodů je potřeba izolace elektricky vodivých materiálů. Pyrolytický grafit není elektrický izolant, ale ve druhém příkladu použití (kapitola 7.2) je jasně ukázáno, jak při použití kombinace pyrolytického grafitu a PET lze při spojit dosáhnout elektrické izolace při zachování tepelné vodivosti na úrovni hliníku a mědi. To bylo demonstrováno na geometrii se dvěma DPS, což ukazuje, že tato možnost je použitelná v mikroelektronice.

Se vzestupem flexibilních zařízení existuje potřeba tepelného managementu těchto zařízení. Použitelnost fólie pyrolytického grafitu s flexibilní DPS je demonstrována ve třetím příkladu použití (Kapitola 7.3). Pyrolytický grafit zde opět vyniká jako nejvhodnější materiál, s maximální teplotou o třetinu nižší, než u hliníku.

Celkově se grafitová fólie v těchto třech případech použití ukázala jako ideální materiál, který přináší výsledky s nejnižší teplotou, nebo - v druhém případě použití - se stejnou teplotou, ale s přidanou hodnotou v elektrické izolace.

DECLARATION

I declare that I have written the Master's Thesis titled "Application of graphite in thermal management of microelectronics" independently, under the guidance of the advisor and using exclusively the technical references and other sources of information cited in the thesis and listed in the comprehensive bibliography at the end of the thesis.

As the author I furthermore declare that, with respect to the creation of this Master's Thesis, I have not infringed any copyright or violated anyone's personal and/or ownership rights. In this context, I am fully aware of the consequences of breaking Regulation § 11 of the Copyright Act No. 121/2000 Coll. of the Czech Republic, as amended, and of any breach of rights related to intellectual property or introduced within amendments to relevant Acts such as the Intellectual Property Act or the Criminal Code, Act No. 40/2009 Coll., Section 2, Head VI, Part 4.

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Brno

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Introduction

Thermal management in microelectronics is an innovation drive field with a lot of interest from various sides of the technological industry. Currently, we are in times where our pocket computers are way more efficient and powerful than our desktop or hall computers were a decade ago, and coming with this trend hand in hand is thermal management and heat dissipation requirements. In many instances, the techniques that were once a standard cannot achieve the required cooling performance, and then there is a need for another specialty than later on becomes a new standard.

In the recent years, there has been a lot of development in the field of thermal management and thermal architecture, but there is still the problem of microchips producing too much heat, so in some cases, the power has to be throttled down so the device is not overheating as a whole. Even though there are still two main materials being used in this field - aluminum and copper. In this thesis, the option of using carbon-based materials, especially pyrolytic graphite foil is discussed.

In the practical part of the thesis, there are several use cases simulating the possibilities of pyrolytic graphite foil use in thermal management of microelectronics. Cases are demonstrating the heat spreading (in both static and transient mode), possible use of combination of graphite and PET to ensure good conductivity while enabling electrical insulation, and in the last case, the use of pyrolytic graphite with flexible PCB is simulated.

1 Thermal management in microelectronics

Thermal management in microelectronics is a complicated field, but it can be divided into parts, as the heat travels. In the cooling applications - microelectronics - heat from the heat source must at first travel by thermal conduction of some kind to a surface that is exposed to the cooling fluid. This demonstrates multiple ways of improving cooling itself.

First of all, which is out of the topic of this thesis though, is a reduction of the heat source itself. In other words, the thermal management of the system as a whole can be always improved simply by reducing the amount of heat that is produced by the heat source.

The second way or place where and how to improve a given system is by improving the thermal conduction, the path through the heat travels to the surface area.

The third way is by making the surface, where system exchanges heat with the cooling fluid, as big as possible, more exactly making the contact area where heat can be exchanged the largest possible, alongside with making the heat transfer the fastest by choosing the right material of the radiator.

The fourth way is by adjusting the cooling fluid itself - its composition, density, and heat transfer properties, but also its temperature and secondary heat exchange system for the fluid itself.

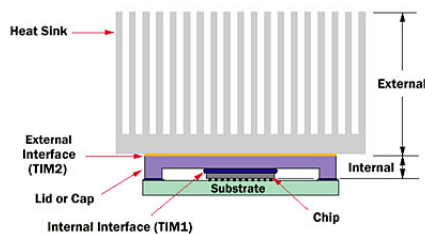


Fig. 1.1: Chip package with thermal conduction path to heat sink via TIMs [1]

As can be seen in Figure 1.1, heat must be conducted from the chip itself to the lid, and then to the heat sink before it can be transferred to the flowing air. Thermal interface materials (TIMs) may be used to help and facilitate the thermal conduction from the chip to the lid and from the lid to the heat sink. It can be in a form of thermal paste or surface heat spreader in a the form of a flat plate with good thermal conductivity. [1]

1.1 Current techniques

1.1.1 Air Cooling

Air cooling is considered a standard, as it is easy to implement and can be powerful enough for a lot of applications, traditional air-cooling techniques are close to their limitation for cooling of high-power applications. This limit is coming from standard fans with heat transfer around $150 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$ that can be reached with acceptable noise levels. However, some new initiatives have emerged to extend the useful range of air cooling. [1]

Piezo Fans

Piezoelectric fans have multiple advantages, as they are low power, small, low noise devices that can further improve air cooling. They can be used in multiple applications, namely laptops and mobile phones. Piezoelectric fans use a vibrating blade that creates airflow, as can be seen in Figure 1.2 [2]

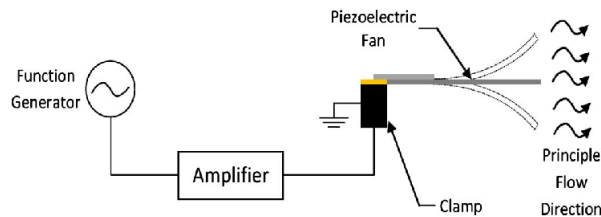


Fig. 1.2: Operation of a piezoelectric fan [2]

Synthetic Jet Cooling

Synthetic jet flow is a flow where the surrounding fluid is made to flow through small opening back and forth, which creates pulsating flow, that introduces stronger entrainment than conventional-steady jets with the same or similar Reynolds number. Pulsating also breaks the wall boundary layers more effectively, which leads to a noticeable increment in the cooling effect. [3]

Nano lightning

Really interesting and novelty approach for increasing the heat transfer coefficient is known as "nano lightning". It is based on microscale ion-driven airflow, which is being developed by nanotubes creating strong electric fields. The air is ionized and these molecules are then moved by another electric field, which can move them exactly because of their ionization. Therefore, the secondary airflow is introduced. These methods can lead up to $4 \cdot 10^5 \text{ W}\cdot\text{m}^{-2}$ of heat flux. [5]

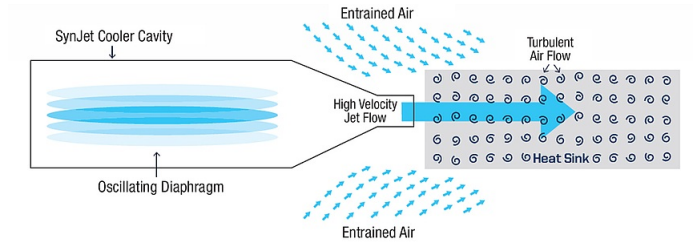


Fig. 1.3: This simplified representation depicts how SynJet cooling generates high-velocity pulses of air to combat thermal issues in space-constrained environments [4]

1.1.2 Liquid Cooling

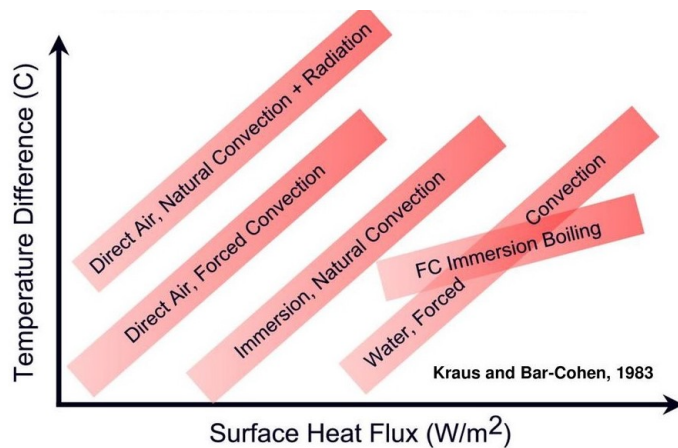


Fig. 1.4: Relative cooling capability of various modes of convective heat transfer and coolants. [6]

The need for liquid cooling is easily coming from the need for higher efficiency of the cooling, where the cooling fluid normally used - air is simply not efficient enough. It is caused by the continuing push towards more and more packed microchips, as it was described by Moore's law and at it is still being true in 2019. These microchips require way greater heat dissipation and although the heat produced by these chips isn't following Moore's law exactly, the air as fluid is just not enough. It can be seen and observed that the manufacturers specify heat dissipation and maximum allowable temperature for reliable long term operation. Although the thermal optimum of some components is relatively high, the need for cooling stays.

There is a firm connection between these two parameters, as can be seen, on Figure 1.4. The figure shows suitable heat transfer mechanisms and technologies based

on heat flux and the temperature difference between the surface of the chip and the surrounding medium. Forced convection using water can be used for cooling of devices with high heat flux and water is greatly more efficient in cooling devices than air, especially in forced convection.[5]

Liquid cooling is generally divided into two groups: direct and indirect cooling. Whereas direct cooling is a situation when coolant is in direct contact with the cooled device or its surface, indirect cooling is when there is no direct contact. Both direct and indirect cooling are commonly used in electronics.

Heat Pipes

First and currently probably the most used example of indirect cooling is heat pipes. These are not only indirect but also passive and therefore do not need any source of electrical power, which helps in the means of thermal architecture in the big picture - as there is no need for a more powerful power source for the device. The pipe itself is a vacuum pumped and sealed vessel that is partially filled with liquid. The internal walls of the pipes are covered by wick, which plays the role of a passive capillary pump, as they're lined with porous medium. If heat is applied, the liquid starts to evaporate and the pressure gradient existing there causes the vapor to flow to the cooler regions, where it condensates and it is being transported back using the porous medium on the walls of the pipe, closing up the loop. [7]

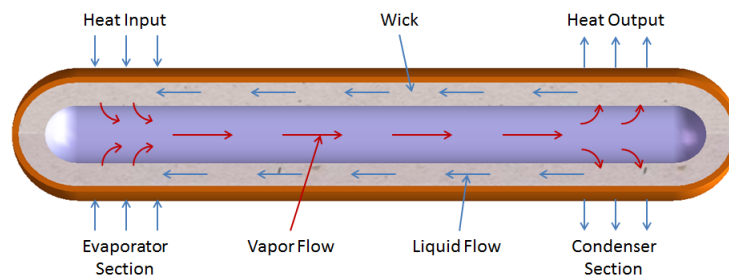


Fig. 1.5: The heat cycle of heat pipe. [8]

Heat pipes do provide enhanced heat transport - in many circumstances better than the copper itself from a heat source to a heat sink, as they are good for fast transport of the heat, but there is still a need for transporting the heat out of the device. Effective thermal conductivity of heat pipe can be from 50 000 to 200 000 $\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$. Although there are no limits for the length of the heat pipe, the ones with length less than 1 cm are actually less efficient than the same length of pure copper. [7]

Cold Plates

A cold plate is essentially the same thing as an air-cooled heat sink, with the only difference of the fluid being liquid that normally has forced flow of liquid. They are active devices, as the flow is forced and there is a need for a pump of some kind, but on the other hand, the pump can be entirely separated from the device, as the cooling cycle can run outside of the device - this solution can be really beneficial especially in weight or vibration-sensitive devices, where placing the pump and power source out of the device can have a high advantage. The other benefit with placing it out of the device is - again - heat dissipation, as the heat from both power source and the pump is vented out of the device.

Cold plates can have one or multiple cooling loops, as the coolant inside the loop directly touching the cold plate pressed to the microchip can be cooled at radiator of some kind, where it exchanges heat with another coolant and so on. This can be needed if the coolant of the first kind is efficient in heat transport but expensive or dangerous.

Microchannels and Minichannels

Micro and mini channels are other methods of increasing the heat transfer coefficient, this time by using holes with the diameter in sizes around micrometers and lower millimeters, resulting in laminar flow. These have a really good heat transfer coefficient, and they actually follow the rule smaller the channel better the coefficient, but due to pressure drop on even smaller channels, the boundaries of this miniaturizing lies within micrometers. The microchannels itself can have various shapes and designs trying to maximize the cooling effect and get the best results.

Liquid Metal Cooling

Liquid metal cooling works on the same basis as cold plate, but with the waste difference of the coolant being a metal. There is research involving the use of Ga-Sn-In eutectics that actually can remain in the liquid state all the way down to -19°C . The idea is to use magneto-fluid dynamic pumps, with moderate flow and high pressure. The coolant itself would use a heat exchanger and air to cool down. [1]

Immersion Cooling

As the name is suggesting, immersion cooling is a direct method of cooling via liquid fluid, where the device is immersed into the liquid. The heat is transferred by the circulation of the fluid and in some cases by boiling. With boiling, there is a vapor

generated by the heat, which goes up the case, where it is cooled down by secondary exchanger and condensates to close the loop. If the heat is exchanged purely by the circulation of the coolant, then we talk about the single-phase method, if the vaporization is used, we talk about the two-phase method, as there are two phases of the fluid - liquid, and vapor.

Fluids used for the immerse cooling have to have really good insulating properties so that they can safely be in contact with the electronics without creating a conductive connection. The materials most used for this are mineral or synthetic oils, which are normally used for the immersion cooling of high power devices in the energy industry, such as transformers, or in the radiology for cooling ox x-ray tubes.

The immersion can be applied just to a certain component, similar to a heat sink or cold plate, but this technology is not used commonly due to the high risk of spilling the coolant to the rest of the device. More often is what is called an open bath, where the whole device is submerged and the surface of the coolant is open for air. The open bath method can be used with both one or two-phase technology, and even though we talk about an open bath, it normally is a sealed tank, as it is not open to the general environment. The size of the open bath can be from small PCBs to full server configurations submerged into the fluid. [9]

1.1.3 Solid-State Cooling

Peltier Cooler

The Peltier cooler is a small electronics heat pump with an advantage of no moving parts and silent operation with no vibrations. The cooler operates using DC and based on the direction of the flow, one side of the Peltier is cool and the other is hot. Peltier is a semiconductor-based element. When a positive DC voltage is applied to the n-type thermoelement, electrons pass from the p to the n-type thermoelement and the cold side temperature decreases, as heat is absorbed. The cooling is proportional to the current flowing through and the number of the thermoelectric couples in the element. The problems with Peltier elements are that only certain differences can be made between the hot and cold side of the element, so with the goal to make the cold side as cold as possible, you need to cool down the hot side. For that you can use another Peltier or heat sink, cold plate, etc. [1]

1.2 Challenges

1.2.1 Power-dense Regions

In modern devices, the architecture of the electronics is complicated and highly structured, but often to a level creating non-uniform heat dissipation across the die surface, with localized functional areas - so-called power-dense regions, where the density of power can be five to ten times higher than the average of the die. These regions can produce hot spots, with a temperature higher than average and size between $500 \mu m^2$ and $5 mm^2$.

As for electronics, the reliability is not determined by the average, but by the area with the highest temperature. Because of that, the real need for cooling is highly affected by the needs of the hot regions, even though some other parts of the device, or even of the PCB can even have the temperature under the optimum. The hot spots then dictate both packaging and material selection to enable heat spreading through the device and making the heat peaks as minimal as possible - i.e. making the difference between the hot spot and average temperature the smallest. [10]

In recent years, there are even cases when consumer market electronics has to be throttled down to reduce power because of poor thermal architecture. This is the last resort and the overall effort is to minimize the number of cases like this. As mentioned earlier, one way out of this is by spreading the temperature more equally over all of the devices.

1.2.2 Complicated chips and packages

The number of metal layers interconnecting the microprocessors technology had increased from seven in 2001 to thirteen in 2014. [10] That creates a higher density of the structure, where the metal layers play the role of impedance for heat flow. At the same time, these "System on a Chip" (SoC) are changing its structure from the 2D planar chip into a 3D structure with nanowires connecting different levels of the system creating a thermal architecture maze with more attention needed.

The packaging itself is also becoming more of a thermal challenge, as the single flip-chip can be cooled down by classic techniques, but as the architecture is getting more and more complicated, the layers are stacked one on top of another and the heat dissipation can create a high thermal peak rising far behind surrounding temperature. And the 3D structures are connected not just by nanowires as mentioned before, but as flip chips, they are connected using solder bumps. These are metallic with high thermal conductivity and provide really good and stable thermal connection, but on the other hand, they actually are interconnecting on only a fraction of the die area, as the need to connect certain conductive paths. Unfortunately,

to prevent contamination and support the structural strength of a given chip, the surroundings of the solder bumps are often occupied by underfill material, such as epoxy and similar ones with low thermal conductivity (around $0.2 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$). [11] Therefore new underfill materials supporting the heat spreading across and on the layer of the die are needed. [10]

1.2.3 Flexible and touchscreen devices

Although the power for mobile devices is in lower values than for PCs or servers, the more dense packaging and limited space for thermal management - fans or heat sinks are limiting the possible ways of thermal architecture, often reaching for solutions such as using the packaging of the device for heat dissipation. For touchscreen devices, there is a need for material being a good conductor while being transparent to allow the right functionality. Unfortunately, these materials do not often have good thermal properties, so the architecture needs to count on that and lead the heat via deeper and more thermally conductive ways.

The field of flexible electronics is still a new thing for the consumer market, but it is becoming stronger and growing every day. With this growth, also heat spreading in this area is becoming a hot topic, especially without the possibility of using traditional technologies such as fans and heat pipes, or nearly any of the other technologies described earlier, as these are not compatible with the flexibility itself.

2 Materials used for thermal management

Even though there are many challenges in today's thermal management of electronics, the one topic connecting them together is the challenge of finding the way of equally distributing the heat across the device. The second challenge connected to this is the problem of minimizing heat peaks not by as much distributing the power equally to the device, more as outlet of the heat to the heat sink, outlet, etc. similarly as heat pipes are providing.

There is a big need for transporting the heat across the device itself for more efficient thermal management and higher possible power, as it was discussed in Chapter 1.2.1. Known bulk materials used in electronics applications have a high range of thermal conductivity, starting at approximately $0.2 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ for polymers and going all the way up to $3450 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ for isotopically purified diamond. [10]

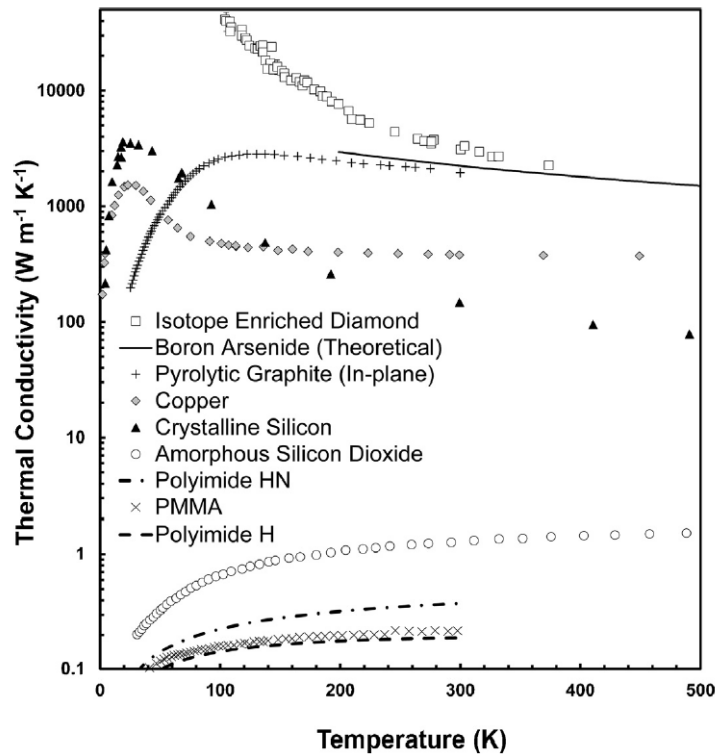


Fig. 2.1: Representative temperature-dependent thermal conductivity values for various bulk solids: isotope-enriched diamond, boron arsenide, pyrolytic graphite, copper, crystalline silicon, amorphous silicon dioxide, poly(methyl methacrylate) (PMMA), and two types of polyimide.[10]

2.1 Aluminum

Aluminum is a light, conductive, and corrosion-resistant metal with a strong affinity for oxygen. Thanks to this combination of properties, aluminum is widely used material with applications ranging all from the aerospace industry, architecture and construction to marine and mechanical engineering, and of course electronics and thermal management. Aluminum is the second most widely used metal, mainly because of its lightweight and electrical conductivity, its strength, and machinability. Excellent thermal properties and resistance to corrosion have led to its use in air conditioning, refrigeration, and heat-exchange systems.

In aluminum alloys, other elements are added on purpose to improve the properties of the metal in a certain way. Many alloys have been developed the aim is to improve strength and other structural properties of aluminum and also to improve its corrosion resistance. In general, the addition of different metals can improve the structural abilities but on the contrary, it weakens its corrosion resistance. [12]

Aluminum is commonly used for heat sinks in thermal management of micro-electronics, because of the thermal conductivity of $220 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ and low cost. The drawback can be the need for silicon addition to enhancing the casting capabilities, which is causing non-homogeneity in the internal structure and decreasing the thermal conductivity by a third. Because of that, there is a need for different manufacturing technique that allows aluminum to keep its thermal properties, but on the other hand, it increases the price 2-4 times. [13]

2.2 Copper

Copper is also widely used metal, and as it occurs in nature in directly usable form, it is being used from 8000 BC. Today, copper is used in buildings for roofing and plumbing, in electronics, it is used as the main material for conductive ways, coils wiring and thermal management - mainly for heat exchangers and heat conductive pathways.

Copper has desirable properties for the use in thermal management, starting with high thermal conductivity - around $400 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$, corrosion resistance, high allowable stress, and internal pressure. Pure copper slug is the most common copper heat sink material and it is also often used as heat spreader on the chips, as a cold plate for liquid cooling or heat pipe material. [13]

2.3 Allotropes of carbon

Carbon is an element extremely important for all life on our planet, and it is also one of the most used elements for technology applications, ranging from drugs and synthetic materials to steel. This is caused by the special ability of carbon to bind itself to almost all elements in high variety.

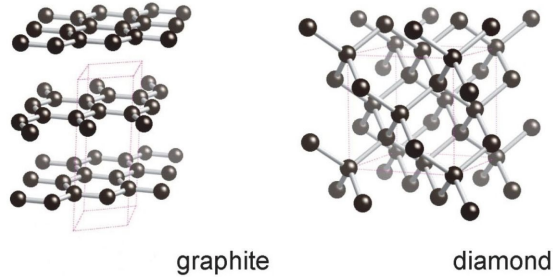


Fig. 2.2: Traditional carbon allotropes [14]

Elemental carbon occurs in two natural allotropes, diamond, and graphite. Both forms have different but unique physical properties like hardness, thermal and electric conductivity, and lubrication behavior. For a long time, these were the only two allotropes of carbon known to humankind, but that changed in 1985, with the discovery of fullerenes, followed by carbon nanotubes in 1991 and then graphene in 2004. [15]

The youngest from the carbon allotropes family is two-dimensional graphene, basically a single graphite sheet. Graphene was for actually a really long time considered just a theoretical material, but Andre Geim and Konstantin Novoselov shocked all of the scientific circles with proving that graphene is real, and more of it, actually doing so using Scotch tape. And in 2010 they got Nobel Prize in Physics for it. Officially, the method is called mechanical exfoliation, but it really is using tape. [16]

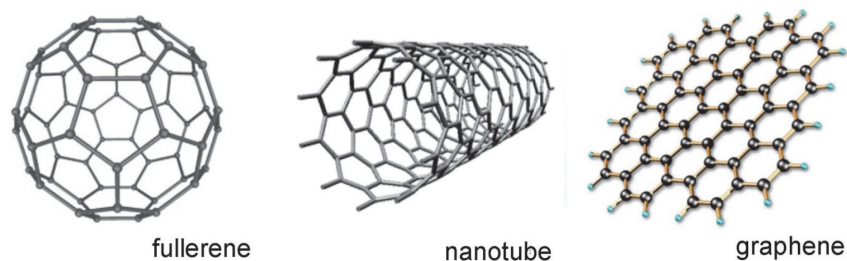


Fig. 2.3: Carbon allotropes discovered since 1985 [14]

2.3.1 Diamond

Diamond is the hardest stable substance known, precious gem, and really important abrasive material - industrial synthesis has been realized and it is widely used for manufacturing.

Diamond has the highest heat conductivity, with scientific papers claiming values higher than $1800 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ and it is going up to $3450 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ for isotopically purified diamond [10]

Because of these thermal properties, there are researches focusing on creating heat spreader from synthetic diamonds claiming, for example, that with the diamond heat spreader attached to a liquid-cooled microchannel heat sink, the maximum temperature can be reduced by 11.5% - 22.9%, on heaters with the power of 10 W to 50 W [17].

2.3.2 Graphite

Graphite is one of the most common allotropes of carbon, and unlike diamond, it does conduct electricity - and it is used for arc lamp electrodes. Graphite is the most stable form of carbon under standard conditions. Graphite can be found and made into various forms, like crystalline - which are small flakes of graphite, amorphous graphite, lump graphite, graphite fiber - which is a name sometimes used for carbon fiber and highly oriented pyrolytic graphite, which is highly pure synthetic graphite.[18]

Graphite can be also prepared via exfoliation, like graphene, and with relatively high heat conduction of $200 - 500 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ alongside the layers. [20]

Highly Oriented Pyrolytic Graphite - HOPG

HOPG is based on pyrolytic carbon, which is produced by heating hydrocarbon to a temperature near its decomposition, thus allowing the graphite to crystallize - pyrolysis. [21]

As can be seen in Figure 2.4, the annealing temperature of the pyrolysis has a high influence on the conductivity.

HOPG has exceptionally high thermal conductivity along the layer plane - as much as $1600 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$, and very small conductivity at the plane perpendicular to the layer, where it can go as low as $7 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$. So it can conduct heat one way but insulate the other. This anisotropy is caused by the structure, where layers do have strong σ bonds, but parallel stacking of these layers are bonded by the van der Waals forces caused by the interactions between π -electron clouds on the neighboring layers. [20]

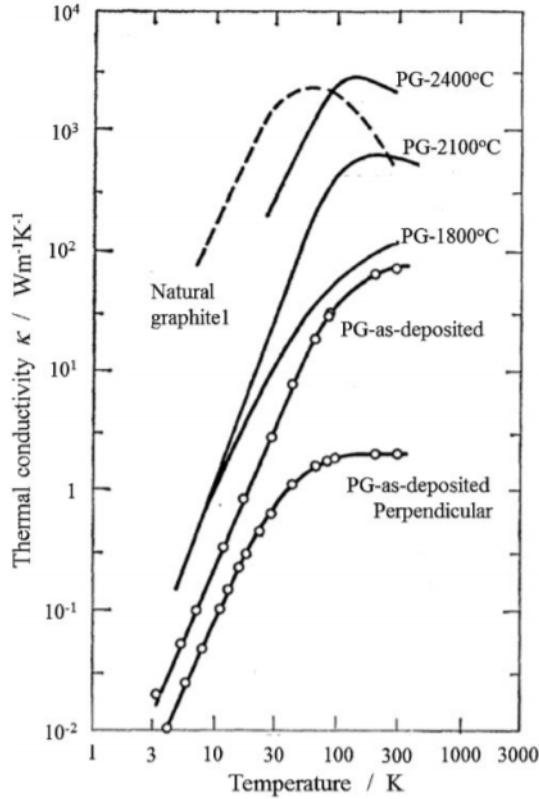


Fig. 2.4: Temperature dependence of heat conductivity for pyrolytic graphite with different annealing temperatures and natural graphite. [19]

There is a number of graphite products - foils and membranes - for the use in the field of microelectronics, with very high heat conductivity. For example, based on pyrolytic carbon there is Pyroid-HT from MINTEQ, based on graphite, and Kapton is PGS line from Panasonic. Based on natural graphite it is Grafoil from Graf Tech.[20] Heat conductivity of these foils vary, depending on both on thickness and manufacturer, but they do provide highly different heat conductivity in the layer plane and the plane perpendicular to the layer, with differences as big as $1800 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$. [22]

Because of the high emissivity of graphite (0.98), there also is research going on with the coating of aluminum heat sink with graphite powder to improve the cooling. In one such research ([23]) it is found that graphite works like really good coating for heat transfer improvement, but actually works even better in combination with Al_2O_3 and SiO_2 mixed all together.

2.3.3 Graphene

Graphene is basically a single layer of graphite, and it can be even called a 2D structure, as the layer is extremely smaller in the dimension perpendicular to the plane, than in other dimensions. It can be said that the graphene plane is building material for other allotropes, as by stacking the graphite is made, by rolling it is nanotube or eventually even fullerenes. Nowadays, graphene is divided into single-layer graphene (SLG), few-layer graphene (FLG), and multi-layer graphene (MLG). [24]

2.3.4 Fullerenes and Nanotubes

Fullerenes and nanotubes are basically sheets of graphite connected together, forming new allotopes. The chemistry and physical properties of fullerenes have woken up a lot of interest, with a special focus on solar cell and biological applications, which look like the most feasible one. The nanotubes are interesting as well, especially thanks to their electronic and mechanical properties - depending on the rolling of the graphene sheet there can be conductive or semiconductive behavior of the nanotube. The tubes can be both single or multiple-walled and can have open or closed ends - if they are closed, they can look like a really long fullerene. Modified nanotubes have a high potential in nanoelectronics and tissue engineering, for example. [25]

3 Heat

If there is a difference in temperature between two bodies, energy is transferred and this energy is called heat. Thermal energy from the hotter body flows to the colder one, which causes the change of temperature of the bodies, or it may also cause a change of the physical state of a given body (bodies) without actually changing its temperature. This can cause a change from solid to a liquid - melting, from solid to a vapor - sublimation, from liquid to vapor - boiling or from one solid form to another - crystalline transition. [26]

3.1 Heat transfer

Heat can be transferred using one of these three mechanisms: conduction, convection, and radiation. Each one of them works differently, but they can - and are - often combined. It is very often that there are all of these three mechanisms in place simultaneously. On the other hand, for simulations or heat transfer estimations it is not uncommon to not include all of them into the "equation", thus making it way easier to solve with no or little difference in the result of the simulation.

3.1.1 Conduction

Conduction does occur in solids, liquids, and gasses and it is the heat transfer mechanism in which heat (thermal energy) transfers through interactions between atoms, molecules, and the matter in general. Conduction does not involve motion of the matter or its surroundings. The mechanism is based entirely on collisions of the particles. Because of that, gases have low thermal conductivity since they are low in density - thus the distance between particles is boldly different from particle distance of solids - making the transfer of heat slower and less effective. The conduction of energy in liquids its close to gases - but more complex, as the molecules are closely spaced and under the influence of molecular force, which then affects the energy exchange during the collision. Solids can be split up into two different groups, where one is nonmetallic solids with heat transfer caused by lattice vibrations. The second group is metals, being better conductors because of having free electrons able to carry thermal energy. [27] Conduction is described by Fourier's law:

$$q = -\lambda \cdot \frac{dT}{dx} \quad (3.1)$$

Where q is the local heat flux density [$\text{W}\cdot\text{m}^{-2}$], λ is the material's thermal conductivity [$\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$] and $\frac{dT}{dx}$ is the temperature gradient [$\text{K}\cdot\text{m}^{-1}$]. This equation

shows that the local heat flux density is the amount of energy that flows through a unit area per unit time.

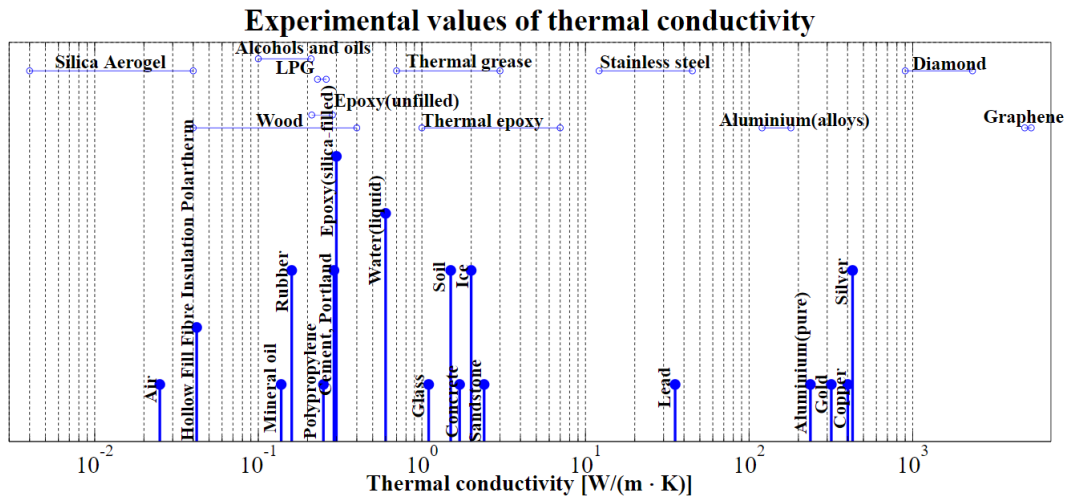


Fig. 3.1: Experimental values of thermal conductivity. [28]

The figure 3.1 shows wide range of values for the thermal conductivity, from silica aerogel through soil, lead, aluminum alloys and copper to graphene.

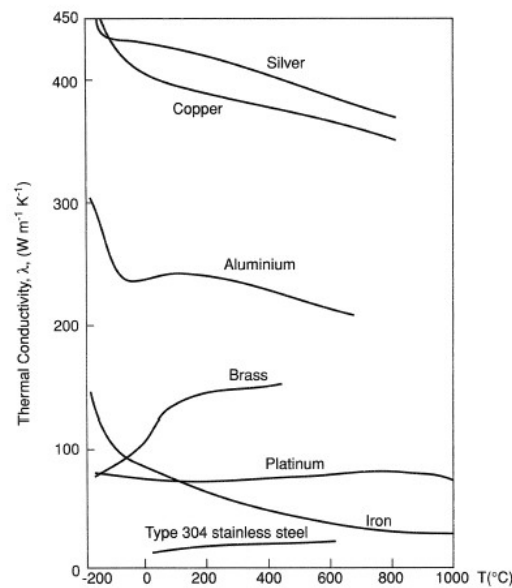


Fig. 3.2: Variation of thermal conductivity of some metals with temperature.[29]

As seen in figure 3.2, for most materials, λ varies with temperature.

3.1.2 Convection

Heat transfer, where energy is being exchanged between the solid face and an adjacent moving fluid (liquid or gas) is called convection. There are two elements of the convection: energy transfer due to random molecular motion - diffusion, and the second is energy transfer by bulk or macroscopic motion of the fluid - advection.

The mechanism of convection itself is based on gravity and expansion of fluids, where the layer of the fluid adjacent to the surface with higher temperature will get warmer, thus expand in volume (Charles's law), decrease in density, and becomes lighter. The cooler and heavier fluid will replace it at the surface level due to gravity and the circle can start again.

Rayleigh-Bénard convection

Rayleigh-Bénard convection is a fluid flow in a plane horizontal layer of fluid heated from below. It is the most comprehensively studied example of nonlinear systems exhibiting self-organization. The fluid develops a regular pattern of convection cells - Bénard cells. Buoyancy and gravity are the reason for these Bénard cells appearing it is the most organized and described type of convection. [30]

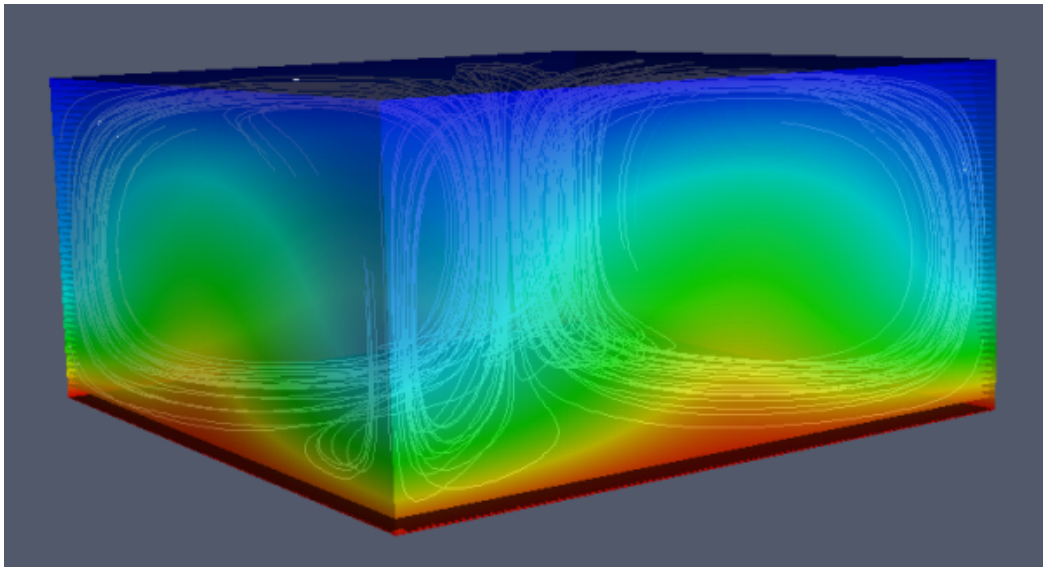


Fig. 3.3: Simulation of Rayleigh-Bénard convection in 3D. [31]

Natural Convection

When the motion of the fluid, which is adjacent to a solid face, is caused by buoyancy forces due to changes in the density of the fluid invoked by the difference in temperatures between solid and fluid, it is called a Natural Convection.

Forced Convection

As Natural Convection does not need any external force or energy, Forced Convection is being the exact opposite, where external force - e.g. fan, pump, etc. is used to accelerate the change of the fluid adjacent to the solid, thus making the heat transfer faster. The rapid motion of the fluid increases the gradient of temperature and maximizes the speed of heat exchange.

Convection Heat Coefficient

The rate of heat exchange between a fluid with temperature T_f and a solid face area A with temperature T_s is described by Newton's law of cooling:

$$Q = \alpha \cdot A(T_s - T_f) \quad (3.2)$$

Where α is convection heat transfer coefficient [$\text{W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$]. It varies, based on fluid motion, geometry, and thermodynamic and physical properties. The coefficient h is a simplified correlation to the fluid state and the flow conditions.

There is a difference between Fourier's law (equation 3.1) and Newton's law (equation 3.2). Fourier's law is used to tell transfer rate, i.e. how fast energy is transferred. On the other hand, Newton's law is telling cooling rate - how fast the temperature changes.

As convection relies on the exchange on fluid adjacent to a solid face, there is a concept of thin boundary layer - transition between a surface and the flow of fluid, as illustrated in this figure (3.4), where $u(x, y)$ is the x -direction velocity and $\delta(x)$ is fluid boundary layer thickness:

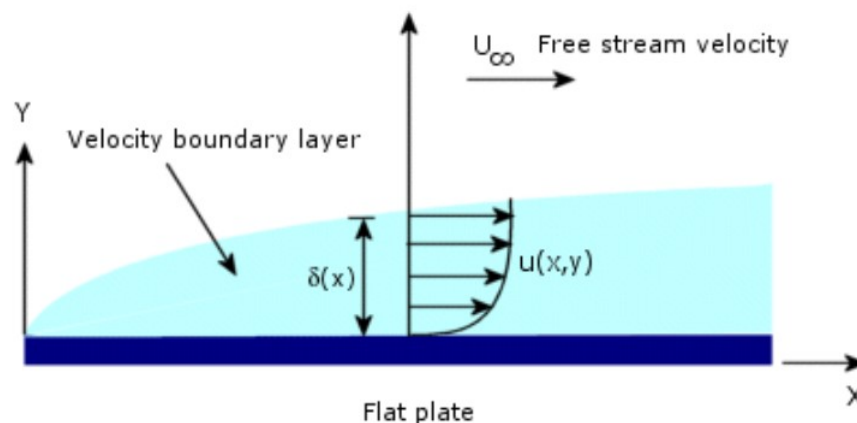


Fig. 3.4: Flow over a flat plate [32]

The temperature transition from the surface temperature to the surroundings can be made to similar figure (3.5):

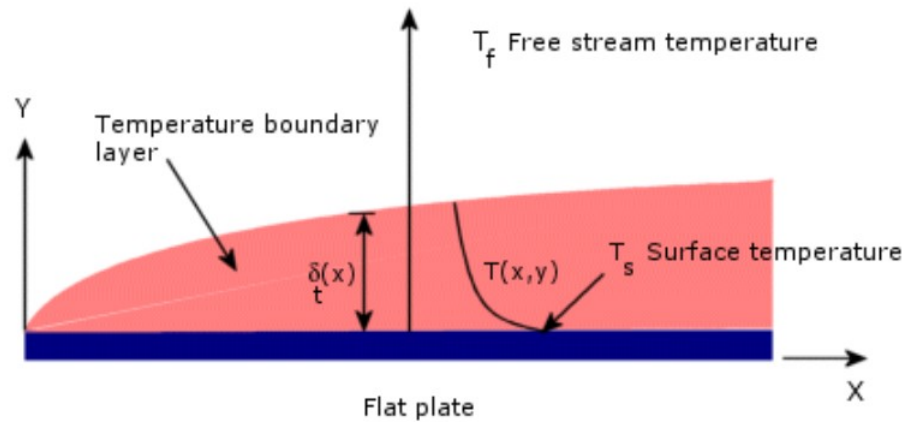


Fig. 3.5: Temperature transition over a flat plate [32]

The mechanism of heat transfer through the boundary layer is conduction, in the stationary fluid next to the wall being equal to the convection rate from the boundary layer to the fluid - that can be written as:

$$\alpha \cdot A(T_s - T_f) = -\lambda \cdot A \cdot \frac{dT}{dx} \quad (3.3)$$

Thus the coefficient of convection in certain settings can be stated by measuring the heat transfer rate and the temperature difference, or diversely by measuring the temperature gradient adjacent to the surface and the temperature difference. Measuring the temperature gradient can be accomplished in a research laboratory, and handbooks often do contain tabulated values of the convection heat transfer coefficients for a variety of configurations. [32]

Tab. 3.1: Heat transfer coefficients [33]

Type of fluid and flow	Heat transfer coefficient ($\text{W} \cdot \text{m}^{-2}$)
Air, free convection	6 - 30
Water, free convection	20 - 100
Air or superheated steam, forced convection	30 - 300
Oil, forced convection	60 - 1800
Water, forced convection	300 - 18000
Water, boiling	3000 - 60000
Steam, condensing	6000 - 120000

Prandtl Number

Prandtl number is a dimensionless number correlating viscosity of a fluid with the thermal conductivity, thus making the relation between momentum and thermal transport capacity of the fluid:

$$Pr = \frac{v}{h} = \frac{\eta}{\rho \cdot h} = \frac{\eta \cdot c_p}{\lambda} = \frac{\text{momentum transport}}{\text{heat transport}} \quad (3.4)$$

where h is thermal diffusivity defined as $h = \frac{\lambda}{\rho \cdot c_p}$. The Prandtl number is a property of a fluid, the ones with small Prandtl number are free-flowing fluids, which have high thermal conductivity - ideal option for heat-conducting liquids. [34]

Tab. 3.2: Typical values for Prandtl number [35]

fluid	Pr
noble gases with hydrogen	0,16 - 0,7
oxygen	0,63
air	0,71
seawater (20°C)	7,2
water (18°C)	7,56
engine oil	100 - 40 000

Usually, the Prandtl number is assumed to be around 0.7 for gases and around 6.9 for water.

3.1.3 Radiation

All bodies with a temperature above absolute zero (0 °K) have thermal energy, which is emitted in the form of electromagnetic waves. This form of thermal energy transfer is called radiation. As the transfer itself is done by electromagnetic waves, there is no need for medium, because electromagnetic waves can travel even in a vacuum. Energy can be emitted in the ultraviolet, visible, and infrared spectrum, depending solely on the temperature of the body itself.

Black-body radiation

The thermal radiation, which is spontaneously emitted by many ordinary objects can be described with the help of approximation as black-body radiation. Black-body radiation is the radiation emitted by the black body in thermodynamic equilibrium with its environment. It has a specific spectrum of wavelengths - as the temperature of the body decreases, the peak of the black-body radiation curve moves to the lower

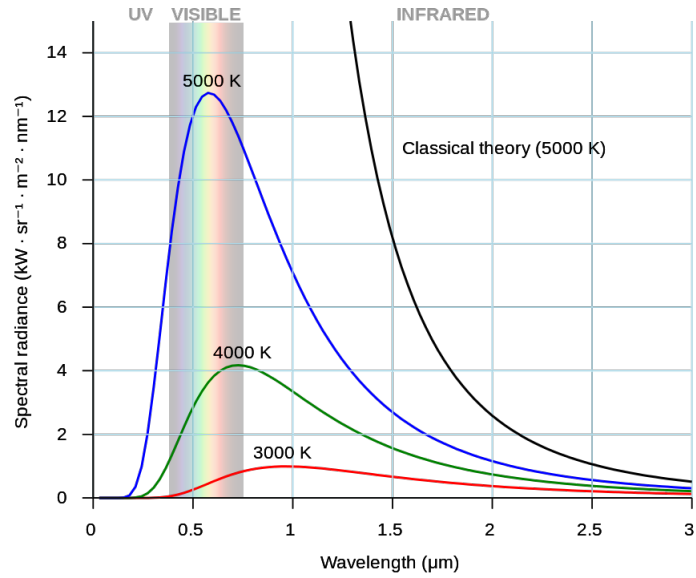


Fig. 3.6: Black body curves of Planck for various temperatures and comparison with classical theory of Rayleigh-Jeans. [36]

intensities and longer wavelengths. A black body at room temperature appears black, as most of the energy has wavelengths in the infrared spectrum - and thus cannot be perceived by the human eye. [37]

4 Graphite heat dissipation testing

For the purposes of this thesis, the simulations will work with a commercially available product - Pyrolytic Graphite Sheet (PGS) from Panasonic. They have both catalog [38] and datasheet [39] available online, so the product information from these sources will be used for all of the simulations and use case demonstrations. All of the simulations in the thesis are run in SolidWorks Flow Simulation.

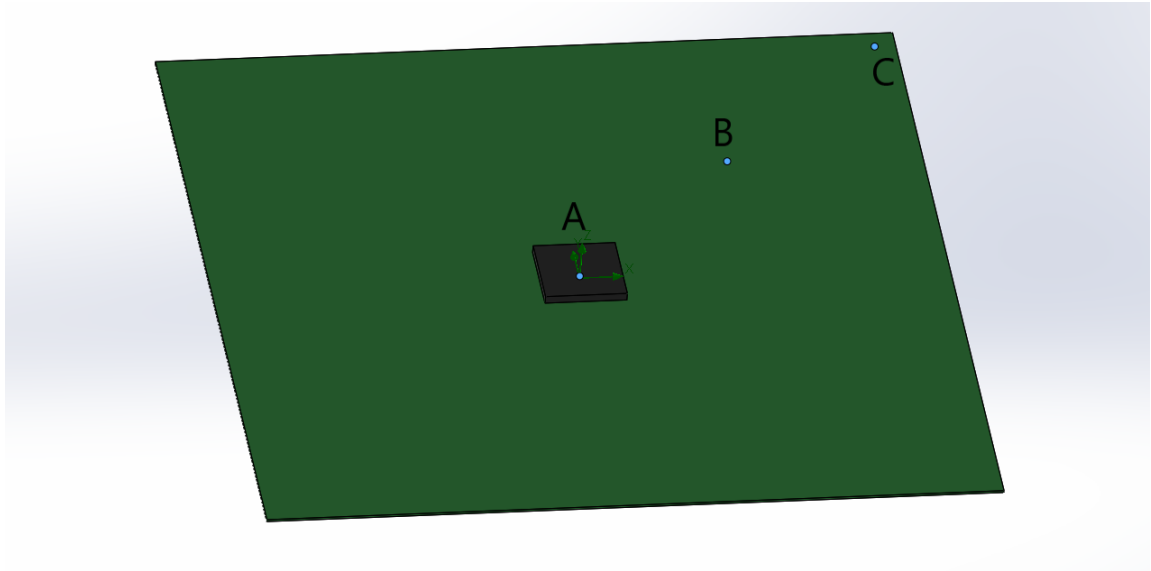


Fig. 4.1: Heat conductive material with 12 W heat source and three analysis points.

To prove the asset that the use of the PGS is bringing, there is an easy example: as can be seen in Figure 4.1, the design is simple - 90 x 90 x 0,03 mm desk from a thermally conductive material, which has a microchip 15 x 15 x 1 mm placed in the middle. The chip plays the role of a 12 W volume heat source. For better analysis, there are three points where the temperature can be analyzed - point A is in the chip itself, point B is middle way on the diagonal, and point C is in the corner of the material.

The simulation is set to end when the temperatures will converge - when the value of the temperature will no longer change in specified points. As can be seen in Table 4.1, the PGS really is conducting heat the best, as it has the lowest temperature in A, but the highest in points B and C, showing that it can spread the heat across the material most efficiently. The distribution of the heat can also be visible on the Figure 4.2.

To show the thermal abilities of PGS even more clearly, the simulation was run in transient mode - then it does not stop when the values are converged, but it runs for specified physical time of 1800 s (time in the simulation itself, not in real world).

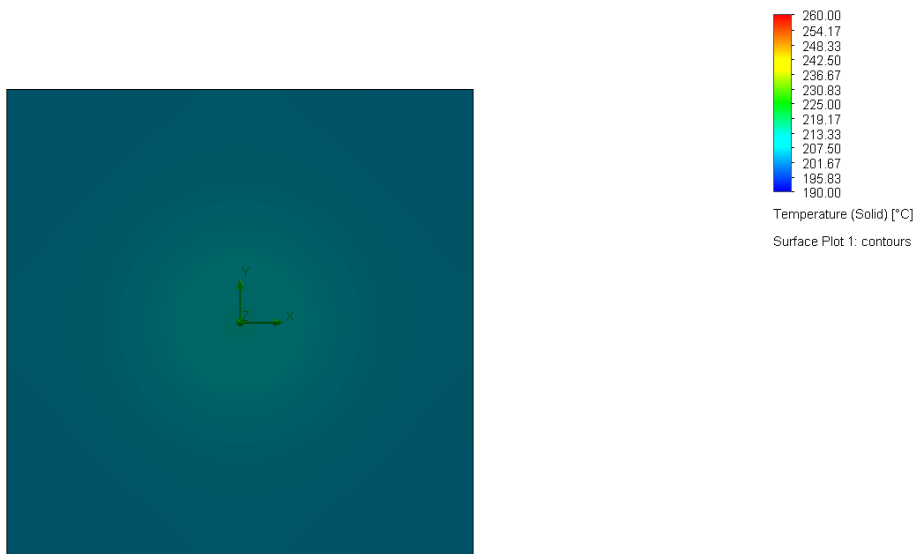
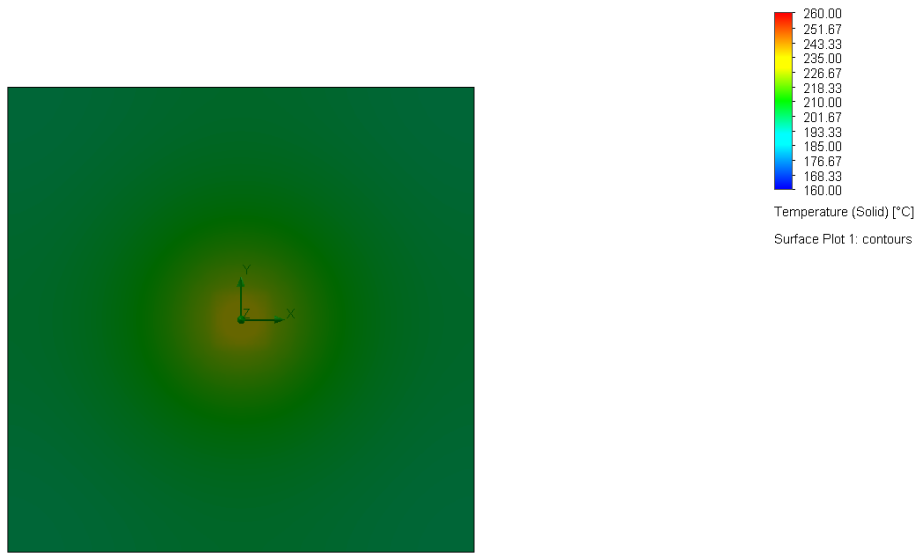
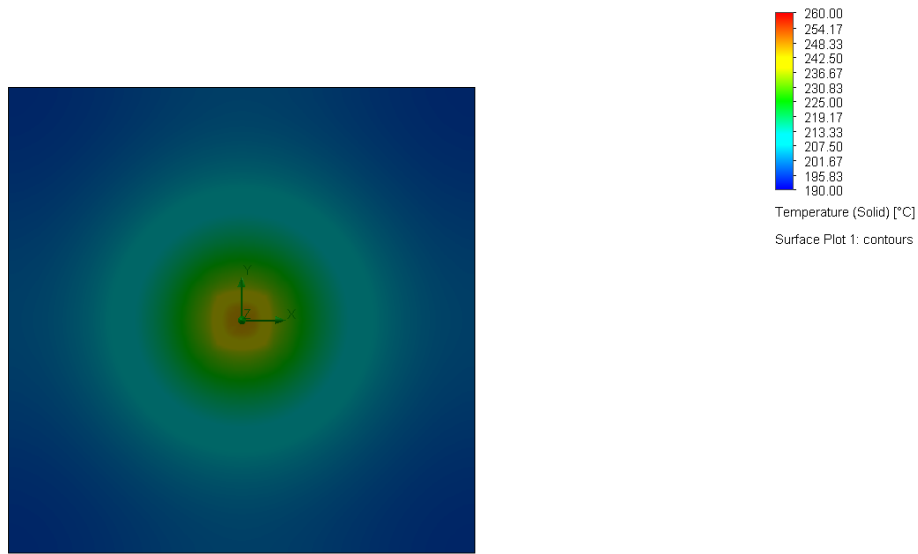


Fig. 4.2: Distribution of the temperature on aluminum, copper and PGS.

Tab. 4.1: Converged temperature in points A,B,C for aluminum, copper and PGS

material	A [°C]	B [°C]	C [°C]
aluminum	247,03	204,23	196,49
copper	231,07	204,62	199,83
PGS	213,17	205,05	204,06

All of the other values are kept as in the static example, with just one change - the chip is turned off at time of 700 s.

In Figure 4.3 there are three graphs comparing the development of temperature in points A, B, and C for aluminum, copper, and PGS. If we look at the first 700 s of the graph: In point A, the highest temperature is when using aluminum, then with copper and the lowest with PGS. In point B, the temperatures are basically the same for all three of the materials. And in point C, the temperature is the same for aluminum and copper, but it is higher for PGS. That means that PGS leads the temperature the best, as it spread the temperature across the material - that is the same result as with the statics experiment.

If we look at the time after 700 s, we can see the temperature dropping similarly at all three points. And in all of them, it takes the longest for copper to cool down, then there is aluminum, and PGS is the fastest one, proving itself as good heat conductive material.

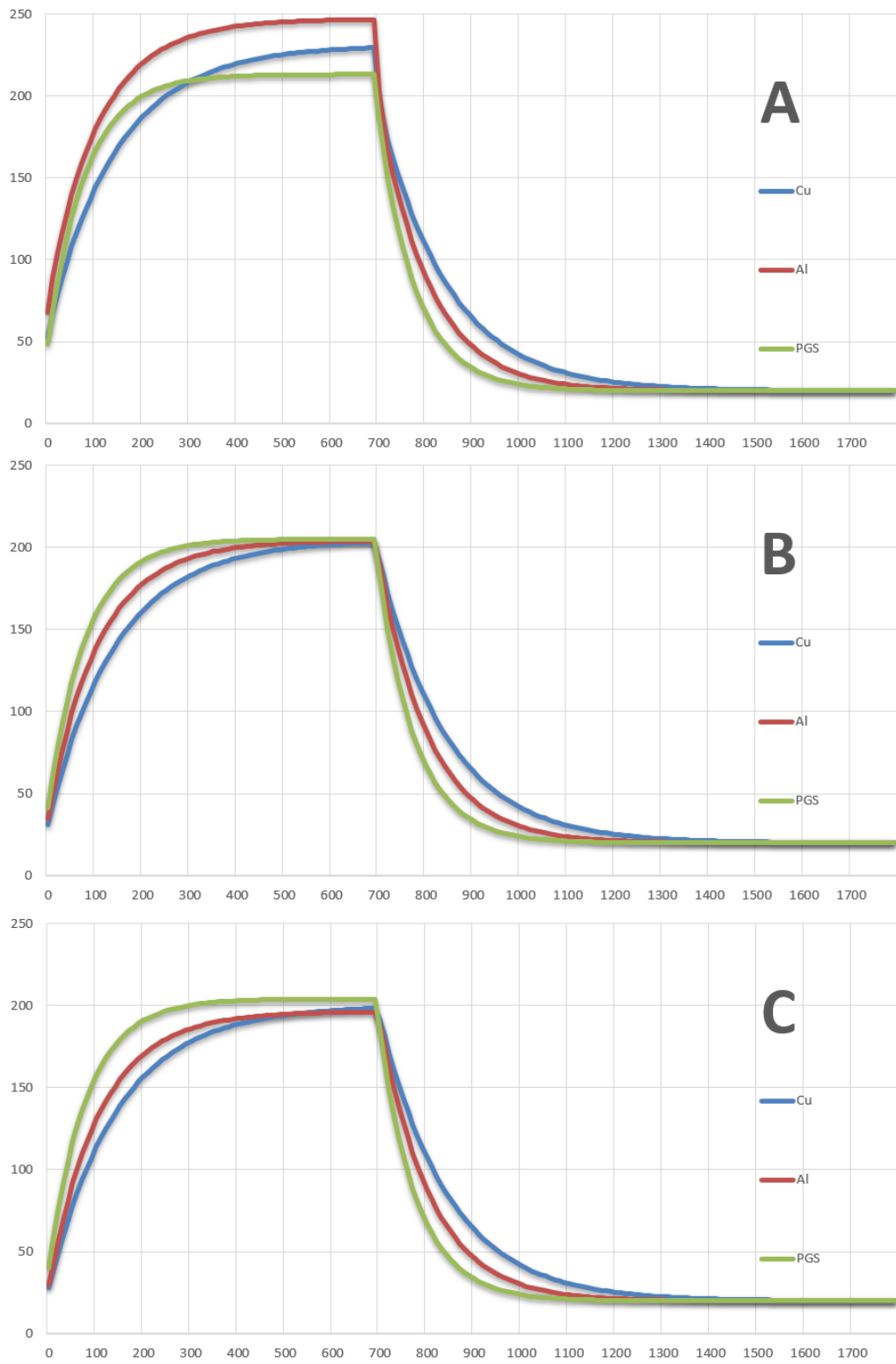


Fig. 4.3: The development of temperature in points A, B and C for aluminum (red), copper (blue), and PGS (green).

5 Numerical Solution Methods

The thermal management problems and material properties of used materials, or the fluid flowing and cooling the devices - all of these can be described by mathematical models and equations, than can be solved using the right tools, providing us with the results we need to analyze the situation and propose the best solution.

The starting point is the selection of the right mathematical model and its boundary conditions, which depend on the tool that is used - in the case of this thesis it is SolidWorks Flow Simulation and ANSYS Steady-State Thermal. The next step is also determined by the tool - and that is the discretization method used for approximating the differential equations describing the behavior by a system of algebraic equations for set variables at discrete locations. There are multiple methods, where the most used ones are finite difference, finite volume, and finite element method, with SW Flow using the finite volume method and ANSYS using the finite element method.

The discrete locations are defined by the numerical grid, which is basically a discrete representation of the geometry of the problem. The numerical grid divides the geometry into a finite number of volumes (or elements), and they can be structured or unstructured. Structured grids are the ones where the volumes all have the same shape - cuboid. The unstructured grid is different by combining multiple types of finite volumes - not just cuboids, but also prisms and pyramids. These finite volumes are called control volumes.

After the model is cut into these grids - the process itself is called meshing - the equations are applied each of the control volumes. At the center of each control, the volume is a computational node where the variable results are calculated and then interpolations are used to express variable values at the surface. [40]

For example, the spreading of heat through metal rod is solved by dividing the rod into little finite volumes and then solving the temperature in each volume as a separate problem, but using the values of the neighboring volumes as a boundary condition for the computation.

6 Goals of this thesis

This thesis started by explaining current challenges in thermal management of microelectronics and continued on to explaining basic techniques used in thermal management and the basics of heat transfer.

In the practical part of this thesis, the goals are:

- Creation of 3 use cases, demonstrating cooling of a general structure
- Demonstration of using pyrolytic graphite as an alternative for commonly used aluminum and copper
- Numerical simulation of the use cases
- Analytical comparison of results for PGS, aluminum, and copper
- Determining the ideal material for each use case

7 Use cases of Pyrolytic Graphite Sheet

Pyrolytic Graphite Sheet is a real material that can be used in microelectronics. But how and when? To answer these questions, three use cases were simulated and analyzed, to show the possibilities of this material. Each of these use cases is made to demonstrate different abilities of the PGS, and in all of them, the PGS is compared to aluminum and copper. All three of the use cases are designed with a focus on creating them really close to reality, thus they can serve as the groundwork for more detailed studies and simulations.

7.1 Use Case 1: Electronics inside poly-carbonate enclosure

In this example, the use of PGS for transferring the temperature across the material with a really bad heat conductivity - poly-carbonate - will be demonstrated. This use case is then somehow similar to the one in chapter 4 as PGS is here used mainly for its excellent heat-spreading capabilities. Poly-carbonate as a material for the enclosure was chosen as it is commonly used for making various cases and boxes for electronics, so the example will simulate a possible use case. It is important to mention that poly-carbonate is a terrible heat conductor.

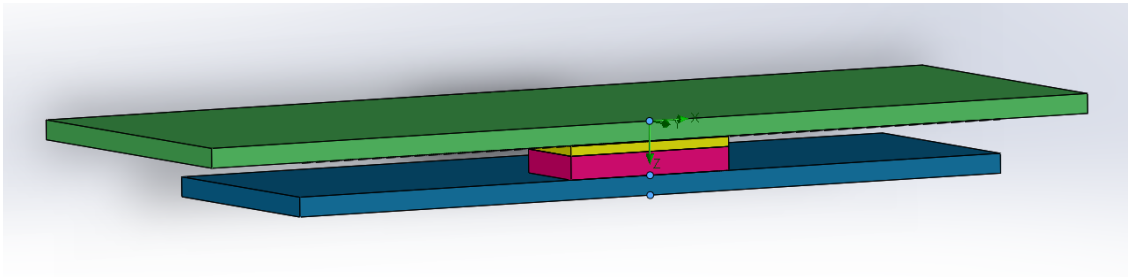


Fig. 7.1: Cut through the design with layers described bottom up - blue is PCB, pink is the IC, yellow silicon, barely visible black layer is the thin added material, that is variable for each iteration and the top green layer is the poly-carbonate.

The geometry itself is quite simple: PCB board with an integrated circuit (IC) behaving like a 0,5 W volume heat source, covered by silicon (the layers of IC and silicon simulates a chip) and by 0,3 μm of material - poly-carbonate, aluminum, copper, or PGS - and covered by a poly-carbonate desk. The dimensions can be seen in Table 7.1 and the cut through the model itself can be seen in Figure 7.1. On the same figure, you can see three control points, where the temperature is measured. Points are distributed subsequently: The first one is at the bottom of the PCB, the second one is between the PCB and the IC, and the third is on the upper face of the poly-carbonate. All of these three points are aligned along the z-axis. On the top face and the sides of the poly-carbonate desk on the top of the design, there is a heat transfer coefficient $\alpha = 10 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$, simulating air running over the plate.

Tab. 7.1: Dimensions of the design.

material	dimensions [mm]
PCB	25 x 40 x 1
IC	9 x 9 x 1,2
Silicon	9 x 9 x 0,5
"material"	25 x 40 x 0,03
Poly-carbonate	35 x 50 x 1

7.1.1 Results

In Table 7.2, there are the results: temperatures for the points mentioned above, simulated for different materials. The table is clearly showing that using PGS, we can reach the lowest temperatures in all three of the measurement points, Keeping the poly-carbonate plate from melting and preceding the IC to overheat. (The fourth material here - poly-carbonate - is in the simulation to show how would the temperature spreading look like without anything added - but show that the better heat spreading is not provided only by extra volume, as there is the 0,03 μm layer added.)

Tab. 7.2: Converged temperatures in three different points for four types of material.

material	PCB [°C]	IC [°C]	poly-carbonate [°C]
poly-carbonate	193,98	194,18	184,99
aluminum	58,18	58,38	56,12
copper	54,96	55,15	53,06
PGS	51,05	51,18	49,32

To clearly see the heat spreading on the poly-carbonate plate at the top of the design, you can see Figure 7.2 and Figure 7.3 where it is clearly visible how with poly-carbonate layer, the heat is spreading is really poor (the color legend had to be adjusted for that). The second picture is aluminum, where the shape of the IC is still visible, but the heat spreading is better and the heat expands deeper into the material. The third picture shows the copper, where although the IC is still somehow visible, the heat is spread more equally and you can clearly see how the layer of the material is smaller in surface than the poly-carbonate plate. The last image is PGS, with equally distributed temperature in the places where the plate is underlaid with the PGS.

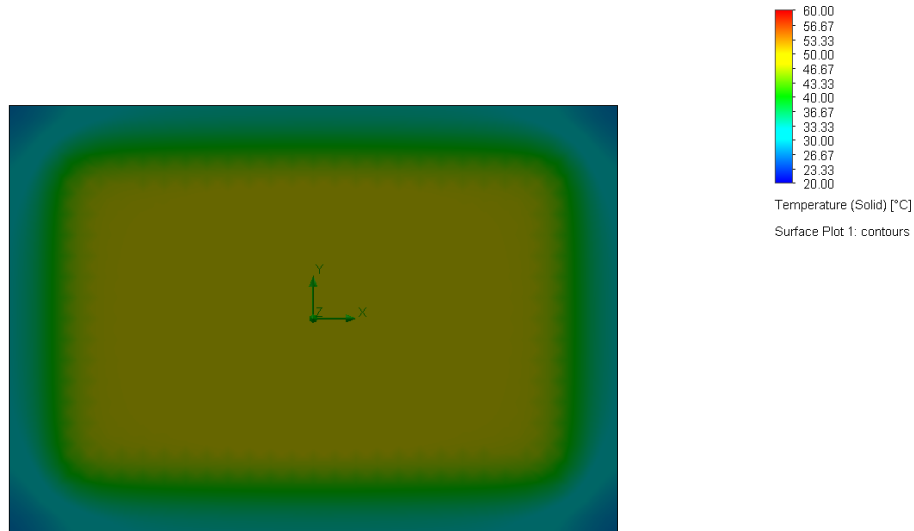


Fig. 7.2: Thermal view of the top plate with underlaid poly-carbonate.

To even more understand the heat spreading, it can be demonstrated using maximal and minimal temperatures on the top plate. In all four cases, the maximal and minimal temperatures are located at the same spots - maximum in the middle of the plate, where the center of the IC lays underneath. The minimum is then located in the corners. As can be seen in Table 7.3, the PGS actually have the lowest maximal temperature, but the highest minimal. That is a clear example of its heat conductivity, as it leads the heat beneath the material to the most distant corner more effectively than any other material used in this simulation.

Tab. 7.3: Minimal and maximal temperatures of the top plate for different underlaid materials.

material	minimum [°C]	maximum [°C]
poly-carbonate	21,47	184,99
aluminum	25,70	56,12
copper	26,02	53,06
PGS	26,42	49,32

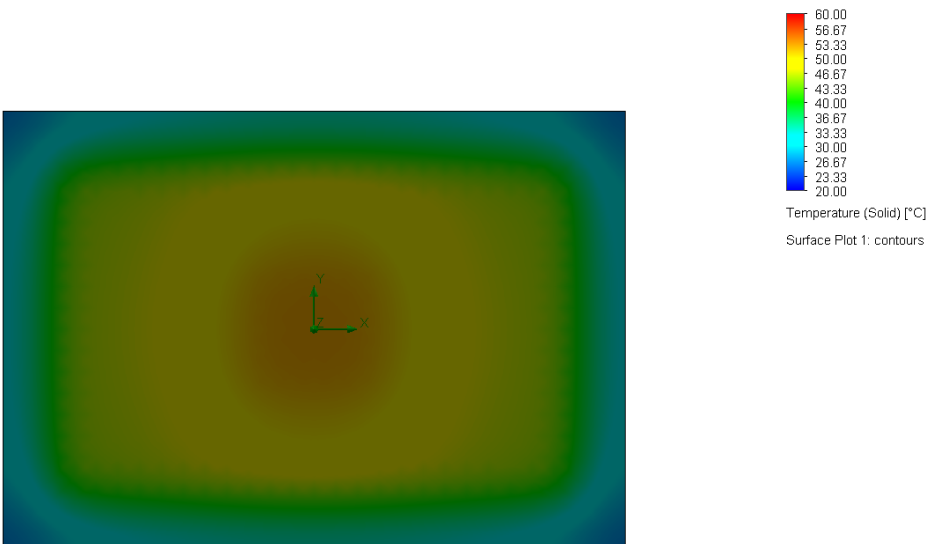
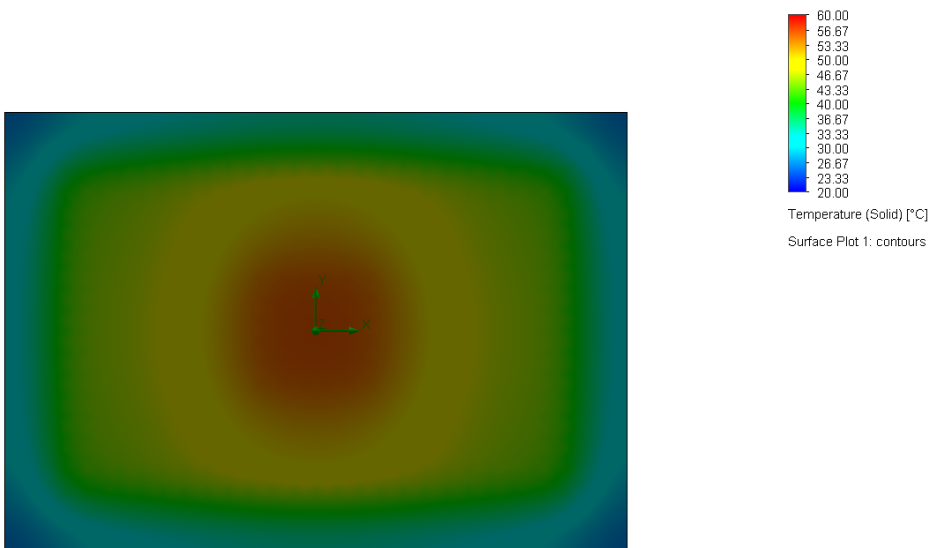
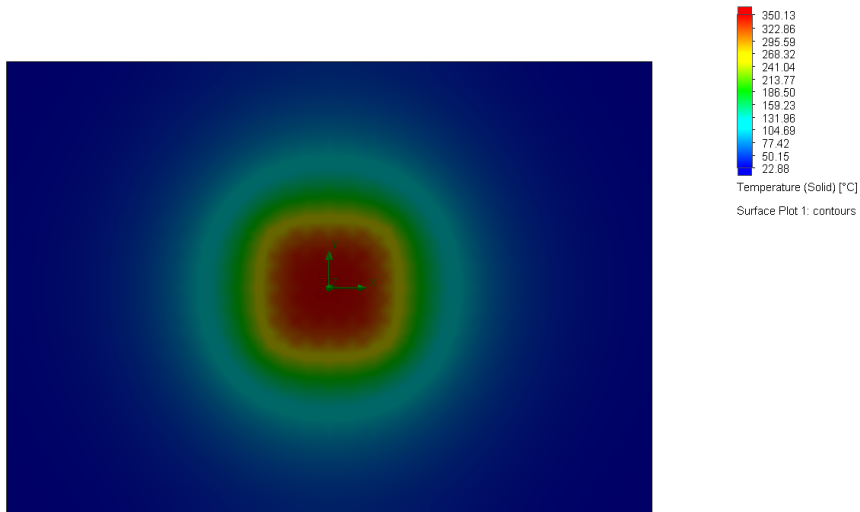


Fig. 7.3: Thermal view of the top plate with under laid layer - poly-carbonate at the first image, then aluminum, following with copper.

7.2 Use Case 2: Using a combination of PGS and PET to ensure electrical insulation

Using aluminum and copper for cooling and heat spreading has one more disadvantage. As both of them are very good electrical conductors. PGS is also electrically conductive, but there is a combination of PGS and Polyethylene terephthalate (PET) on the market. Thanks to layering electrically conductive PGS with electrically insulating PET, the product has good thermal properties (but of course way worse than pure PGS) and also behaves like an electrical insulator. In the datasheet for this product, the producer is claiming that it can withstand 1 kV of voltage. [39]

As was demonstrated, PGS can deliver good thermal results even in a very thin layer. But on the other hand, it is an excellent heat conductor in the XY plane, but a terrible one in the z-axis, as it is an anisotropic material. On the contrary, aluminum and copper are isotropic materials with heat spreading abilities the same for all three axes.

There comes an idea: if the PGS with PET layered can give us better or same results as aluminum or copper with no electrical insulation. If yes, it is a clear advantage, as you can use it as a heat spreader in the middle of two PCBs that has to be insulated one from each other. As the goal of this thesis is to show real use cases, the PGS + PET product is here used as it is, with acrylic adhesive tape on the bottom - as seen on the picture 7.4. Unfortunately, the manufacturer is not providing any info on the thermal conductivity of the acrylic tape and the PET layer, so there was done a small research and the average values of these materials are used, as can be seen in the table 7.4.

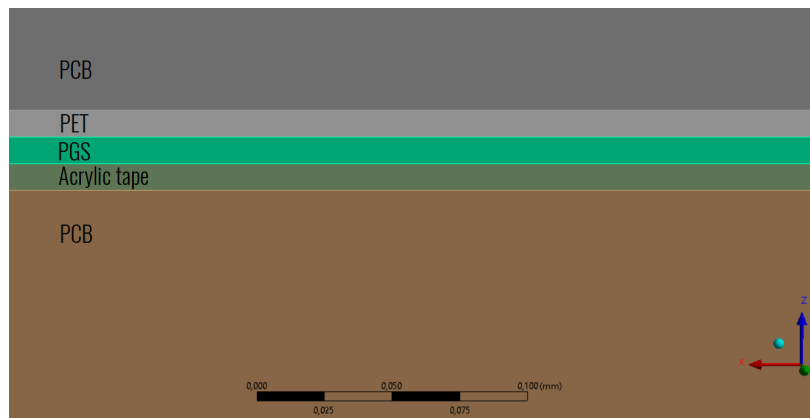


Fig. 7.4: Side view of the geometry used in this use case - from the top goes PCB, PET, PGS, acrylic tape and the second PCB.

Tab. 7.4: Thermal conductivity of the PET + PGS + acrylic tape combination.

material	heat conductivity (x,y,z) [$\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$]
PET	0,35 x 0,35 x 0,35
PGS	1900 x 1900 x 10
acrylic adhesive	1 x 1 x 1

As said earlier, this use case is showing heat spreading with a possible electrical insulation layer. As heat sources, there are chips with the heat loss of 1W (volumetric heat source). One chip is in the middle of the first PCB and four chips are in the corners below the second PCB - as can be seen in the picture 7.5. The dimensions can be found in table 7.5. For simulations run with aluminum or copper, all of the three layers marked as "PET", "PGS" and "acrylic adhesive" were set to be aluminum or copper, thus making the thermally conductive layer three times bigger than it is for PGS.

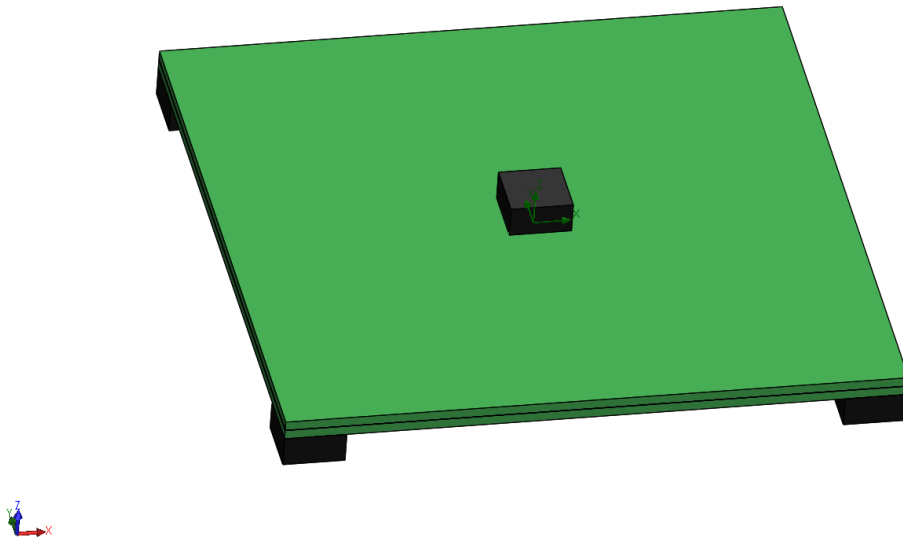


Fig. 7.5: Side view of the geometry used in this use case - from the top goes PCB, PET, PGS, acrylic tape and the second PCB.

Even though the simulation was originally computed in the SolidWorks Flow, due to meshing problems - as SolidWorks Flow has very limited options when it comes to meshing different bodies with meshes of different sizes - the simulation software was changed to ANSYS Workbench, more precisely it's Steady-State Thermal solver. This solver is not using the Finite Volume Method, but instead, it does use the Finite Element Method.

Tab. 7.5: Dimensions of the design.

material	dimensions [mm]
chip	10 x 10 x 5
PCB	100 x 100 x 1,6
"PET"	100 x 100 x 0,01
"PGS"	100 x 100 x 0,01
"Acrylic Adhesive"	100 x 100 x 0,01

The geometry in this use case was created to also show one way of making thermal calculations, that can be demanding on the computer. The geometry can be cut by symmetrical axes and the just one part computed and the results then mirrored to the rest of the geometry. That way, it can be computed with mesh much more delicate with the same computing time and CPU demand. To have a better understanding of this symmetry, the image 7.6 is showing one-quarter of the model - the part that was actually used for the analysis.

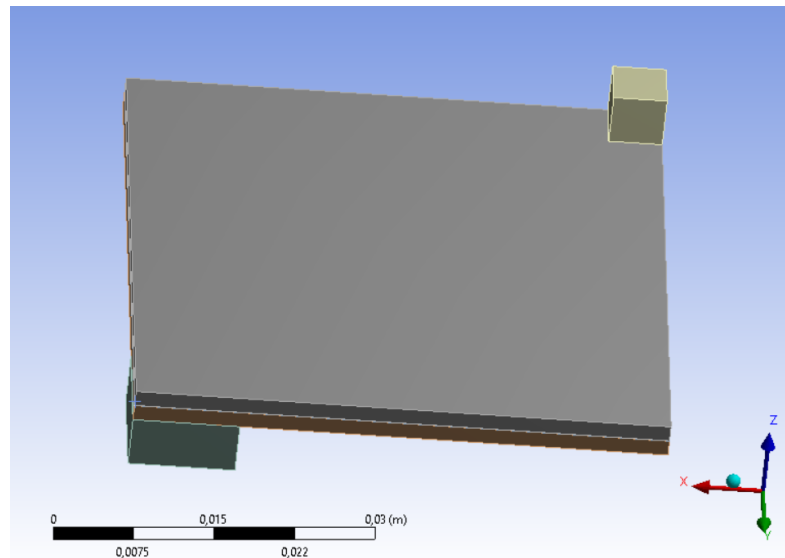


Fig. 7.6: One quarter of the model, as due to symmetry there is no need to compute whole geometry.

As PCBs are heterogeneous materials with anisotropic thermal conductivity, there a need to compute their thermal conductivity based on the thermal conductivity of the materials they are made from. If we are thinking the most commonly used base material for PCB - FR4, which is dielectric, we are getting values of $0,3 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$. For the conductive part of the PCB, we are thinking of copper with thermal conductivity $401 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$. The thermal conductivity of PCB can be

determined in several ways, for example by a method that is being used here - layer definition, where we need to know the thickness of the PCB and number of conducting layers. The equations 7.1 and 7.2 are showing that the conductivity is needed to be computed for both in-plane conductivity (K_{in}) and through-plane conductivity (K_{thro}), where t is the total thickness of the PCB, n_C is the number of conducting layers, for each layer there is need to specify the volume fraction of the conductor material in the layer A_i and the layer thickness t_{Ci} :

$$K_{in} = \frac{\sum_{i=1}^{n_C} t_{Ci} \cdot \left[\frac{A_i}{100} \cdot K_C + \left(1 - \frac{A_i}{100}\right) \cdot K_D \right] + \left(t - \sum_{i=1}^{n_C} t_{Ci}\right) \cdot K_D}{t} \quad (7.1)$$

$$K_{thro} = \frac{t}{\sum_{i=1}^{n_C} t_{Ci} \cdot \left(\frac{A_i}{K_C} + \frac{(1 - \frac{A_i}{100})}{K_D} \right) + \frac{(t - \sum_{i=1}^{n_C} t_{Ci})}{K_D}} \quad (7.2)$$

By using the values specified in table 7.6 and the equations 7.1 and 7.2, the resulting thermal conductivity is $21,33 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ for xy plane and $0,31 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ for z axis.[41]

Tab. 7.6: PCB settings

variable	value
FR4 thermal conductivity	$0,3 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$
copper thermal conductivity	$401 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$
total thickness t	1,6 mm
number of layers n_C	4
Layer 1: volume frac. of conductor A_i	20%
Layer 1: layer thickness t_{Ci}	0,07 mm
Layer 2: volume frac. of conductor A_i	80%
Layer 2: layer thickness t_{Ci}	0,035 mm
Layer 3: volume frac. of conductor A_i	80%
Layer 3: layer thickness t_{Ci}	0,035 mm
Layer 4: volume frac. of conductor A_i	20%
Layer 4: layer thickness t_{Ci}	0,07 mm

For the chips solver settings were used, as they are anisotropic as well, the values being here $5 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ for XY plane and $20 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ for the z-axis. On all of the external surfaces of the design, there is a heat transfer coefficient $\alpha = 5,5 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$, simulating air running over the plate.

7.2.1 Results

In contrast with the first use case, where just heat maps and temperatures were compared, for this second use case, there is a comparison of both temperatures and heat fluxes of all of the three material variations of this simulation use case. To even more understand the behavior of the graphite sheet and to see how it can be beneficial for microelectronics, the comparison is done on the geometry as a whole and then on multiple faces in the geometry: the top face of the PCB, and then top faces of the so-called PET and PGS layers - to clarify here, the geometry for simulations ran with aluminum and copper was not changed, and the selected material (Al or Cu) was assigned to all of the three $10\ \mu\text{m}$ layers - "PET", "PGS" and "acrylic adhesive". The last analyzed face is the bottom face of the lower PCB.

In figure 7.7 we can see temperature distribution on the model, here analyzed for the combination of PET, PGS, and acrylic adhesive. As will be discussed later, the temperature distribution is almost the same for all of the material variations.

At first sight, it can be clearly seen that the chips do not have the same temperature, even though they have the same heat loss. That is due to their different placing in the geometry, where the chip placed on the top has four times bigger the area where it can lose the power - it is still just one-quarter of the whole geometry.

The higher temperatures can be also found on both of the PCBs in the areas near to the chips, as the PCB itself is not good to heat conductor (values of thermal conductivity of $21,33\ \text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ for XY plane and $0,31\ \text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ for z-axis). Because of that, the temperature is minimal on the diagonal connecting the two corners without chips - between $58,4$ and $59,3\ \text{°C}$ for all three of the material variations.

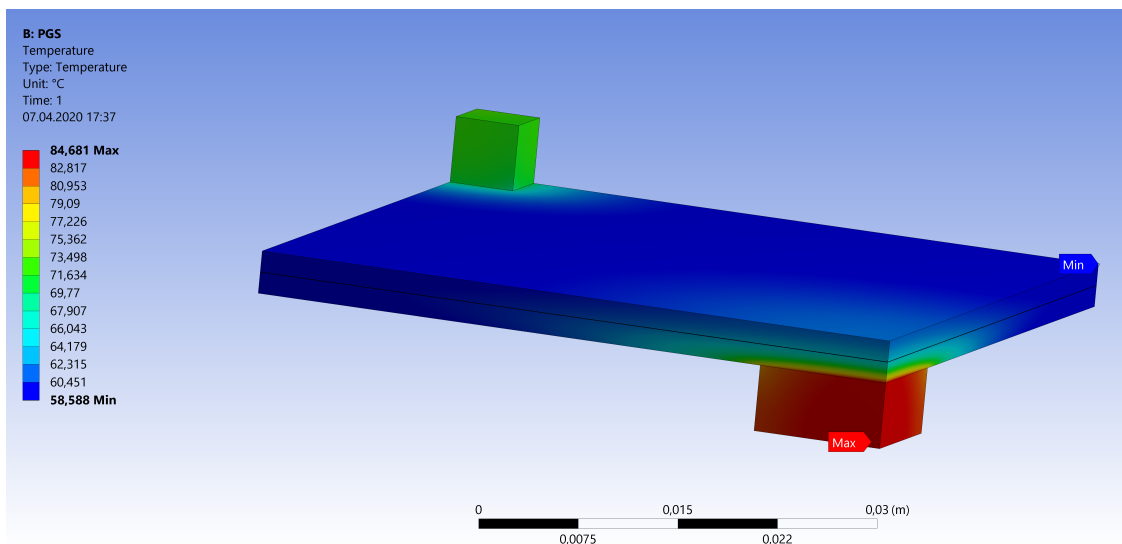


Fig. 7.7: Temperature distribution for the whole geometry.

For an easy comparison of the material variations and the temperature differences between them, the table 7.7 was created. For each examined geometry or face it compares minimum, maximum and average values of the material variations, comparing all three of them together in the last column, where the maximal values were taken and the Relative Standard Deviation is computed.

Thank this table it is clear that the differences between temperatures are minimal, in all but one case smaller than 1% difference. Even more interesting is that the 1,45% difference is for the case of the whole geometry of this use case, where PGS comes up slightly colder than copper.

As stated earlier, the chips themselves have different temperatures - that can be also seen on the comparison, as the top facing PCB have more than 10 °C lower temperature from the bottom face of the lower PCB, as the lower chip is losing more heat into the PCB there.

This table is clearly showing that by using a combination of Polyethylene terephthalate, Pyrolytic Graphite Sheet, and acrylic adhesive tape, we can reach very similar results as for using aluminum or copper while ensuring electrical insulation up to 1 kV. That is an important added value, as these PCBs can be designed without special focus on them being placed back to back.

Tab. 7.7: Table is describing temperatures on selected geometries for all three material variations of the simulation.

selected geometry	material	MIN [°C]	MAX [°C]	AVG [°C]	RSD MAX[%]
whole geometry	Al	58,37	82,22	61,31	1,45
	Cu	58,49	84,91	61,32	
	PGS	58,59	84,68	61,33	
top face PCB	Al	58,37	72,27	59,76	0,07
	Cu	58,49	72,33	59,79	
	PGS	58,59	72,39	59,80	
top face "PET"	AL	58,98	66,51	60,39	0,80
	Cu	59,16	65,80	60,42	
	PGS	59,30	65,22	60,43	
top face "PGS"	AL	58,98	66,51	60,39	0,80
	Cu	59,16	65,80	60,42	
	PGS	59,30	65,26	60,43	
bottom face of lower PCB	Al	58,46	84,51	61,11	0,26
	Cu	58,58	84,20	61,14	
	PGS	58,67	83,97	61,16	

One can object that surface temperature of 60 °C can be on the higher end of operating temperature, but this can be solved by expanding the PGS sheet to the side and/or connecting it to some kind of radiator. This can be done thanks to the understanding of heat exchange inside the geometry, which can be analyzed and displayed as heat flux.

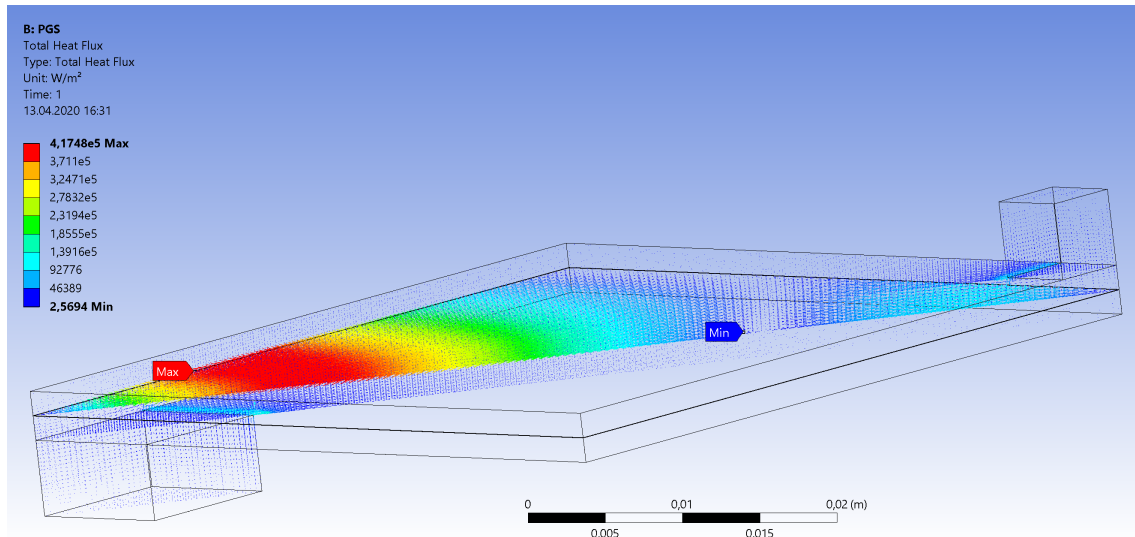


Fig. 7.8: Heat flux distribution for the whole geometry.

In figure 7.8 can be seen that the heat flux is located mainly in the inner layers, which is logical, as they have way higher heat conductivity than the PCB. To better see the values of the heat flux, there was a path created, and on this path, values are measured and displayed on subsequent graphs. The path is starting in the corner of the upper chip, connecting to the corner where the lower chip is. It is located straight on the layers selected - "PET", "PGS" and PCB. In the graph 7.9 we can see heat flux on the "PET" layer. In the graph, there are two maximums, the first one slightly after the corner of the upper chip, the second one just before the corner of the lower chip. In this graph, the aluminum has the highest values of heat flux, followed by copper and PGS.

To examine heat flux on the "PGS" layer, look at the graph 7.10. There are a couple of interesting things to be seen. First of all, PGS has way greater value than Al and Cu, which makes sense because of their highly different heat conductivity. The second interesting thing is that if we compare this graph with the previous one (Fig. 7.9) we see that on the "PET" layer, we have values of $0,5 - 1 \cdot 10^3$, but on the "PGS" layer, we have values $4,5 - 6 \cdot 10^5$, meaning the values of heat flux for Al and Cu are different by the order of two! This is interesting but also important for the understanding of the difference of heat transfer on the face and inside of a material.

Fig. 7.9: Heat Flux on "PET" layer

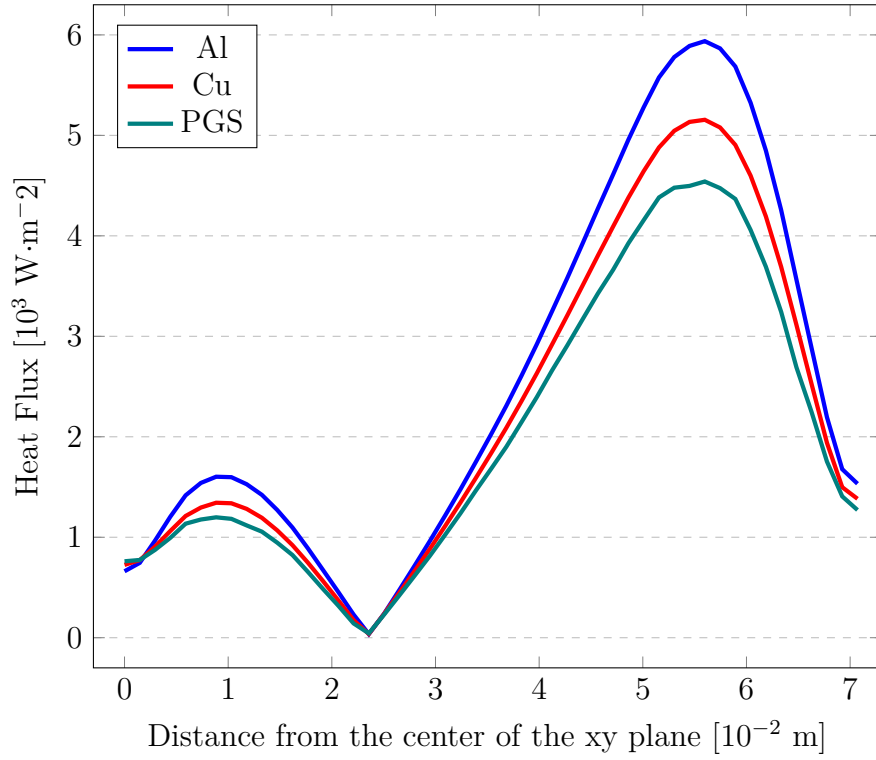
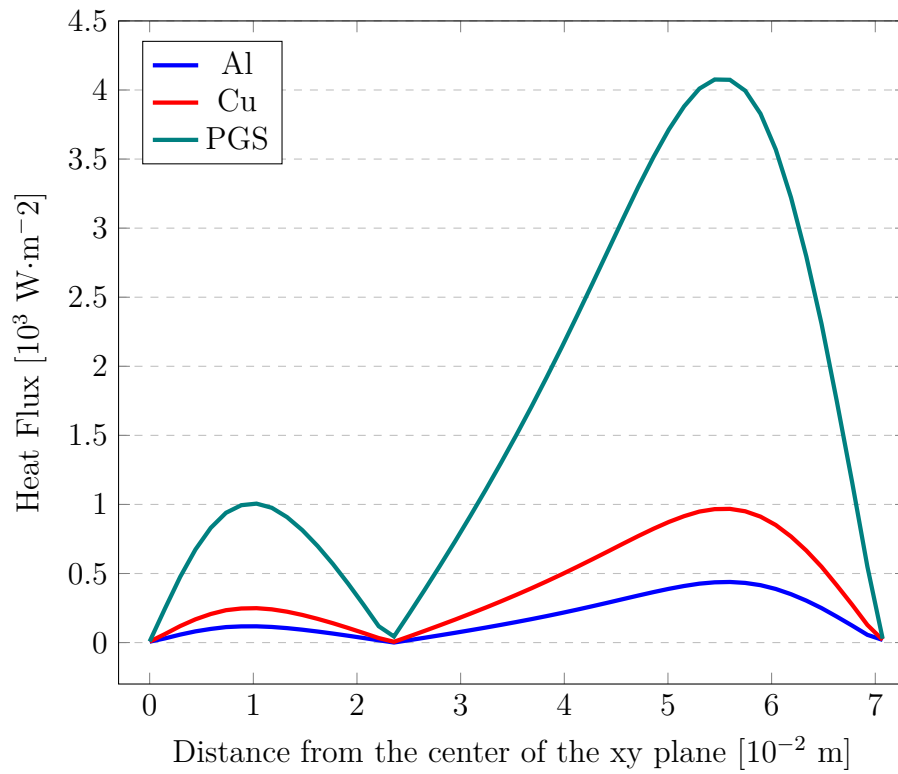
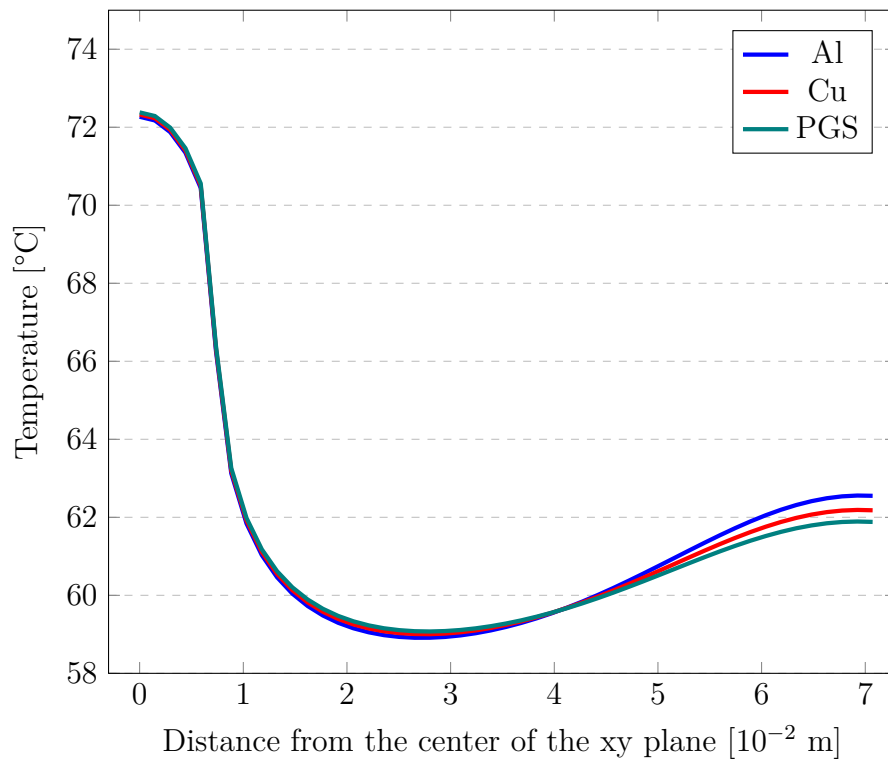


Fig. 7.10: Heat Flux on "PGS" layer



A comparison of the temperature on the upper PCB can be seen on the graph 7.11. It is, once again, showing the temperature along the path described earlier. Here we can see how it drops as the distance from the upper chip is getting bigger. Then it slightly rises for in the location of the bottom chip, even though the chip lays underneath multiple layers of material.

Fig. 7.11: Temperature on the upper PCB



7.3 Use Case 3: Heat conduction around the corner

In the first use case, there was a simulation of heat spreading and on the second one, there was heat spreading combined with electrical insulation. In this third use case, we will look at heat conduction with a heat source with low intensity, on a relatively small body - but with a curve - which is interesting due to the anisotropy of the PGS.

To make it even more interesting, the geometry was simulated and analyzed with two different material settings for the base material. At first, it was done with an aluminum base, with the goal of showing how differently is heat flux flowing through thermally isotropic and anisotropic materials, which are actually good heat conductors - as all three of Al, Cu and PGS are.

On the contrary, in the second material setting, the aluminum base in the geometry is replaced with a base made of flexible PCB. That is a use case demonstrating the need of heat conductor for flexible devices, as was mentioned in section 1.2.3. Furthermore, PCBs are anisotropic, as they are heterogeneous.

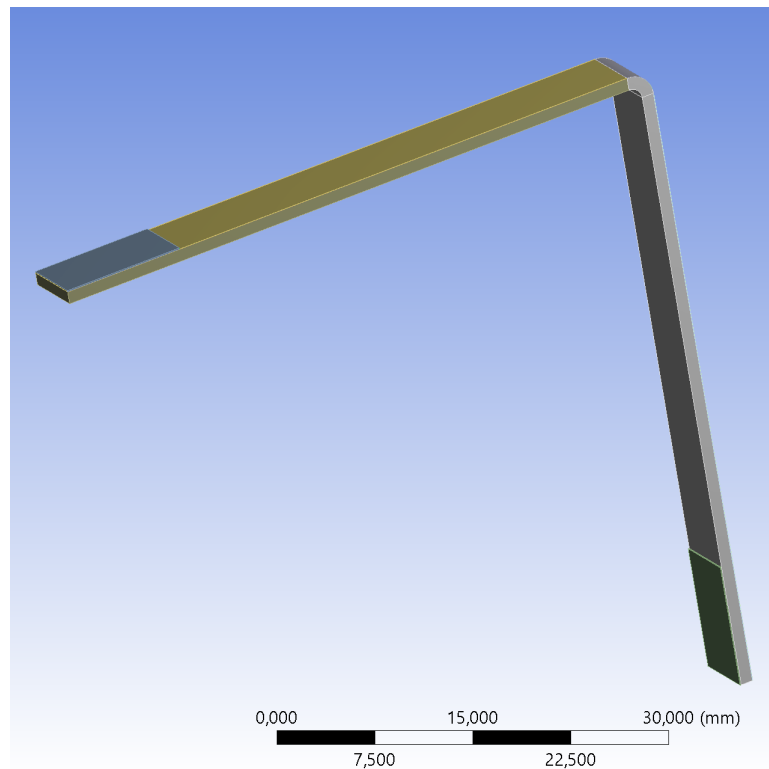


Fig. 7.12: Geometry used for the third use case.

The table 7.8 is showing the dimensions of the geometry. It can be seen as a long but thin, narrow bar (with two thin layers on the top), that was bent in the middle.

Tab. 7.8: Dimensions of the design.

part	dimensions [mm]
chip / cooler	10 x 5 x 0,1
Aluminum / PCB Base	101,57 - 103,17 x 5 x 1
"Acrylic Adhesive"	101,57 - 103,17 x 5 x 0,01
"PGS"	101,57 - 103,17 x 5 x 0,01

This case is a little bit more complicated on the side of the settings of the solver, that the previous is. That is once again connected to the anisotropic characteristics of the materials used. Well, it can be said that it should be the same as for the previous use cases, as there also are two anisotropic materials used - PGS and PCB. But in this case, two factors are stepping in: the first one is the fact that these two straight parts are perpendicular to each other, the second one is the rounded corner piece.

Why are these factors influencing the solver settings? Because when we set that material has low heat conductivity alongside its axis z, then in the piece perpendicular to the first one this setting will be applied alongside the axis x or y of the material. For the rounded corner piece, it is even more interesting, as the Cartesian coordinate system, that is used normally, will not work here due to its limitations. On a rounded corner, to be able to use the Cartesian system, we would need to split the geometry to the infinite number of pieces and set a slightly different system for each of them. But there is a way more elegant solution - it is simply using the Cylindrical coordinate system.

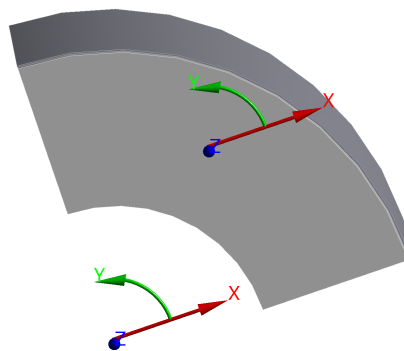


Fig. 7.13: Different Cylindrical coordination systems need to be used for PGS layer (lower system) and PCB layer (upper system).

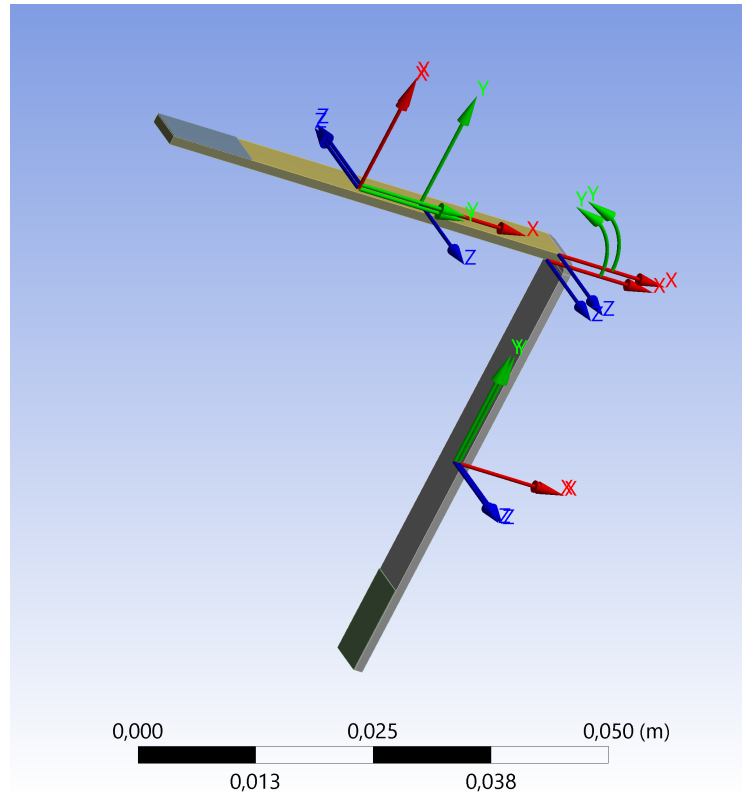


Fig. 7.14: All of the coordination systems used for this analysis.

To be able to set all of these different coordination systems, the geometry had to be cut to different parts, and then the special system was assigned to each part that has an anisotropic material in some of the material variations.

In this use case, there is just one heat source - the chip on top of the design, placed on the heat conductive layer of Al, Cu, or PGS, depending on the case. It is producing heat of 0,2 W, which is then flowing throughout the geometry and it is being cooled by the cooler, attached to the base side on the other end of the design. The cooler is set at a permanent temperature of 10 °C, demonstrating a powerful cooling system attached at this point. The placement of that cooler can be clearly visible on the picture 7.14.

All of the outer surfacing faces have a heat transfer coefficient of $5,5 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$, simulating air running over the plate. The chip has the same settings as chips from the previous use case - that is $5 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ for the lateral plane and $20 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ for the vertical axis.

This design was, in the same way as the previous ones, computed for three different material settings - the top two layers being Al, Cu, or combination of acrylic adhesive tape and PGS. But in this case, as said earlier, these three variations were computed for both aluminum base and for a base made of flexible PCB, more precisely flexible polyimide PCB.

By using the values specified in table 7.9 and the equations 7.1 and 7.2, the resulting thermal conductivity is $2,56 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ for xy plane and $0,80 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ for z axis. The other materials are using the same settings as in the previous chapters.

Tab. 7.9: PCB settings

variable	value
polyimide thermal conductivity	$0,8 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$
copper thermal conductivity	$401 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$
total thickness t	1,0 mm
number of layers n_C	4
Layer 1: volume frac. of conductor A_i	20%
Layer 1: layer thickness t_{Ci}	0,0022 mm
Layer 2: volume frac. of conductor A_i	80%
Layer 2: layer thickness t_{Ci}	0,0022 mm
Layer 3: volume frac. of conductor A_i	80%
Layer 3: layer thickness t_{Ci}	0,0022 mm
Layer 4: volume frac. of conductor A_i	20%
Layer 4: layer thickness t_{Ci}	0,0022 mm

7.3.1 Results

As this use case can be seen as two use cases mixed together, the results section here combines them and comments on all of the six material variations. To better understand what is happening in the geometry and to see if the PGS can be beneficial in this use case, there are a couple of analysis in this section, reviewing temperature as well as heat flux of the system.

The comparison of the two different material variations (Al or flexible PCB, with layers made of Al, Cu or PGS) for both options of the base can be seen as temperature comparison of the whole system in Table 7.10) and then on selected faces Table 7.11.

Tab. 7.10: Comparison of all the variations for the whole geometry.

base	layer	MIN [°C]	MAX [°C]	AVG [°C]	RSD MAX[%]
Al	Al	10,00	24,88	17,59	1,14
	Cu	10,00	24,71	17,51	
	PGS	10,00	24,22	17,25	
Flex	Al	10,00	117,66	51,06	14,37
	Cu	10,00	105,15	48,62	
	PGS	10,00	82,36	42,74	

From the Table 7.10 it is clearly visible, that for the aluminum base, the results are almost the same, as the temperatures are really similar and the Relative Standard Deviation of the maximal values is just around one percent, thus from this is looks like PGS has no advantage over "classic" material used in the thermal management of microelectronics. The difference is too small to be actually beneficial for the device as a whole, assuming for example just the added cost in the manufacturing itself, not even considering the price of PGS itself.

On the contrary, for the base made of flexible PCB, the difference is clearly visible and the Relative Standard Deviation of the maximal values is around fourteen percent, making it worth using the PGS. Not just the difference itself, but also the highest temperatures of the geometry are important, as in here the maximal temperature of 117 °C or 82 °C can be the difference between working and overheated (fried) chip. As the glass transient temperature of polyimide PCBs is much higher than the one of FR4 classic PCBs, there is no worry about melting the PCB in this case.

If we compare the two bases - aluminum and flexible PCB, we can clearly see the difference. Even though they have the same exact conditions, the behavior is very different. The biggest difference isn't in the temperatures, but in the RSD MAX,

where the base made out of flexible PCB is showing that it is really not a good heat conductor, as the difference between maximal temperature for Al and PGS layer is bigger than the maximal temperature of Al on the Al base. It is all based on the heat conductivity, and it will be more discussed later in the section.

Results showing the temperatures on different faces are also interesting, as we can see in the table 7.11. As in the previous table, it is clearly visible, that the material configuration with flexible PCB is reaching higher temperatures than the one with aluminum base. Also, the trend of much bigger Relative Standard Deviations of the maximum values for the flexible PCB is corresponding to the behavior of the whole geometry. The values of the RSD for PCB are higher at every face, including face 4 (Upper face of the corner piece of the "PGS" layer), even though the difference is the smallest for this face. That can be happening due to the size and location of this face. Even though it is similar size as face 1 (Upper face of the chip) it is located further on on the path that the heat travels, and so the heat going into this face is not that big. The size of the face plays an important role, as on a smaller face the better heat spreading is not that clearly visible. That is because the heat conductivity is a unit based on length, so it is more visible at bigger length. As we can see, the minimal values of face 3 are basically the maximums of the face 4.

On the Figure 7.15 we can see the faces used in the table 7.11 as they are represented by the numbers 1-5, the temperatures and heat fluxes at Figures 7.16 and 7.18 are then shown on a path along the edge of the geometry, going from point A to point B.

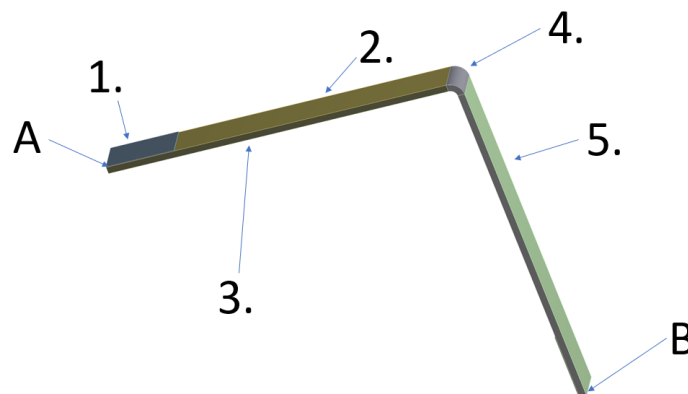
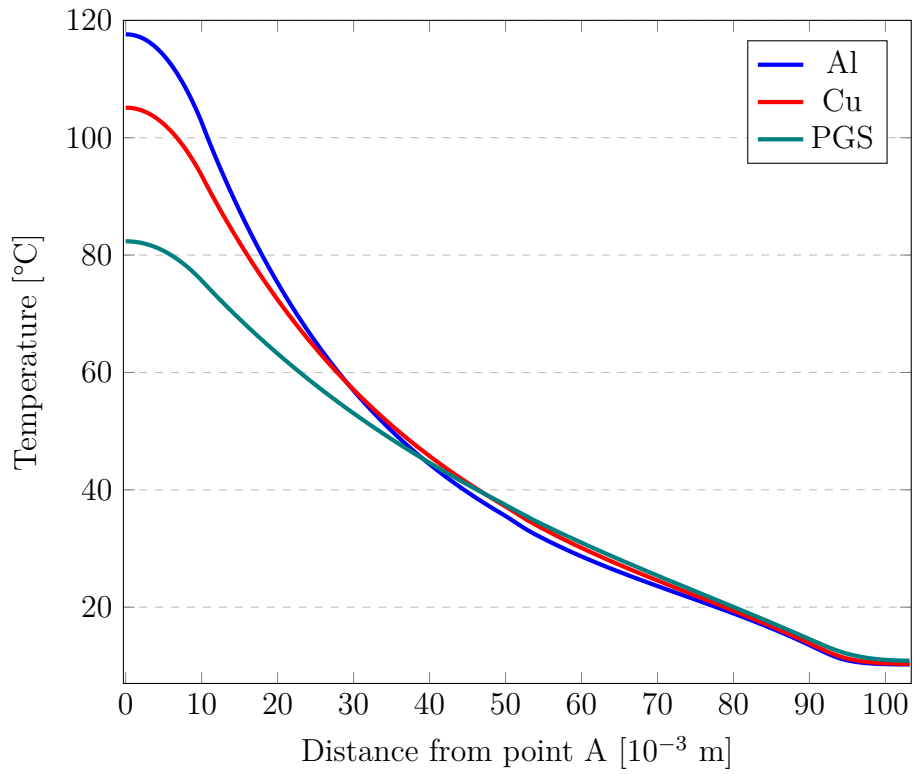
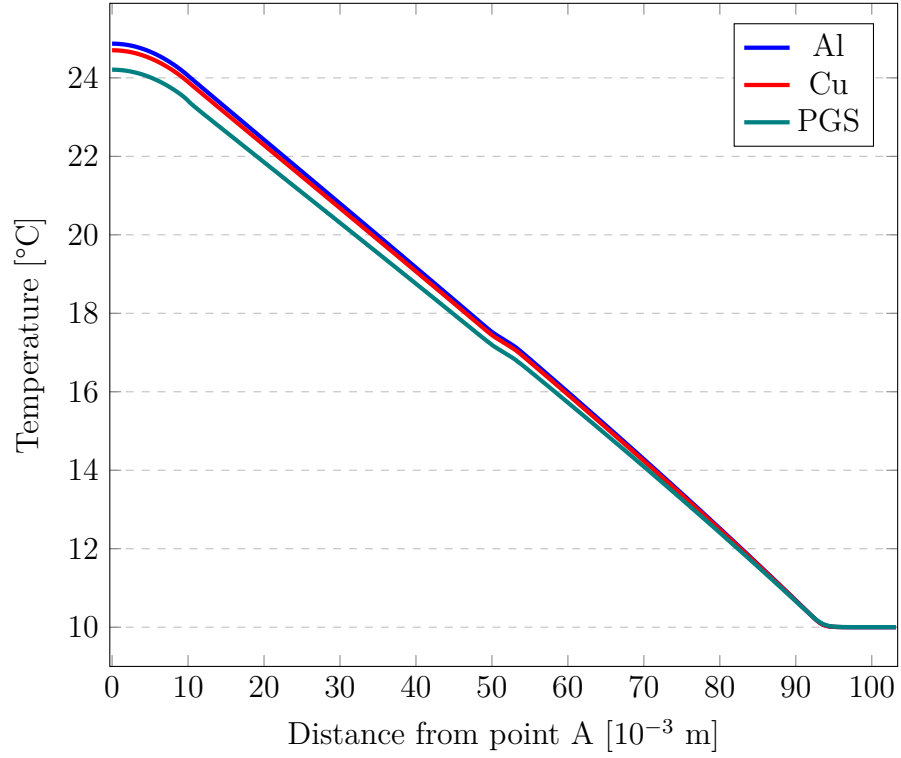


Fig. 7.15: Measurement faces and edge points of the geometry.

Tab. 7.11: Comparison of all the variations shown at different faces.

base	layer	MIN [°C]	MAX [°C]	AVG [°C]	RSD MAX[%]
1: Upper face of the chip					
Al	Al	24,07	24,88	24,61	1,14
	Cu	23,91	24,71	24,45	
	PGS	23,44	24,22	23,96	
Flex	Al	102,76	117,66	112,76	14,37
	Cu	93,67	105,15	101,36	
	PGS	75,74	82,36	80,16	
2: Upper face of the first piece of the "PGS" layer					
Al	Al	17,52	24,87	21,55	1,14
	Cu	17,44	24,70	24,43	
	PGS	17,20	24,21	21,03	
Flex	Al	35,54	117,65	71,27	14,37
	Cu	37,16	105,14	68,11	
	PGS	37,43	82,35	59,39	
3: Lower face of the first piece of the base					
Al	Al	17,51	24,86	21,55	1,22
	Cu	17,43	24,70	24,42	
	PGS	17,17	24,16	21,02	
Flex	Al	35,49	116,35	70,87	14,29
	Cu	37,11	104,05	67,73	
	PGS	37,37	81,61	59,08	
4: Upper face of the corner piece of the "PGS" layer					
Al	Al	17,13	17,53	17,33	0,83
	Cu	17,05	17,45	17,25	
	PGS	16,81	17,19	17,00	
Flex	Al	32,92	35,54	34,22	2,26
	Cu	34,61	37,16	35,87	
	PGS	35,23	37,41	36,31	
5: Upper face of the last piece of the "PGS" layer					
Al	Al	10,00	17,13	12,96	0,83
	Cu	10,00	17,05	12,92	
	PGS	10,00	16,80	12,83	
Flex	Al	10,24	32,93	19,84	13,26
	Cu	10,35	34,61	20,57	
	PGS	10,88	35,20	21,31	

Fig. 7.16: Temperature on the edge of the top layer



The declining temperature on the edge of the layer can be seen on the Figure 7.16, where on the first graph we can see the temperatures for the material variation using the aluminum base, whether on the second graph we can see the material variation using the flexible PCB as a base.

For the first material variation, it is nicely visible, that the declining trend is almost linear, except the beginning and the very end. It is the closest to linearity for the aluminum layer, which makes sense, as with aluminum base and aluminum layer it is basically an aluminum bar bent in half. This bend is also visible on the temperature graph, looking like a small bump, located between 50 and 60 x 10⁻³ m from the point A and reaching temperature approximately 17 °C. It can be compared to the Table 7.11, where for the face 3 corresponding temperatures between 17,19 and 17,53 °C can be seen. Another thing, that is interesting in this first graph, is the difference between PGS and the duo of classic materials - aluminum and copper. In the beginning, close to point A, the difference is the biggest. As the temperature declines and the distance from point A rises, the temperature of the PGS is behaving more and more like the other materials. That can be easily explained, as here we can see the top edge of the top layer. For PGS, the vertical thermal conductivity is very low compared with the other materials, but on the other hand, it is way higher in the plane. Because of that, the heat is spreading fast in the planar and just slowly in the vertical direction. In the beginning, the heat is transported just by the PGS layer, but as the distance from A is getting bigger, the heat is also dispersed into the aluminum base, which in this case behaves like a thermal reservoir, holding the heat from spreading faster. At the distances of 92 x 10⁻³ m and after we can see a flat line at 10 °C, which is the effect of the settings discussed earlier.

On the second graph, we can see the results for the flexible PCB base. It has some common features with the previous graph, for example, the flatlining at the end of the graph. There are also other interesting things to observe, starting with the PGS line. In this case, the line is starting at the lowest temperature, and ending at the highest, overall being much closer to linearity than the other two. That is, once again, the effect of the high thermal conductivity, as the material is spreading heat so fast, the temperature differences between the beginning and the end of the layer are way smaller. In fact, if we would compare the temperature range, by subtracting the minimal temperature from the maximal, we would get 116,66 °C for aluminum, 95,15 °C for copper, and only 72,36 °C for PGS. That means Al has the temperature range bigger by 37% than PGS. That is also explaining why is the aluminum creating some sort of wave from 40 to 70 · 10⁻³ m. Interesting is, that there is no bump on the second graph, making it almost impossible to guess where the bend is.

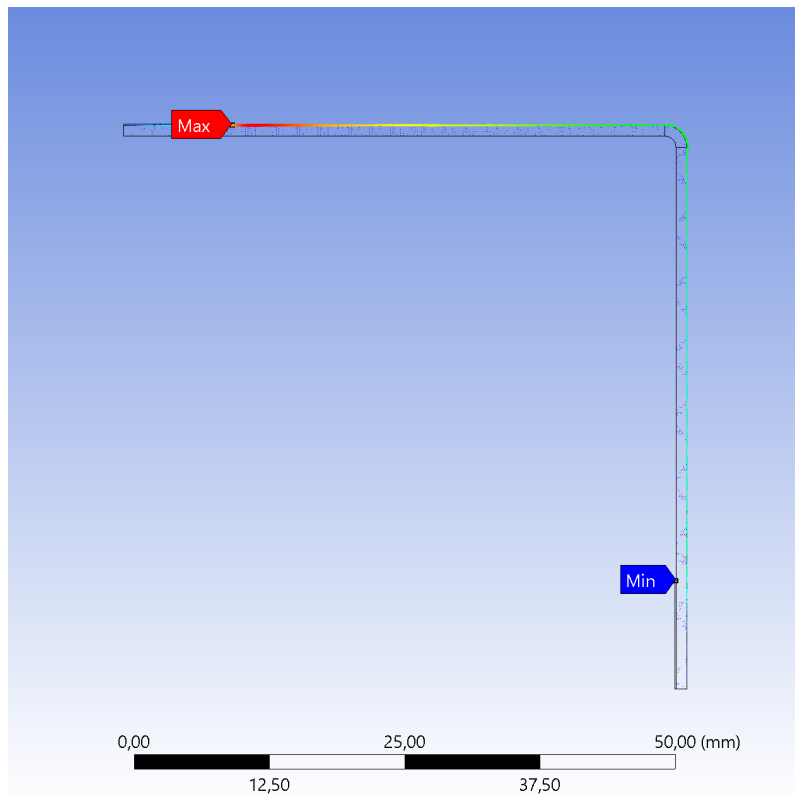
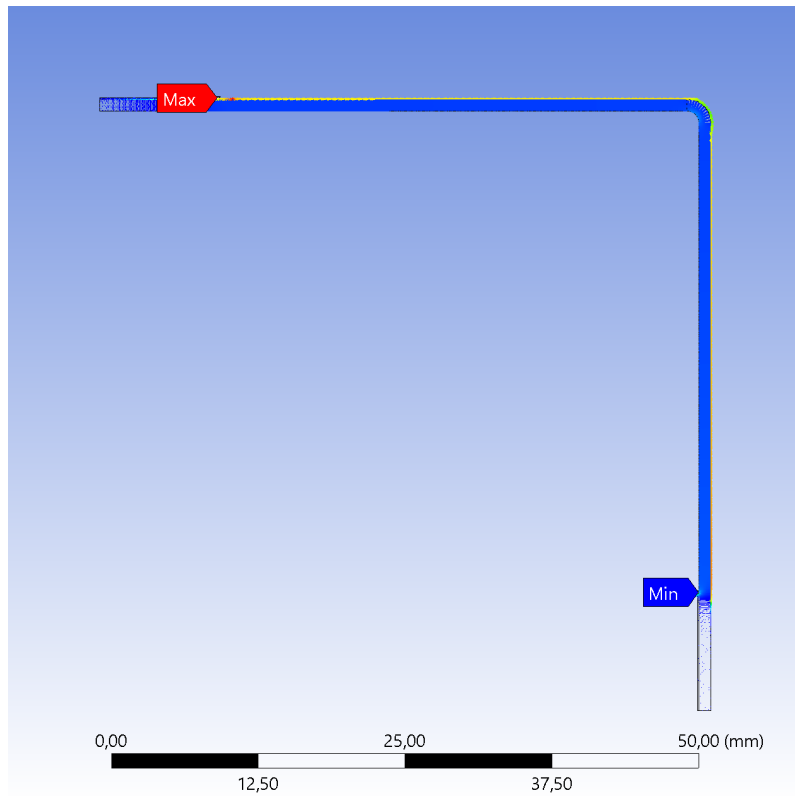
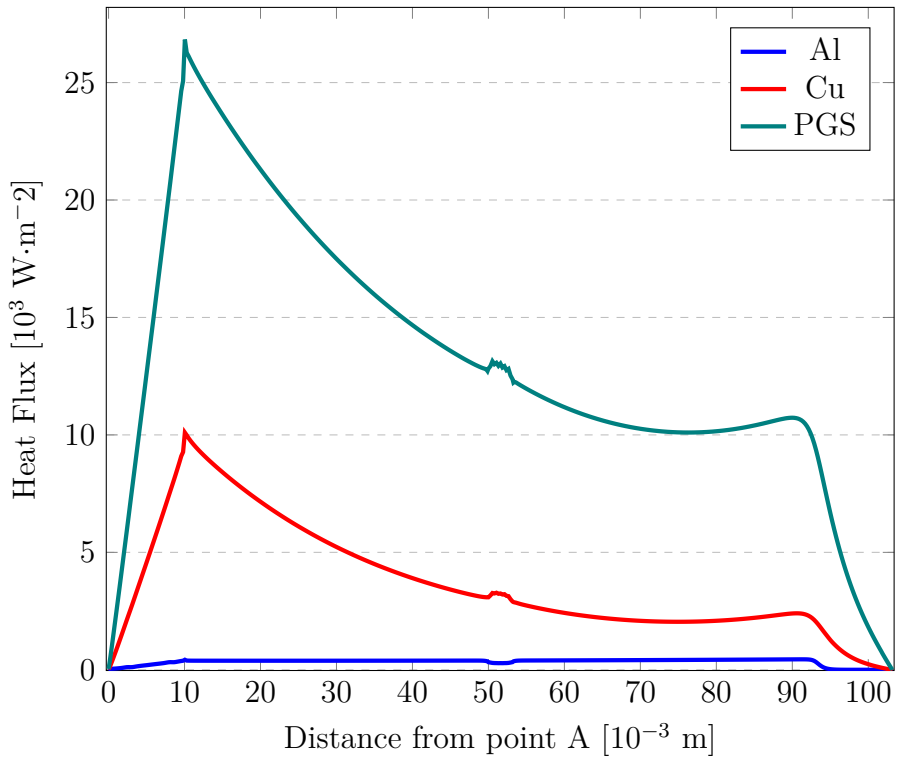
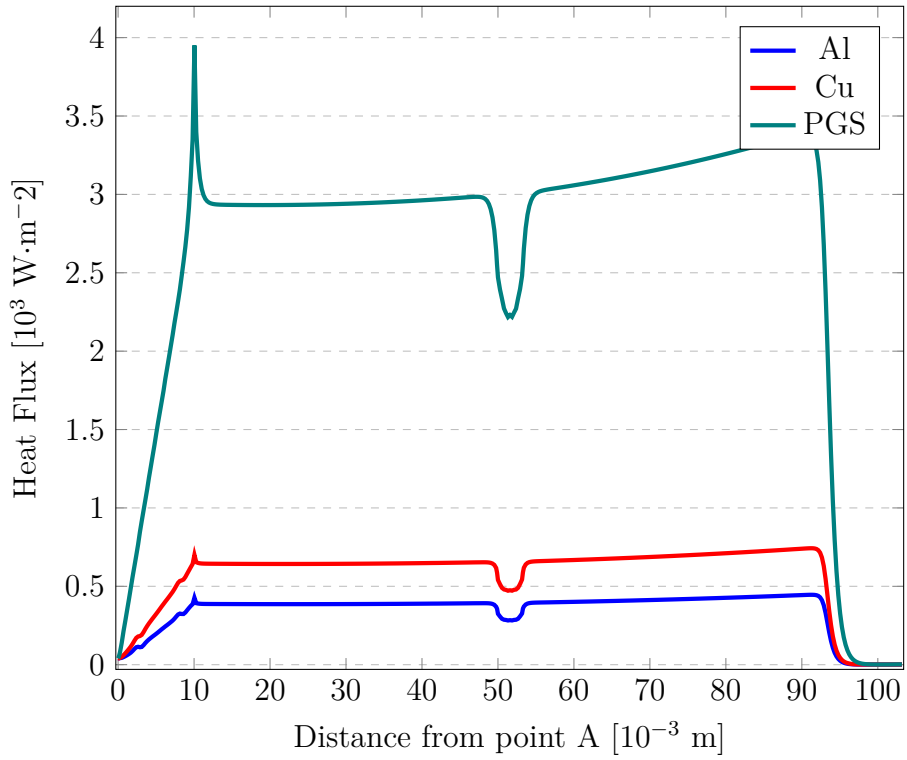


Fig. 7.17: Comparison of heat flux in the base of the design between aluminum base (the first picture) and flexible PCB base (the second picture).

Fig. 7.18: Heat flux on the edge of the top layer



Temperature is a result of heat flux in the material, and even though some of it was already explained, it is interesting to show the heat flux on the geometry itself. In Figure 7.17, there are two screenshots, comparing side looks at the geometry, with vectors proportional to the heat flux displayed. Both of these are with the PGS layer on top. It is clear that for the aluminum base the heat flux is distributed in the base, although the top layer is reaching the highest values, as the PGS has that bigger of a heat conductivity than aluminum. On the other hand, the flexible PCB base is almost transparent, with just a few blue dots in the mass of the base, showing close to none heat flux in the base.

This distribution of heat flux is can be further observed on the graphs from Figure 7.18. On the first graph, we see the aluminum base, and on the second one, the flexible PCB base can be seen. Once again, this is showing the heat flux on the edge of the top layer of the design. Continuing on the distribution of the heat flux - on these graphs is visible how the heat flux with the flexible PCB base is higher by an order. One of the reasons for this is the nearly non-existent heat flux in the base.

When looking at Figure 7.18 two features are visible at first sight. The first one is the peak at 10×10^{-3} m, which is caused by the design - the chip is ending here, thus creating a sudden drop in the heat flux. A similar feature can be seen at 90×10^{-3} m and further, as the cooling pad is starting there. The second feature is the curve in the middle, caused by the bend. It is truly interesting, how the aluminum and the flexible PCB base have an exactly different effect here, making the curve in at exact different direction.

Overall it is clearly visible that the PGS have in both cases the highest heat, especially compared to the aluminum layer, which is also the only layer material variation that doesn't have bigger heat flux in the second graph.

8 Conclusion

This thesis starts by explaining current problems in thermal management of microelectronics, such as the creation of hot spots, complicated System On a Chip designs with 3D stacking of individual chips and flexible electronics and touchscreen devices. These three challenges can be solved by using not only two most commonly used materials in the field - aluminum and copper, but also by using pyrolytic graphite sheet, which has great heat conductivity and it can be very thin. It is also extremely flexible, allowing the use in the field of flexible electronics.

One of the most challenging problems is the creation of hot spots and unequal distribution of heat through electronics. Solution for better heat spreading might be in the use of pyrolytic graphite, which has high conductivity in the layer plane and can well help with the challenge of hot spots. To demonstrate this, there was a small demonstration in Chapter 4. This chapter is showing the benefits PGS can bring to the thermal management of microelectronics, behaving like a very good heat spreader. There are also transient simulation graphs showing how PGS is the fastest in both temperature growth and regress. The idea of using PGS for heat spreading is further developed and tested on more challenging and real-world design in Use Case 1 (Chapter 7.1).

Thermal management of microelectronics is a challenging field, and one reason for that is the need for insulating the electrically conductive materials. PGS is not an electrical insulator but in the Use Case 2 (Chapter 7.2) it is clearly shown how the combination of PGS and PET can be electrically insulating material while keeping heat conductivity of aluminum and copper. That was demonstrated on a geometry featuring two PCBs, showing it's usability in microelectronics.

With the rise of flexible devices, there is a need for thermal management of these devices. The usability of PGS with flexible PCB is demonstrated in Use Case 3 (Chapter 7.3). Once again, PGS is looking like the material to use, with a maximal temperature lower by a third from aluminum.

Overall, in these three Use Cases, the PGS had shown itself as the ideal material in all three of them, delivering results with the lowest temperature, or - in the second Use Case - with the same temperature, but with added value in the electrical insulation.

Bibliography

- [1] LASANCE, Clemens. 2005. *Advances In High-Performance Cooling For Electronics* [online] Available at: <https://www.electronics-cooling.com/2005/11/advances-in-high-performance-cooling-for-electronics/>. Article.
- [2] GILSON, Gareth M., et al. *Piezoelectric fan cooling: A novel high reliability electric machine thermal management solution*. *IEEE Transactions on Industrial Electronics*, 2012, 60.11: 4841-4851.
- [3] PAVLOVA, Anna; AMITAY, Michael. *Electronic cooling using synthetic jet impingement*. *Journal of heat transfer*, 2006, 128.9: 897-907.
- [4] JONES, Lee and Alyson RODGERS. *Synthetic jet cooling for small form factor computing* [online]. Available at: <http://smallformfactors.mil-embedded.com/articles/synthetic-form-factor-computing/>
- [5] SEHGAL, Satbir Singh. *Studies on Liquid Flow and Heat Transfer for Cooling of Integrated Circuits Using Microchannels*. 2012.
- [6] KRAUS, Allan D.; BAR-COHEN, Avram. *Thermal analysis and control of electronic equipment*. Washington, DC, Hemisphere Publishing Corp., 1983, 633 p., 1983.
- [7] DUNN, Peter D.; REAY, David. *Heat pipes*. Elsevier, 2012.
- [8] *Standard Heat Pipes*. *MyHeatSinks* [online]. Available at: <https://myheatsinks.com/heat-pipe-solutions/standard-heat-pipes/>
- [9] *Server Immersion Cooling*. 2019. In: *Wikipedia: the free encyclopedia* [online]. San Francisco (CA): Wikimedia Foundation. Available at: https://en.wikipedia.org/wiki/Server_immersion_cooling
- [10] MOORE, Arden L.; SHI, Li. *Emerging challenges and materials for thermal management of electronics*. *Materials today*, 2014, 17.4: 163-174.
- [11] LEE, Woong Sun; YU, Jin. *Comparative study of thermally conductive fillers in underfill for the electronic components*. *Diamond and related Materials*, 2005, 14.10: 1647-1653.
- [12] GÁNDARA, MJ Freiría. *Aluminium: The metal of choice*. *Mater. Tehnol*, 2013, 47.3: 261-265.

- [13] EKPU, Mathias, et al. *Advanced thermal management materials for heat sinks used in microelectronics*. In: *18th European Microelectronics and Packaging Conference. IEEE, 2011. p. 1-8.*
- [14] RYUU. 2017. *What are diamond and graphite in relation to carbon? Socratic QA [online]*. Available at: <https://socratic.org/questions/what-are-diamond-and-graphite-in-relation-to-carbon>
- [15] HIRSCH, Andreas. *The era of carbon allotropes*. *Nature materials*, 2010, 9.11: 868.
- [16] NOVOSELOV, Kostya S., et al. *Electric field effect in atomically thin carbon films*. *science*, 2004, 306.5696: 666-669.
- [17] HAN, Yong, et al. *Enhancement of hotspot cooling with diamond heat spreader on Cu microchannel heat sink for GaN-on-Si device*. *IEEE Transactions on Components, Packaging and Manufacturing Technology*, 2014, 4.6: 983-990.
- [18] ANTHONY, John W., Richard A. BIDEAUX, Kenneth W. BLADH and Monte C. NICHOLS. 1990. *Handbook of Mineralogy. I (Elements, Sulfides, Sulfosalts)*. Chantilly, VA, US: Mineralogical Society of America.
- [19] Slack, G. A. (1962). *Anisotropic Thermal Conductivity of Pyrolytic Graphite*. *Physical Review*, 127(3), 694-701.
- [20] Inagaki, M., Kaburagi, Y., Hishiyama, Y. (2014). *Thermal Management Material: Graphite*. *Advanced Engineering Materials*, 16(5), 494-506.
- [21] L. C. F. Blackman, A. R. Ubbelohde (1962). "Stress Recrystallization of Graphite". *Proceedings of the Royal Society of London*. A266 (1324): 20-32.
- [22] *Pyrolytic Graphite Sheet Evolves to Meet Tough Thermal Demands*. 2015. In: *ElectronicDesign [online]*. Available at: <https://www.electronicdesign.com/circuit-protection/pyrolytic-graphite-sheet-evolves-meet-tough-thermal-demands>
- [23] TSAI, Wei-Yu, et al. *High thermal dissipation of Al heat sink when inserting ceramic powders by ultrasonic mechanical coating and armoring*. *Materials*, 2017, 10.5: 454.
- [24] GEIM, Andre K.; NOVOSELOV, Konstantin S. *The rise of graphene*. In: *Nanoscience and Technology: A Collection of Reviews from Nature Journals*. 2010. p. 11-19.

- [25] Falcao, E. H., Wudl, F. (2007). Carbon allotropes: beyond graphite and diamond. *Journal of Chemical Technology and Biotechnology*, 82(6), 524–531.
- [26] Heat. In: *Encyclopædia Britannica* [online]. *Encyclopædia Britannica*, April 2018. Available at: <https://www.britannica.com/science/heat>
- [27] Conduction. In: *SolidWorks Help* [online]. 2018 Available at: https://help.solidworks.com/2018/english/SolidWorks/cworks/c_Conduction.htm
- [28] BEJAN, Adrian. 1993. *Heat Transfer*. John Wiley.
- [29] HEWITT, G. F., G. L. SHIRES a IU. V. POLEZHAEV. *A-to-Z Guide to Thermodynamics, Heat and Mass Transfer, and Fluids Engineering* [online]. Boca Raton, [Fla.]: Begellhouse, 2006. ISBN 0-8493-9356-6.
- [30] GETLING, A. Rayleigh-Bénard convection. *Scholarpedia* [online]. 2012, 7(7). DOI: 10.4249/scholarpedia.7702. ISSN 1941-6016.
- [31] Wikipedia contributors. "Rayleigh-Bénard convection." *Wikipedia, The Free Encyclopedia*. *Wikipedia, The Free Encyclopedia*, 2 Jul. 2019. Web. 13 Oct. 2019.
- [32] Convection. In: *SolidWorks Help* [online]. 2018 [cit. 2019-10-12]. Available at: https://help.solidworks.com/2018/english/SolidWorks/cworks/c_Convection.htm
- [33] AFSHIN, J. Ghajar. 2014. *Heat and Mass Transfer: Fundamentals and Applications*. McGraw-Hill Education - Europe.
- [34] RAPP, Bastian E. 2016. *Microfluidics modeling mechanics and mathematics*. Boston, MA: Elsevier.
- [35] Coulson, J. M.; Richardson, J. F. (1999). *Chemical Engineering Volume 1 (6th ed.)*. Elsevier. ISBN 978-0-7506-4444-0.
- [36] KULE, Darth. 2010. Black body curves of Planck for various temperatures and comparison with classical theory of Rayleigh-Jeans. In: *Wikipedia* [online]. Available at: https://en.wikipedia.org/wiki/File:Black_body.svg
- [37] LOUDON, Rodney. *The quantum theory of light*. OUP Oxford, 2000.
- [38] *Pyrolytic Graphite Sheet: The Advanced Thermal Management Solution For Today's Designs*. In: *Panasonic* [online]. Available at: https://b2b-api.panasonic.eu/file_stream/pids/fileversion/910

- [39] *PGS Graphite Sheets: Datasheet. 2019. In: Panasonic [online]. Available at: https://b2b-api.panasonic.eu/file_stream/pids/fileversion/1652*
- [40] *URBAN, Ferdinand. 2009. Thermodynamic conditions in quenching chamber of low voltage circuit breaker. Doctoral Thesis. Brno University of Technology.*
- [41] *Dassault Systemes (2019) Technical Reference. SolidWorks Flow Simulation 2019.*