A short thermal properties journey for the PCB/package level

AcubeSAT-THE-BH-032

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1 Introduction

This is a **summary** report for the research about thermal properties of the materials used for AcubeSAT's PCBs. A bunch of resources, documentation and issues are listed because during the process some conflicts and uncertainties emerged. I should mention, also, that thermal analysis is very demanding and complex topic, so the documentation of the sources and thinking-paths are valuable tools to spot the possible wrong assumptions and **fallacies. The until now estimating values for this research can be found in this spreadsheet**.

2 Electronic packaging

There are many reference points that the electrical components can be grouped. The most common one is based on how they interconnect with the PCB. If holes should be used, then we are using the through hole technology (**THT**) and if the device is mounted, then we are using the surface mount technology (**SMT**). The devices that are using the last one as an interconnection method are called SMDs and they can be divided to many categories too. For now we will divide them to the **leaded** and the **leadless**. In the first one belong the packages that their leads extend beyond the package and the second one is when they don't. We are going to focus in the SMDs because if not everything, almost all the components that are going to be used in the AcubeSAT's boards except the PC104 connectors will use the SMT.

Before diving into what is hidden under the hood of the black boxes that we are looking in the PCB, we need first to demystify the terminology. **Packaging** is an abstract word and is used a lot in the electronics but it has several meanings and it may refer to a different "thought layer". There are the chip packaging, the PCB packaging and the systems packaging where a lot of PCBs are interconnected with each other. In a different way, packaging can be referred to **integrated circuit** and **electronic**. Electronic packaging has to do with everything about the interconnection of the die with the external circuitry of a PCB. The integrated circuit packaging is actually the last step of the electronic one. It is referred to the encapsulation process, the protection of the IC from the rest of the environment.

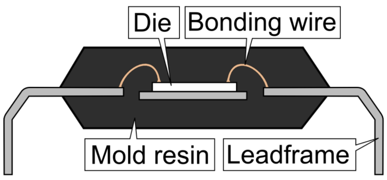
But lets stick more in the electronic packaging definition. There are four main level:

1. **Semiconductor** (or die, chip, IC) level. The wafer is separated into chips and one of them is inside of the package. The die, most of the times, is Si based, but GaAs is used too for high speed. In the die level, metalization (Al, Cu, Ag) also takes place for protection of oxidation.
2. **Chip in a carrier**. This is where all the bonding takes place. The die is attached to a leadframe or a substrate and the wire bonds serve the role to interface the integrated circuit with the outer leads (these terms will be explained soon). For the die attachment we have conductive or non conductive adhesive (but always thermal conductive) . If there is an exposed pad for example and electrical connection is desired then the first one is used[1].

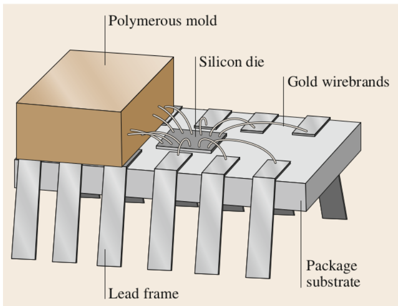
[1] Most of the times the exposed pad will be grounded but you need to be sure checking the datasheet otherwise problems may occur

3. **PCB level**. The chip is mounted on the board either with leads or no leads. Then the leads via copper tracks are connected with other components.
4. **System level**, PCB to PCB interconnect. This is where multiple PCBs are connected all together for an application.

In order to understand a little bit more all of these new/fuzzy terms like die, leadframe, substrate, wirebonds (bonding-wires) we will violate a little bit the rules and we will give an example of a package based on the through-hole technology. Thus let's take a look of a very well-known package that showed among the first ones in the job market. This is the dual line package (**DIP**). As we can see, the leadframe is the structure that houses the chip and interfaces the integrated circuit with the leads. The interface that change the pitch from the die to the outer leads is called **interposer**. Sometimes leadframe and interposer are used interchangeably. The materials used in the leadframe is copper or copper alloys and it is usually plated with tin or gold over nickel for oxidation-protection and to ensure wirebondability and solderability for the assembly process (integration of IC package to PCB). The die is attached to the leadframe pad using an organic compound (die attachment), epoxy resin with metal fillers (e.g. silver). Finally, for the encapsulation, the most used and cost-effective solution is the plastic package. It is epoxy resin with ceramic fillers like fused silica or alumina. It should be noted that **mold compounds** are called the materials used in the encapsulation process.



(a) *DIP cross section view*

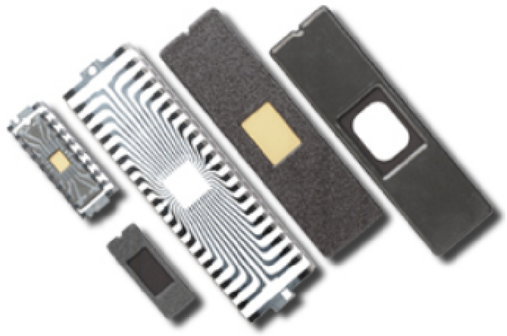


(b) *DIP leadframe*

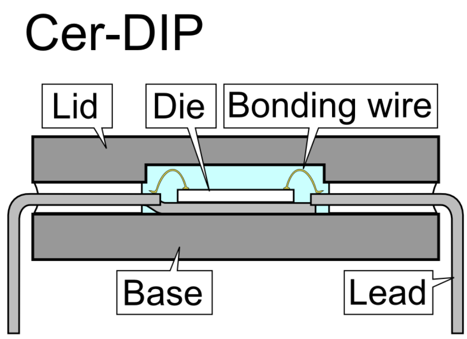
The DIP package that we have mentioned belongs to the plastic leadframe-based packages. That implies that the IC packaging can be, for once more, categorized in terms of material packaging to the **plastic and ceramic** ones and in terms of housing/supporting the die to the **leadframe and the substrate**.

For the difference between the ceramic and the plastic we are going to use the Cer-DIP as an example. Yes you guess right, it is a DIP but with ceramic materials for the packaging. So, a typical ceramic packaging has a ceramic base, a leadframe that is embedded to glass and a lid. The ceramic material that is used most often is the Aluminum oxide (alumina) and for the lid metal or ceramic ones. The benefits of ceramic packaging is the hermetic feature, the increased reliability and the greater thermal conductivity (one order of magnitude more) than plastic polymeric epoxy resin based packages. The main drawback is the cost and thus it is avoided for mass production.

Before proceeding further, for one more time we will make another division and we will describe the leadframe-based and the substrate packages. For the leadframe style we have mentioned the DIP, but what about the substrate-style? So to understand this we will make a huge jump and we will move to a more advanced packaging method, to the family of grid array and more specific to the Land Grid Array (**LGA**). In this category is

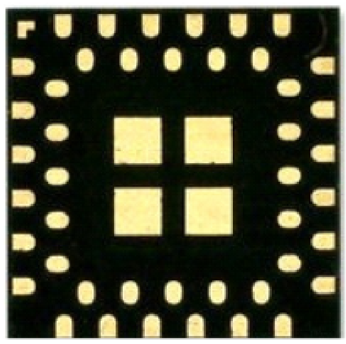


(a) Three main parts of a CER-DIP: base, leadframe, lid

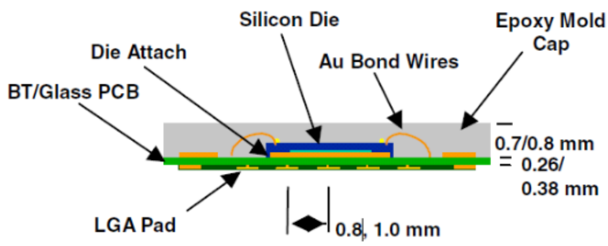


(b) Cross section view of a ceramic package

included the component RFFM6406 UHF TX-RX of the communication subsystem so it is sure worthy describing, or I should say scratching the surface of this type. A general cross view of a LGA is like this (Figure7b). The die is now glued instead of a leadframe to a substrate that is actually a laminate that is like a PCB! So we have a "PCB inside a PCB". It may have a lot of copper and dielectric layers along with soldermask to the top. The die is attached to the top layer. Then the wirebonds are attached to some exposed copper areas of the top layer and with vias the integrated circuit is now connected to the exposed pads in the bottom surface that serve the interface of the die with the rest of the circuit. This type of packages are used in demanding applications for high speed signals that its thermal and electrical performance is crucial and for populated areas with no room to breathe due to the small size but the increased functionality!



(a) Bottom side



(b) Cross section view

Figure 3: *LGA*

Now that we have an **overview** of the packaging and the terminology, we are going to examine the packages of the components of the AcubeSAT's board that we assume as thermal critical from a thermal point of view. The list of these can be found in the aforementioned spreadsheet[2]. It should be noted that the following analysis of the IC packages isn't complete and it isn't oriented for a detailed 3D IC simulation. The goal is to find out if we need to create eventually these kind of detailed models based to the materials and their thermal properties that will be listed in the continue of this report. So if eventually a more detailed approach is necessary, thorough investigation should

[2]This report may be outdated in the long run if more packages are going to be added

be made for the standardized dimensions of the internal structure of each package.

Also the **material declaration**, the document that lists all the materials used in packaging, isn't provided for all of them. To be more specific this particular type of doc is successfully indexed by manufacturers such as ST Microelectronics, Texas Instruments (TI) and Analog Devices that generally have great documentation and support. For the rest, by the code-name[3] of the package (e.g. QFP, SOIC), we can safely make an abstraction for the anatomy and the materials used. This is not accurate, but it bares the risk for the scope of this report. In other words, if the package is a well known and among the standardized ones, there are many chances that will be identical with other references that using the same package (of course some details may be different). For these with the missing material declaration, if we are finally going to follow the detailed approach, we need, except the standardized dimensions, to contact the vendor and request more information (it is worthy mentioning that this kind of contact may be unsuccessful, so a more "delicate" approach would be more suitable).

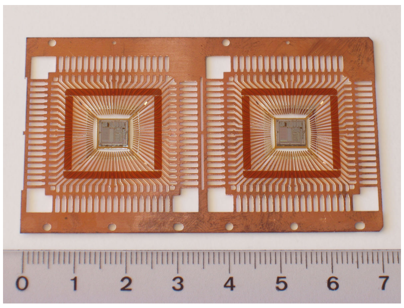
Finally, about the approach that we are going to follow for the upcoming IC packages, it should be added that in the physical dimensions aspect, we will focus more to the thermal desired lead-PCB interconnection.

2.1 LQFP

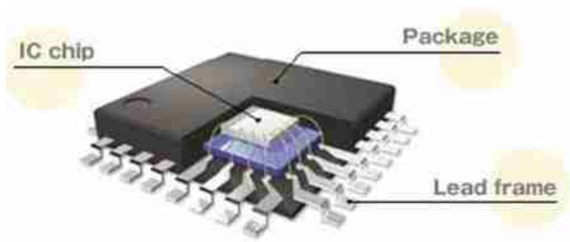
LQFP stands for Low profile Quad Flat Package, it has 144 pins and it belongs to the very well-know QFP series. There are slight variations for the physical dimensions of the components associated with this code-name, but the AcubeSAT's components with this tag are all the same. These are the **OBDH**, **SU and ADCS MCU**.

First, from the material declaration (see the complete document here) we can validate that it is a plastic leadframe-based package. Indeed, we can see references for the leadframe and the encapsulation. But let's make a summary for the listed-materials.

As we can see in the table I. in the die level the base material is the Silicon and all the other metals are used for the so called metallization that serves the role of oxidation-protection for the chip. The die attachment is a typical epoxy resin with silver as filler metal and for the leadframe we have a copper alloy that it is pre-plated with nickel over gold.



(a) *Two QFP leadframes*



(b) *QFP package anatomy*

[3] The IC package naming convention is a function of the physical dimensions, pins, pitch and the overall anatomy of the package. Most of them are standardized but vendors may use different names

Parts	Material	Mass
Die	Silicon	24.184
	Aluminum	0.045
	Copper	0.397
	Cobalt	0.001
	Tantalum	0.129
	Titanium	0.005
	Tungsten	0.003
	Silicon Nitride	0.101
	Silicon Oxide	0.257
Leadframe base	Copper	233.880
	Iron	5.760
	Zinc	0.288
	Metallic Phosphorous	0.072
Leadframe plating	Nickel	9.021
	Palladium	0.140
	Gold	0.140
Die attachment	Copper	2.170
	Iron	0.155
	Silica fused	0.310
	Metallic Phosphorous	0.016
	Diluent	0.155
	Allyl Compound	0.155
	Hardener	0.140
Bonding wires	Gold	2.376
	Palladium	0.024
	Silver	0.000
	Copper	0.000
Encapsulation	Epoxy resin A	20.706
	Epoxy resin B	41.412
	Silica Amorphous A	811.789
	Silica Amorphous B	88.001
	Carbon Black	5.177
	Phenol resin	67.295
Finishing	Nickel	0.679
	Palladium	0.011
	Gold	0.011

***Table I**: Material declatation OBC MCU*

2.1.1 Thermal properties

About the thermal properties, an all in one solution for the requested ones (thermal conductivity, heat capacity, absorptivity, emissivity) couldn't be indexed. Instead a lot of references have been found scattered around the web. Also these values are dependent of that reference and there are some deviations/conflicts. For now, we are going to list the materials and its properties of the most used ones in the IC packaging. We are going to assume the die as only silicon, the leadframe as a **copper alloy** (Cu-Fe) plated with gold over nickel, the wirebonds as gold and the encapsulation as an abstract **epoxy mold compound** (EMC)[4]. For more materials, some tables have been added to the end of this report (section 6) along with their references. Also there is the section 5 with databases for thermal properties for further investigation. About how to approach the thermal properties of the materials, some comments have been added to the Lessons learned (section 4).

Substance	Density (kg/m^3)	Thermal Conductivity ($W/m*K$)	Heat Capcity ($J/kg*C$)	References respectively
Silicon	2330	150	714	Figure 16
Cu-Fe	-	260	-	Figure 28
Epoxy mold compound	1790-1850	0.9-2	800	link, link, link
Plating Ni/Au/Pd	-	-	-	-

***Table II**: Material Bulk properties of QFP*

For the thermo-optical properties in general we are interested for the outer surfaces, like the encapsulation of package (epoxy mold compound or ceramic) and the leads (copper alloy plated with Nickel/Gold/Palladium aka Copper electroplated)

Substance	Emissivity	Absorptivity	References respectively
Copper electroplated	0,03	0,47	[20, p.346]
Epoxy mold compound	0,9-0,95	-	[14, p/9]

***Table III**: Thermo-optical properties*

About these values we should mention that the exact ones for each composition couldn't be indexed. For the copper alloys[5], there are some values in the Table 28 though. Reference for an homogenous approach of the plating Nickel/Gold/Palladium is also missing, but thermal properties for each one of these metals are easily available. For accuracy and more information (such as thickness[6] for the plating materials) we may need to research more about the IC assembly.

Substance	Density (kg/m^3)	Thermal Conductivity ($W/m*K$)	Heat Capacity ($J/kg*C$)	References respectively
Nickel	8908	92	440	[8], Figure 17, [9]
Gold	19320	297	130	[8], Figure 17, [9]
Palladium	12160	71.8	240	[8], Figure 16, [9]
Tin	5765	63.2	0.226	[2], [9]

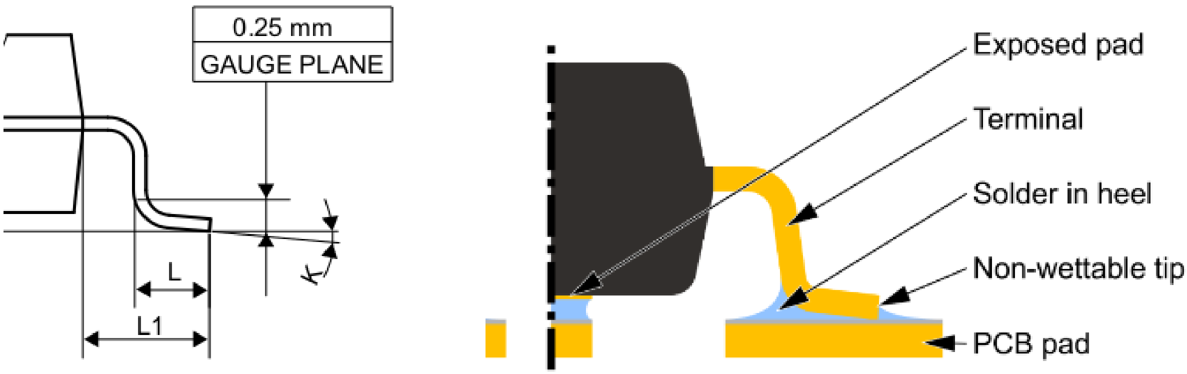
***Table IV**: Material Bulk properties of plating-metals*

[4] For thermal conductivity of various EMC with different fillers see [3]
[5] For copper alloys and its properties see [6]
[6] Interesting reference for plating thickness

2.1.2 Lead-PCB interconnection

Plating is a process involved not only in the PCB but in the IC fabrication too. The goal is to ensure solderability and additional protection from oxidation and other environmental concerns. In other words, plating serves the role to bond two un-solderable surfaces. In the PCB phase, the exposed copper (pads) is plated with electroless gold over nickel and tin. For the IC phase, the base metal of the terminals aka leads are plated either with matte tin (Sn) as a surface treatment (after the mold-process used for the encapsulation) or with nickel/palladium/gold (Ni/Pd/Au) that is pre-plated in the leadframe. So far, the PCB and the IC have solderable surfaces and the only thing left for the bonding is the soldering (process) by the assembly house using either solder paste or electrically conductive adhesive (ECA).

The "stack-up" is actually in simple terms: plated terminals (leads or pads. For this package we have leads) then the solder paste (or conductive adhesive) and then the plated exposed copper of the board.



(a) *OBC MCU Mechanical drawing*

(b) *A perfect soldering of the lead with PCB*

Now let's examine the dimensions of these gullwing[7] leads.The range of values for the depicted L parameter based on the OBC MCU is 0,45 - 0,750 mm and the typical values is 0,6 mm. As we can see from the figures the exact contact area is a little bit unclear. The solder paste is applied to the whole surface of the PCB pad (this is valid from the .bxl files from ST Microelectronics in which there is metadata for the solder paste layer) and only the L part of the lead is attached to the solder. But all together are electrical and thermal conductive. So we can assume as contact area the PCB pad? In other words the contact area is the L * (width of the lead, that is typically 0.220 mm) or the soldered PCB pad (1.35 * 0.35 mm). It is worthy mentioning also that leadframe based packages don't ususally touch the surface of the PCB due to the **standoff** height. The value for this according to the mechanical drawing by the datasheet can range from 0.050 - 0.150

In order to determine the thickness of the solder paste we need to know the stencil design. A typical value will be 130um.

[7]The J shaped leads are the so called gullwing leads

2.1.3 Soldering

For the bonding of two metal surfaces there are two main methods 1) **electrical conductive adhesive** and 2) **solder paste** (solder with flux according to wikipedia).

Conductive adhesives are a composite of thermosetting epoxy adhesive resin and conductive metal (or metal-coated) particles, such as silver, nickel, gold, copper and indium or tin oxides. On the other hand, the solder is a metal alloy and can be divided to the solder with lead (tin-lead, SnPb) and the lead-free. For the first one the most common is the 63Sn37Pb but due to environmental and health concerns, lead usage is prohibited by regulations (RoHS, REACH) so manufacturers are tending to avoiding it. Tin (Sn) and tin-silver-copper (SnAgCu) belong to the lead-free group. In terms of thermal performance, thermal conductivity is higher in solders (60-65 W/mK) than adhesives (3-25 W/mK)[15].

The assembly provider of the in-house AcubeSAT's PCBs is Prisma Electronics. It is unclear which of these two methods in the FM models will be used so clarifications should be requested. Nevertheless if we know the type then we can retrieve thermal data from [13], [31], [7]

2.1.4 Closing

If you have stayed until the end of this package analysis you will realized that the die anatomy and what is inside of the black box is a little bit complex form a thermal point of view because there is a variety of materials that can be used and many surfaces are touching each other with different physical (thickness, size) and thermal characteristics. For the rest of the packages we will not approach them with the same detail. We will make an overview and if more accurate thermal data is required for the packaging, further research will be done!

2.2 TSOP

Another package that is included in the group of packages used in the AcubeSAT's boards is the thin small outline package (TSOP). All the memory modules belong to this category (OBDH MRAM, ADCS SRAM, SU SRAM, SU NAND). This type of package has the leadframe-style too and the mechanical dimensions of the gullwing leads for OBDH, ADCS and SRAM are the same with the previous LQFP and for the SU NAND, the range is 0.4-0.6 with typical 0.5 mm.

For each one of the memory modules the material declaration is not included in the docs, so we don't know: 1) the terminal plating, 2) base material for the leads. Specifically for OBDH MRAM, from a product change notification about the molding compound used, we can see the code-name "**Sumitomo G631H**" that is the same in the material declaration of the ST's LQFP packages. So for the Everspin's MRAM we can safely assume that the encapsulation characteristics are the same with the LQFP. For the terminals plating we can assume again that the base material is copper or a copper alloy (or iron[8] based) with tin or nickel over gold plating. For clarification, we should

[8] The material declaration[1] for another TSOP product by Alliance indicates leadframe is iron-based

contact the vendor.

About the NAND memory module, according to the user guide, the leadframe is plated with the usual matte tin or Ni/Pd/Au and the thickness is specified, but it isn't clarified which one of these is used in our particular module. The thickness though is a valuable info (for the standardized world of electronics) and we can use it as a general reference for plating leadframe thickness too.

- Nickel 0.5 um to 1.2 um
- Gold 0.003 to 0.012 um
- Palladium 0.03 um to 0.11 um

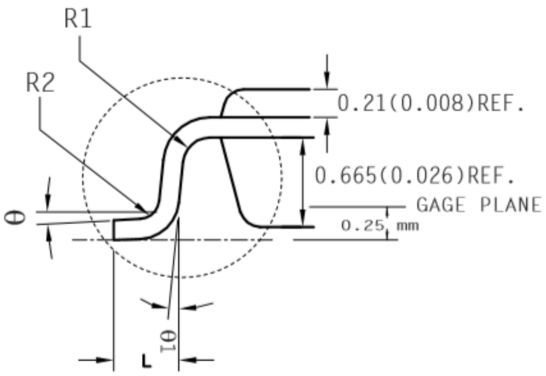
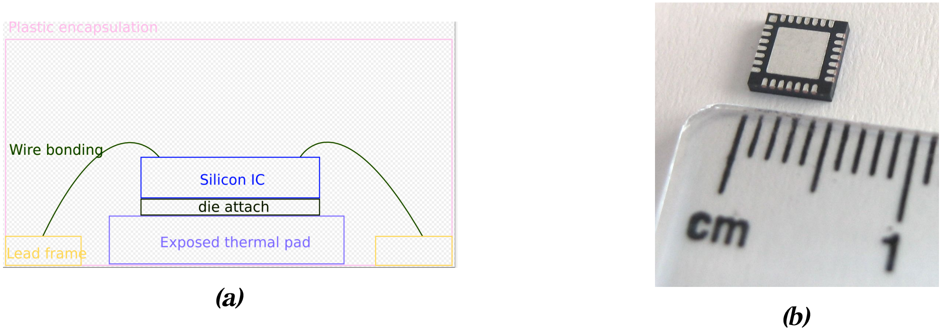


***Figure 6**: Gullwing leads for the TSOP2 package by MRAM technical note*

2.3 QFN

Quad Flat No-leads (QFN) package is used for the COMMS AT86RF215 UHF TX-RX. It belongs in the leadless family and includes an exposed thermal pad for heat dissipation (it is recommended to use vias). Usually the package is plastic and the leadframe copper but the material declaration is missing for this specific component.

It should be emphasized that although there are no leads, according to the datasheet the standoff height range is 0 - 0.05mm (typical 0.02mm).



(a) *(b)*

***Figure 7**: QFN*

2.4 SOIC

A Small Outline Integrated Circuit (SOIC) is the package of the EPS TPS54339EDDA. It has 8 pins with an exposed pad. The Material content is listed in the documentation. It uses a similar leadframe Copper-Iron based with the LQFP, the plating is tin (Sn) and for the encapsulation, a typical epoxy mold compound is used (epoxy resin + fused silica).

2.5 Custom package by Analog

The ADCS Gyro is consisted of two parts. The ADXRS453BEYZ for the z axis and the ADXRS453BRGZ for the pitch and roll. The first one is a low-cost SOIC package but the second one is different with what we have encountered so far. It is a custom leadless "innovative vertical mount package (VMP)", as Analog Devices states, with ceramic materials. It has two terminals. One in the bottom and one in the back. But as Analog Devices claims only the bottom should be used, the other is for internal evaluation purposes.

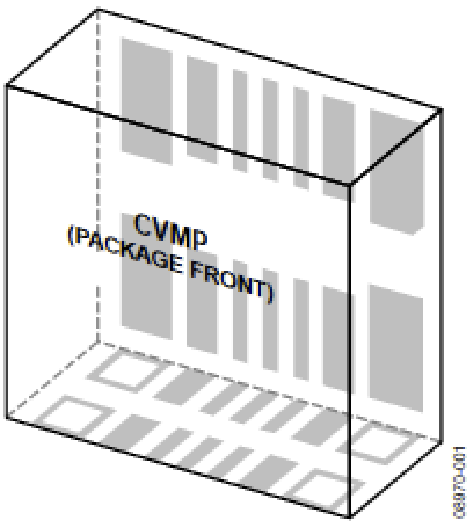


***Figure 8**: Vertical Mount Package*

According to the material declaration, the substrate is aluminum-oxide based, a common ceramic solution and the metal lid iron/nickel. The plating is gold/nickel. The ceramic base will have better thermal performance than the rest of the epoxy mold compounds. So for this package a different model approach may be required. But it should be noted that what is referred exactly as lid and base in terms of dimensions is unclear.

2.6 LGA

The Land Grid Array (LGA) is an advanced packing method and this is for the COMMS RFFM6406 UHF TX-RX. It is leadless and it has an exposed thermal pad. Material declaration is missing. We can assume for now that it is plastic based (so we can use LQFP thermal properties as reference), because according to NXP's application note, the LGA in the construction is identical with the PBGA except the solder balls.

About plating: "The LGA pad uses the same 0.1 um to 0.9 um of electroless gold plating over electroless nickel as has been used reliably for many years in the traditional BGA configuration" [12]

2.7 Thermal characteristics

Until now we have investigated the anatomy and the materials of some IC packages along with its properties. But in the thermal modeling aspect, in order for the supplier to give to the users an overview of the thermal performance, a standardized approach is usually followed. Under the section "Thermal characteristics" or "Thermal metrics" there is some data that can be used to evaluate the junction temperature. This data is produced by thermal simulations with defined by the standards conditions and test boards.

The so called **theta** values are the indicators of this performance and some of them, using the resistor model, are defined as the thermal resistance between 1) die and ambient, 2) die and case, 3) case and ambient.

But most of the times, these theta values are not constant and not applicable for every experimental case. According to the ST thermal management document, this data is used for an early assessment and not for a detailed approach. But the questions still remains: Can you use these thermal metrics to your analysis/simulation?

Another usage of this data is to compare the thermal performance of different components. This is only accurate though if all the the values are based on the same standard. For the JESD51-12.01, the document that describes how to make use of the thermal data can be found in the official site and it can be downloaded it for free.

For more information I strongly suggest the TI application note and the NXP's.

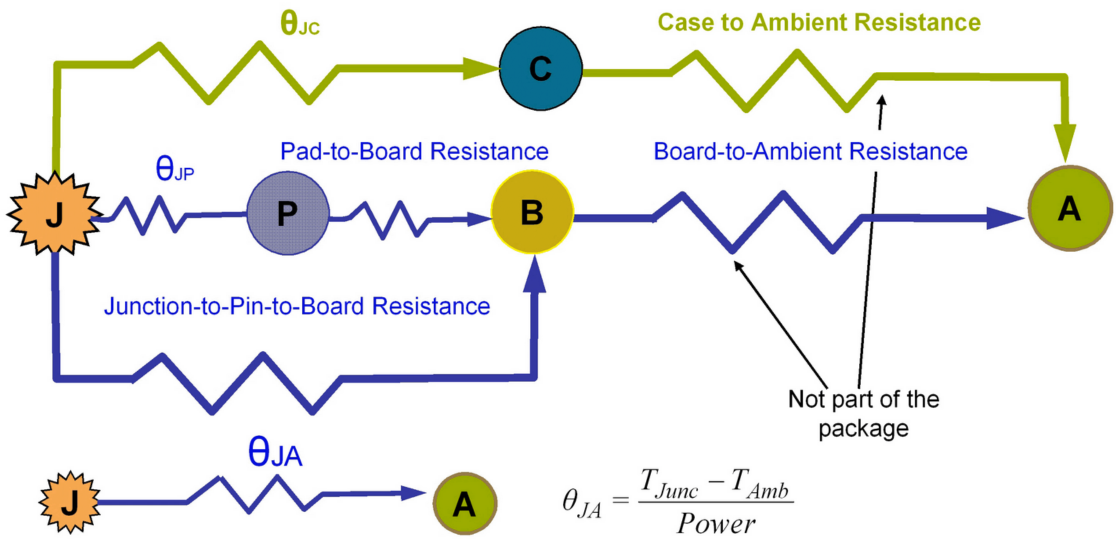


***Figure 9**: A resistor model of an IC package thermal analysis*

3 PCB

In the "Buildup" section, when ordering from Eurocircuits, there are many options for the thickness of the core FR4 and the copper foils.

Approximate thickness values for a typical 4 layer board 1.55[9] mm:

- FR4: 1,4 mm
- Copper: 0,15 mm
- Soldermask: 35 - 40 microns
- Surface treatment: 20 - 25 microns
- Conformal coating: -

[9] In the board thickness only the copper and the dielectric is taken into account

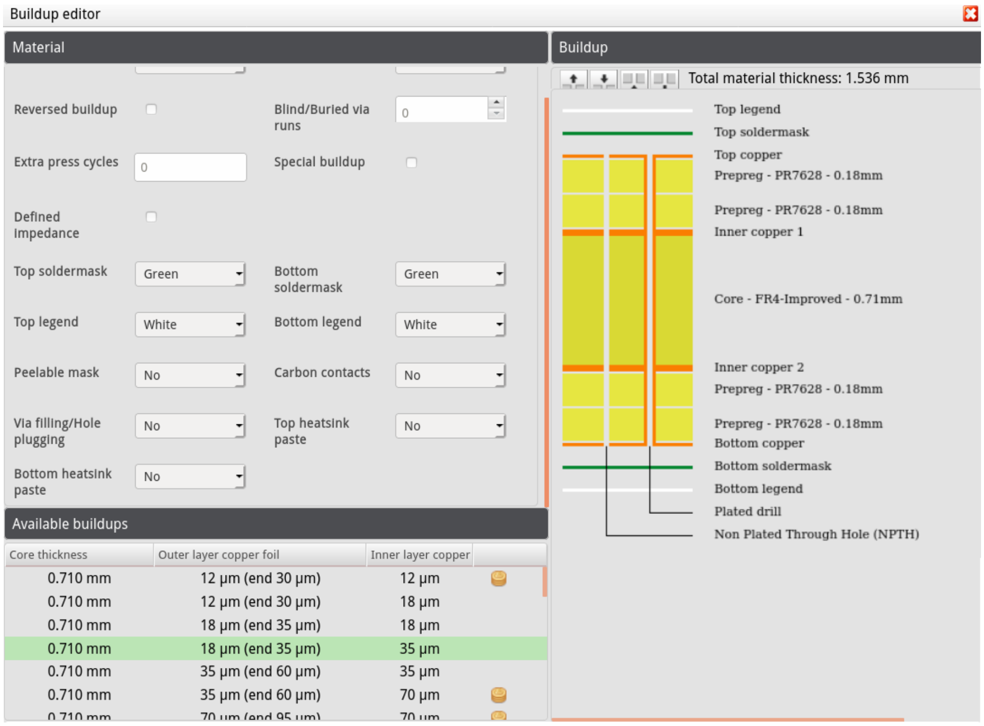


Figure 10: *A typical 4-layer board ordered from Eurocircuits*

3.1 FR4

IS400 is the standard FR4 substrate that Eurocircuits is using. Other FR4 options are also available for different applications. In general FR4 in contrast with others more expensive ceramic substrates based on aluminum and silicon has a low thermal conductivity. So if there are thremal issues, FR4 replacement is also a choice. Usually ceramic substrate thermal conductivity (typically 10 W/mK) can be 10 or even 100 times greater than FR4 (typically 0,3 W/mK) [4, 10]

3.1.1 Documentation

- All files.
- Material declaration
- Datasheet

3.1.2 Thermal properties

Thermal conductivity (W/mK)[a]	0,36
Heat capacity (J/kg*K) [b]	1000
Emissivity [c]	0,9

[a]Reference for the thermo-optical properties Datasheet
[b]References for the thermo-optical properties Figure 14
[c]References for the thermo-optical properties Figure 25

Absorptivity [a]	0,49

[a]References for the thermo-optical properties Figure 25

Issue: The thermal properties emissivity, absorptivity and heat capacity are missing from the datasheet. Alternatively, estimations can be made from other abstract resources (e.g. makeitfrom, wikipedia, handbooks, other applications notes from manufacturers, engineering toolbox).

3.2 Copper

Detailed data about the Eurocircuit's copper foil is missing from their documents. The only information available is the thickness and the overall process of the fabrication. So we could probably assume that the thermal properties will be the same with the well-known pure copper.

Thermal conductivity (W/mK)	401 [32] 20 [19] 392 [26]
Heat capacity (J/kgK)	0,385 [34]
Emissivity	0,87 oxidized [33] 0,8 [19] 0,8 coil tape [11] 0,55 foil tape, tarnished [18] 0,31 beryllium [18] 0,04 polished [33] 0,03 electroplated [19] 0,3 buffed [18]
Absorptivity	0,04 foil tape, tarnished [18] 0,03 buffed [18] 0,31 beryllium [18]

4 Lessons learned

In the beginning of the research, the thinking path about finding materials was oriented to search for each manufacturer the "material declaration" document. Knowing the materials, we will be able to find its thermal properties. But for each part of the component we are interested (e.g. encapsulation) a mixture of materials is used. Thus we assume that we need to focus on the material with the highest concentration. Later for optimization we could find the thermal properties of all them along with a formula to calculate the overall performance. This approach may be not be valid and probably should be avoided. The primary reason is that this concept is error-prone and add significant load, trying to demystify the thermal properties of each material and for each component, lacking at the same time the resources to find reliable data. A more abstract way of thinking is may required. So as it is mentioned before, in the IC packaging, a process which several chemical compounds are involved, we can safely assume the general model of an epoxy mold compound for the plastic packages. The same homogenous approach applies for the FR4 too, but fortunately we were able to find experimental data for our case provided by the supplier.

When approaching the material properties of a mixture of materials, there are many chances that what you are looking for has some kind of a code-name, a specific composition. These are common alloys and it would be helpful to identify it by checking the composition from the material doc.

4.1 Modeling

In some case we find modeling the PCB as an homogenous material and it is worthy mentioning them:

"Printed circuit boards (PCBs) are complex structures usually made up of layers of copper and glass fiber reinforced (fiberglass) epoxy resin, making them difficult to model directly. The layered structure and sharp difference in thermal conductivity between materials leads to highly anisotropic thermal conductivities. Since actually modeling each layer at such small scales and in such detail requires a lot of computational effort and time, the typical practice is to treat the circuit board as a homogenous material and use an effective thermal conductivity" [25]

Material	Absorptivity (α)	Emissivity (ε)	Conductivity [W/mK]	Specific Heat [J/kg/K]
Printed Circuit Board - 4.6% Cu by Volume[14]	0.81	0.9	18.04	1544.11
Solar Cell - Germanium[15]	0.92	0.85	60.6	324
Fiberglass Polyimide[16]	0.75	0.89	0.26	1080
Stainless Steel 316[17]	0.47	0.14	163	420
Stainless Steel 316L[16]	0.47	0.14	163	420
Stainless Steel 17-4 PH[16]	0.47	0.14	180	384
Black Anodized Aluminum[16]	0.65	0.82	121.2	768
7075-T73511 Aluminum[16]	0.27	0.76	121.2	801
7075 Aluminum[16]	0.16	0.3	121.2	801
6061-T6 Anodized Aluminum[18]	0.14	0.76	237	921.096
5052 Aluminum[16]	0.16	0.3	138.5	768
5052-H32 Aluminum[16]	0.65	0.82	138.5	768
Top Panel Portion 5052 Alum. Honeycomb Core[19]	0.16	0.3	172.4718947	768
Bottom Panel Portion 5052 Alum. Honeycomb Core[18]	0.16	0.3	82.40977903	768

***Figure 11**: Material properties table [16, p.115]*

A list of concerns:

- "An especially intriguing problem shows up when printed circuit boards are part of the analysis. The values for the thermal conductivities of PCB's cited in literature are mostly conductivities of the epoxy in the direction normal to the PCB. However,these values are useless in practice because the thermal conductivity of the reinforced epoxy can behighly anisotropicvthe in-plane thermal conductivity is much more important from a practical point of viewvthe very complex patterns of metal tracks and layers will considerably influence the thermal conduction behavior" [22]

- ”Regarding the material properties it was found that small changes, e.g. adding a layer of copper to the circuit board, can significantly decrease the resulting temperatures. This is due to the improved in-plane conductivity, as copper has an unequally higher conductivity than FR4(Cu=394W/mK compared to FR4=0.3W/mK).”
- "While the temperature changes significantly, the overall pattern of the heat distribution remains relatively unchanged. The largest change is the difference between the highest and lowest temperatures, which grows from 6 K to 52 K between $\epsilon = 0.02$ and $\epsilon = 0.82$. Overall, it is clear that emissivity plays a very significant role in the spacecraft temperature. This was expected, since radiation as a mode of heat transfer is far more important in the near vacuum of space, and is the only mode by which heat can be transferred away from the satellite." [25]
- "Because a satellite in orbit is surrounded by the vacuum of space, its only thermal interaction with its environment is through radiation" [30]. "The aluminum external surface is the only **external** part which can be used to control the temperature by modifying the optical properties of the material (with an adequate surface treatment); indeed, the optical properties of the solar cells and of the PCB that are mounted to them cannot be modified" [24].
  Also in the TIGRIsat’s simulations , when they didn’t take into account the surface treatment of the aluminum structure/rails, the temperature had exceed the maximum one. The reason behind this was the big difference between aluminum’s absorptivity (0,379) and emissivity (0,08) due to the aforementioned assumption that there wasn’t any surface treatment [24]. Based on that, the input data of "critical" components should be investigated thoroughly and the change of thermal-optical properties can be also part of the strategy.

4.2 Uncertainty and thermal properties

Many thermal properties can be indexed. This is true. But most of the times, conflicts will emerge. There is a variety of values referred to the same material and input thermal data is also a part of the engineering process. Assumptions and estimations are common and they are function of the general modeling approach. Do I need this property, can I model it with another way, how uncertain is this thermal data, is this material oxidized or even if it isn’t can I benefit assuming that it is?

- "... models of the electrical and electronic components has been created, despite the **difficulty** of determining their thermal and optical properties." [24], "Indeed, the **actual** structure of TIGRIsat is anodized but the actual value of α and ϵ are **unknown**" [24]
- "Often information for properties of individual material is **unavailable** and, where possible, in-house testing using an emissometer should be performed to acquire it." [23]
- "However, there may be quite a few uncertain or inaccurate input parameters existing in the thermal mathematical model (TTM), which may affect the analysis accuracy, including thermal contact resistance between contacting parts, unit

thermal properties (such as thermal capacitance, thermal conductivity, infrared emissivity, and solar absorptivity), unit power dissipation,etc. Therefore,a thermal balance test is essential to verify the basic thermal design and to assure that the TMM is reliable for the temperature prediction because the input parameters are proved to be valid" [28]
- About the accuracy of experimental and numerical thermal analysis of electronic systems: "The final conclusion is inevitable: the situation when all computations at the system level can be used for accurate temperature prediction is still a long way off" [22]

With all of that being said we can understand that we can't trust the thermal data. Experimental data for each application along with tests is a necessary part of the design-cycle. In prototypes, thermocouples and infrared cameras can be used in the same way that oscilloscopes are being used for the electrical domain.

5 Databases

- Glenn R Blackwell.The electronic packaging handbook. CRC Press, 2017
- Safa Kasap and Peter Capper.Springer handbook of electronic and photonic materials.Springer, 2017
- Rao R Tummala et al. Fundamentals of microsystems packaging. 2001
- R.P. Chhabra.CRC Handbook of Thermal Engineering. Mechanical and AerospaceEngineering Series. CRC Press
- M. Pecht, R. Agarwal, F.P. McCluskey, T.J. Dishongh, S. Javadpour, and R. Mahajan.Electronic Packaging Materials and Their Properties. Electronic Packaging. Taylor Francis
- D.G. Gilmore and M. Donabedian.Spacecraft Thermal Control Handbook: FundamentalTechnologies. Spacecraft Thermal Control Handbook. Aerospace Press
- https://theengineeringmindset.com/specific-heat-capacity-of-materials/
- makeitfrom.com. A general online database for various materials. Mined from Wikipedia references
- The Engineering Toolbox. This reference is used quite a lot.
- Table of Total Emissivity
- Table of absorptivity and emissivity of common materials and coatings
- Thermal Properties of Plastic Materials
- Emissivity Values for Common Materials
- CINDAS LLC. This is an interesting database. There are thermal properties even for very specific mold compounds types like "Sumitomo EME-6300HS" (just to remind you, ST is using Sumitomo type mold compounds as encapsulation) but it is proprietary.

6 List of tables

Metal	At. Wt.	Density (20°C)	Melt. Point	Lat. Ht. Fusion	Heat capacity (25°C)		Thermal Exp. coef. (20°C)	Electrical Resistivity (20°C)	$^{\#}$Thermal conductivity
		(g/cm^3)	(°C)	(kg-cal/ g.atom)	(g-cal/ g-at.K)	J/ (kg.K)	(10^{-6} K^{-1})	(10^{-6} Ω.cm)	(W/(m.K))
Aluminum	26.98	2.702	*660.46	2.6	5.817	902.1	23.03	2.62; 2.828$^{\#}$	238.
Antimony	121.76	6.684 (25° C)	*630.75	4.8	6.08	209.0	11.4	39; 39.1$^{\#}$	24.5; 23.8§
Bismuth	208.98	9.8	*271.44	2.63	6.1	122.1	13.4§	115; 119.0$^{\#}$	11.2; 9§
Chromium	51.996	7.1	1860§	3.5	5.58	449.0	8.2	2.6 (0°C)	91.3§
Copper	63.54	8.92	*1084.9	3.11	5.85	385.2	16.6	1.69	416; 397§
Gold	196.97	19.3	*1064.4	3.03	6.0	127.5	14.2	2.4; 2.44$^{\#}$	311;315.5§
Indium	114.82	7.3	*156.63	0.78	6.55	238.7	33; 24.8§	9; 8.37$^{\#}$	80.0§
Lead	207.2	11.34	*327.50	1.22	6.41	129.4	29.1	21.9; 19.8$^{\#}$	35.0
Molybdenum	95.94	10.2	*2623	6.66	5.61	244.8	4.	4.77; 5.14$^{\#}$	138.
Nickel	58.69	8.90; 8.8$^{\#}$	*1455	4.2	6.21	442.6	12.8	6.9; 7.24$^{\#}$	76.; 88.5§
Palladium	106.42	12.	*1554	4.12	6.3	247.7	11.8	10.8; 10.21$^{\#}$	75.2
Platinum	195.08	21.45	*1769	5.2	6.35	136.2	8.9	10.5; 9.83$^{\#}$	69.9; 73.4§
Silver	107.87	10.5	*961.93	2.70	6.092	236.3	18.9	1.62; 1.47$^{\#}$	417.; 425§
Tin	118.71	7.31	*231.97	1.69	6.30	222.1	20.; 23.5§	11.4; 11.5$^{\#}$	66.6; 73.2§
Tungsten	184.83	19.3	*3387	8.42	5.97	135.9	4.	5.48; 5.51$^{\#}$	169.; 174§
Zinc	65.39	7.14;7.04$^{\#}$	*419.58	1.595	5.99	383.3	33.	6; 5.75$^{\#}$	125.;119.5§

***Figure 12**: [13, p.37]*

Metals	**Ag**	**Al**	**Au**	**Bi**	**Cu**	**Ga**	**Hg**	**In**	**Pd**	**W**	**Zn**
T_D (K)	215	394	170	120	315	240	100	129	275	310	234
C_m (J/K mol)	25.6	24.36	25.41	25.5	24.5	25.8	27.68	26.8	25.97	24.45	25.44
c_s (J/K g)	0.237	0.903	0.129	0.122	0.385	0.370	0.138	0.233	0.244	0.133	0.389
κ (W/m K)	420	237	317	7.9	400	40.6	8.65	81.6	71.8	173	116
α_L (K^{-1}) $\times 10^{-6}$	19.1	23.5	14.1	13.4	17	18.3	61	24.8	11	4.5	31
Semiconductors	**Diamond**	**Si**	**Ge**	**AlAs**	**CdSe**	**GaAs**	**GaP**	**InAs**	**InP**	**ZnSe**	**ZnTe**
T_D (K)	1860	643	360	450	135	370	560	280	425	340	260
C_m (J/K mol)	6.20	20.03	23.38	43.21	53.77	47.3	31.52	66.79	46.95	51.97	49.79
c_s (J/K g)	0.540	0.713	0.322	0.424	0.281	0.327	0.313	0.352	0.322	0.360	0.258
κ (W/m K)	1000	156	60	91	4	45	77	30	68	19	18
α_L (K^{-1}) $\times 10^{-6}$	1.05	2.62	5.75	4.28	7.43	6.03	4.89	5	4.56	7.8	8.33

***Figure 13**: [21, p.428]*

Material	Density (kg/m^3)	Specific Heat (J/kg K)	Thermal Conductivity (W/mK)	Ratio
Air	1.16	1005	0.024	1
Epoxy (dielectric)	1500	1000	0.23	9.6
Epoxy (conductive)	10500	1195	0.35	14.6
Polyimide	1413	1100	0.33	13.8
FR4	1500	1000	0.30	12.5
Water	1000	4200	0.59	24.6
Thermal grease	—	—	1.10	46
Alumina	3864	834	22.0	916
Aluminum	2700	900	150	6250
Silicon	2330	770	120	5000
Copper	8800	380	390	16,250
Gold	19300	129	300	12,500
Diamond	3500	51	2000	83,330

***Figure 14**: [29, p.222]*

Ceramic	Relative Permittivity	Thermal Conductivity (W/m K)	Thermal Expansion Coefficient (ppm/°C)	Loss Tangent tan δ (10^{-4})	Elastic Modulus GPa
Al_2O_3	9.8	20	7	2	350
AlN	9	230	4.1	3–10	380
SiC	40	270	3.7	500	380
BeO	6.8	260	5.4	4–7	345
LTCC	4–7	5	3–5	2	150

Figure 15: *[29, p.718]*

Material Type	Density, *p*, g/cm^3	Thermal Conductivity, *k*, W/m–°C	Specific Heat, *cp*, W–s/g–°C	Thermal Coeff. of Expansion, β 10^{-6}/°C
Insulator Materials				
Aluminum nitride	3.25	100–270	0.8	4
Alumina 96%	3.7	30	0.85	6
Beryllia	2.86	260–300	1.02–0.12	6.5
Diamond (IIa)	3.5	2000	0.52	1
Glass–ceramics	2.5	5	0.75	4–8
Quartz (fused)	2.2	1.46	0.67–0.74	0.54
Silicon carbide	3.2	90–260	0.69–0.71	2.2
Conductor Materials				
Aluminum	2.7	230	0.91	23
Beryllium	1.85	180	1.825	12
Copper	8.93	397	0.39	16.5
Gold	19.4	317	0.13	14.2
Iron	7.86	74	0.45	11.8
Kovar	7.7	17.3	0.52	5.2
Molybdenum	10.2	146	0.25	5.2
Nickel	8.9	88	0.45	13.3
Platinum	21.45	71.4	0.134	9
Silver	10.5	428	0.234	18.9
Semiconductor Materials (lightly doped)				
GaAs	5.32	50	0.322	5.9
Silicon	2.33	150	0.714	2.6
Gases				
Air	0.00122	0.0255	1.004	3.4×10^3
Nitrogen	0.00125	0.025	1.04	10^2
Oxygen	0.00143	0.026	0.912	10^2
Liquids				
FC–72	1.68	0.058	1.045	1600
Freon	1.53	0.073	0.97	2700
Water	0.996	0.613	4.18	270

Figure 16: *[17, p.408]*

MATERIAL	Thermal Conductivity (κ) W/cm-°K	MATERIAL	Thermal Conductivity (κ) W/cm-°K
METALS		**INSULATORS**	
Silver	4.3	Diamond	20.0
Copper	4.0	AlN (Low O_2 impurity)	2.30
Gold	2.97	Silicon Carbide (SiC)	2.2
Copper Tungsten	2.48	Beryllia (BeO) (2.8 g/cc)	2.1
Aluminum	2.3	Beryllia (BeO) (1.8 g/cc)	0.6
Molybdenum	1.4	Alumina (Al_2O_3) (3.8 g/cc)	0.3
Brass	1.1	Alumina (Al_2O_3) (3.5 g/cc)	0.2
Nickel	0.92	Alumina (96%)	0.20
Solder (SnPb)	0.57	Alumina (92%)	0.18
Steel	0.5	Glass Ceramic	0.05
Lead	0.4	Thermal Greases	0.011
Stainless Steel	0.29	Silicon Dioxide (SiO_2)	0.01
Kovar	0.16	High-κ Molding Plastic	0.02
Silver Filled Epoxy	0.008	Low-κ Molding Plastic	0.005
SEMICONDUCTORS		Polyimide-Glass	0.0035
Silicon	1.5	RTV	0.0031
Germanium	0.7	Epoxy Glass (PC Board)	0.003
Gallium Arsenide	0.5	BCB	0.002
LIQUIDS		FR4	0.002
Water	0.006	Polyimide	0.002
Liquid Nitrogen (at 77°K)	0.001	Asbestos	0.001
Liquid Helium (at 2°K)	0.0001	Teflon™	0.001
Freon 113	0.0073	Glass Wool	0.0001
GASES			
Hydrogen	0.001		
Helium	0.001		
Oxygen	0.0002		
Air	0.0002		

Source: ICE, "Roadmaps of Packaging Technology" 15810A

***Figure 17**: [5, 6-14]*

Pure metals	**Nb**	**Sn**	**Fe**	**Zn**	**W**	**Al**	**Cu**	**Ag**
κ (W/mK)	53	64	80	116	173	237	400	420
Metal alloys	**Stainless steel**	**55Cu–45Ni**	**Manganin (86Cu–12Mn–2Ni)**	**70Ni–30Cu**	**1080 Steel**	**Bronze (95Cu–5Sn)**	**Brass (63Cu–37Zn)**	**Dural (95Al–4Cu–1Mg)**
κ (W/mK)	12–16	19.5	22	25	50	80	125	147
Ceramics and glasses	**Glass-borosilicate**	**Silica-fused (SiO_2)**	**S_3N_4**	**Alumina (Al_2O_3)**	**Magnesia (MgO)**	**Saphire (Al_2O_3)**	**Beryllia (BeO)**	**Diamond**
κ (W/mK)	0.75	1.5	20	30	37	37	260	1000
Polymers	**Poly-propylene**	**Polystyrene**	**PVC**	**Poly-carbonate**	**Nylon 6,6**	**Teflon**	**Polyethylene low density**	**Polyethylene high density**
κ (W/mK)	0.12	0.13	0.17	0.22	0.24	0.25	0.3	0.5

***Figure 18**: [21, p.431]*

DESCRIPTION	MATERIAL	THICKNESS (cm)	K (W/cm•°K)	THERMAL RESISTANCE (°C/W)
Chip	Silicon	0.075	1.5	0.05
Die Attach	Silver-Filled Epoxy Solder Epoxy	0.0025 0.005 0.0025	0.008 0.51 0.002	0.313 0.0098 1.25
Ceramic Package	Alumina Copper Tungsten Aluminum Nitride	0.08 0.08 0.08	0.2 2.48 2.3	0.4 0.032 0.035
Interconnect	FR4 Board Polyimide	0.25 0.005	0.002 0.002	125.0 2.5
Heat Spreader	Copper Aluminum	0.63 0.63	4.0 2.3	0.158 0.274

Source: ICE, "Roadmaps of Packaging Technology" 15811A

Figure 19: *[5, p.6-12]*

Parameter	Variable Name	Value in [Units]
Initial Solid Temperature	T0	293.15 [K]
Initial Internal Temperature	T0int	200 [K]
Temperature of Space	Tspace	100 [K]
Emissivity of Aluminum	e_al	0.02
Emissivity of FR-4	e_fr4	0.9
Emissivity of Silicon	e_si	0.6
Heat Source Power	P	0.16 [W]
Solar Flux	sflux	1370 [W/m^2]

Figure 20: *[25, p.41]*

Material	Thermal conductivity (W/m-°C)	CTE (ppm/°C)	Heat capacity (J/kg°C)	Maximum use temperature (°C)	Melting point (°C)
Ceramics					
BeO	150–300	6.3–7.5	1047–2093	-	2725
SiC	120–270	3.5–4.6	675	>1000	3100
AlN	82–320	4.3–4.7	745	>1000	2677
Si	125–148	2.33	712	-	1685
Si_3N_4	25–35	2.8–3.2	691	>1000	2173
SiO_2	1.5	0.6	-	>800	-
Al_2O_3	15–33	4.3–7.4	765	1600	2323
Quartz	43	1.0–5.5	816–1193	1140	1938
Diamond	2000–2300	1.0–1.2	509	-	N/A
Steatite	2.1–2.5	8.6–10.5	-	1000–1100	-
Fosterite	2.1–4.2	11	-	1000–1100	-
Titanate	3.3–4.2	7–10	-	-	-
Cordierite	1.3–4.0	2.5–3.0	770	1250	-
Mullite	5.0–6.7	4.0–4.2	-	-	-
Metals					
Molybdenum	138	3.0–5.5	251	-	2894
CuW (10/90)	209.3	6.0	209	-	-
Tungsten	174–177	4.5	132	-	3660
Kovar	15.5–17.0	5.87	439	-	1450

Figure 21: *Substrates [26, p.32]*

Material	Flexural strength (MPa)	Modulus of elasticity (GPa)	Poisson's ratio	Density (kg/m^3)	Knoop hardness (kg/mm^2)
Si	62	109 - 190	0.28	2330	850 – 1150
Ge	-	103	0.28	5340	750 – 780
Te	-	41.3	-	6230	-
Diamond	71.4	-	-	3510	7700
SiC	69	655	0.19	3210	2600
InP	-	-	-	4787	420 – 535
InSb	-	-	-	5775	220 – 225
AlAs	-	-	-	3810	510
AlP	-	-	-	2620	430 – 560
AlSb	-	-	-	4218	360 – 408
GaAs	150	84.95	0.31	5316	535 – 765
GaP	-	-	-	4130	950 – 964
GaSb	-	-	-	5619	450
CdS	-	-	-	4135	55
CdSe	-	-	-	5760	-
CdTe	-	-	-	6200	61
ZnS	-	-	-	4080	180
ZnSe	-	-	-	5420	138
ZnTe	-	-	-	6340	92
PbS	-	-	-	7550	-
PbSe	-	-	-	8120	-
PbTe	-	-	-	8160	-

Figure 22: *[26, p.24]*

Material	Thermal conductivity (W/m-°C)	CTE (ppm/°C)	Heat capacity (J/kg-°C)	Melting point (°C)
Si	124–148	2.3–4.7	702–712	1685
Ge	64	5.7–6.1	322–335	958–1231
Te	2.0–3.4	16.8	197	723
Diamond	2000–2300	1.0–1.2	471–509	>3823
SiC	283	4.5–4.9	670	3070
InP	67–80	4.5	-	1344
InAs	29	4.7–5.3	268	1216
InSb	16	4.7–5.0	144	808
AlAs	84	3.5	-	>1873
AlP	92	-	-	>1773
AlSb	46–60	4.2	-	1323
GaAs	44–58	5.4–5.72	322	1511
GaP	75–79	5.3	-	1738
GaSb	27–33	6.1–6.9	-	985
CdS	40.1	-	320	1750
CdSe	31.6	-	-	1512
CdTe	6	-	-	1365
ZnS	25–46	-	-	2122
ZnSe	14.0	-	-	1790
ZnTe	10.8	6.6	-	1511
PbS	2.3	-	-	1386
PbSe	1.7	-	-	1338
PbTe	2.3	-	-	1190

Figure 23: *[26, p.25]*

Alloy Group	Symbol	Nominal composition	CTE (ppm/°C)	Thermal conductivity (W/m-°C)	Electrical resistivity (μΩ-cm)	Yield bend fatigue strength* (MPa)
Cu-Fe	C19400	2.35Fe0.03P0.12Zn	17.4	260	2.54	475
	C19500	1.5Fe0.8Co 0.05P0.6Sn	16.9	200	3.44	-
	C19700	0.6Fe-0.2P 0.04Mg	-	320	2.16	450
	C19210	0.10Fe 0.034Mg	-	340	2.03	380
Cu-Zr	CCZ	0.55Cr0.25Zr	-	340	2.03	430
	EFTEC647	0.3Cr0.25Sn 0.2Zn	-	-	-	-
Cu-Ni-Si	C7025	3.0Ni0.65Si 0.15Mg	17.2	160	4.31	620
	KLF 125	3.2Ni0.7Si 1.25Sn0.3Zn	-	140	4.89	-
	C19010	1.0Ni0.2Si 0.03P	-	240	2.87	585
Cu-Sn	C50715	2.0Sn0.1Fe 0.03P	-	140	4.89	550
	C50710	2.0Sn0.2Ni 0.05P	17.8	120	5.75	450
Others	C15100	1.0Zr99.0Cu	17.6	380	1.81	380
	C15500	0.11Mg0.06P99.83Cu	-	344	1.99	-
Fe-Ni	ASTM F30 (Alloy 42)	42Ni58Fe	4.0-4.7	12	70	620
Fe-Ni-Co	ASTM F15 (Kovar)	29Ni17Co 54Fe	5.1-5.87	40	49	-

Figure 24: *[26, p.55]*

Material	Heat Capacity (J/kg-K)	Thermal Conductivity (W/m-K)	Density (g/cm^3)	Surface Emissivity	Surface Absorptivity
Aluminum 5052-H32	900[53]	138[54]	2.68[54]	0.115[55]	0.23[55]
FR4	-	-	-	0.9[56]	0.49[55]
GaAs	-	-	-	0.85[57]	0.92[57]

Figure 25: *[27, p.93]*

Material	Absorptivity	Emissivity
Optical Solar Reflectors		
Teflon, Aluminized, 0.5 mm	0.14	0.4
Teflon, Aluminized, 1 mm	0.14	0.6
Teflon, silvered, 2 mm	0.08	0.68
Teflon, silvered, 10 mm	0.09	0.88
Black Coating		
Chemglaze Z306 Black Paint	0.96	0.91
Black Z306 polyurethane paint, 3 mm	0.95	0.87
Ebanol C Black	0.97	0.73
Rough black matte, black paint	0.9	0.9
Films and Tapes		
Kapton, aluminized, 0.25 mm	0.31	0.45
Kapton, black (carbon loaded), 1 mm	0.92	0.88
Tape, 235-3M, black	0.95	0.9
Tape, aluminum	0.1	0.04
White Coatings		
Chemglaze A276 white paint	0.24	0.9
Hughson A-276 white paint	0.26	0.88
Magnesium oxide white paint	0.09	0.9
Polyurethane white paint	0.27	0.84
Other Paints		
Aluminum Paint	0.3	0.31
Chromacoat aluminum paint	0.28	0.05
Silicone aluminum paint	0.29	0.3
Metals		
Aluminum, buffed	0.16	0.03
Aluminum, polished	0.15	0.05
Beryllium copper	0.31	0.03
Copper, buffed	0.3	0.03
Copper foil tape, tarnished	0.55	0.04
Gold, electroplated	0.23	0.03
Silver, polished, unoxidized	0.04	0.02
Stainless steel	0.47	0.14
Titanium	0.4	0.55
Anodized Aluminum		
Black anodize	0.65	0.82
Chromic anodize	0.44	0.56
Clear anodize	0.27	0.76
Plain anodize	0.26	0.04

Figure 26: *[18, p.111]*

Material	Thermal Conductivity, k W/mK	Specific Heat, C_y J/gk	Density, p g/cm3	Coefficient of Thermal Expansion, CTE (ppm3)	Melting temp., K °K	Melting temp., C °C	Young's Modulus, E GPa	Yield Stress, $\sigma\gamma$ MPa	Ultimate Tensile Stress, σ_{uts} MPa	Fracture Toughness, Klc MPa.m$^{0.5}$	Fracture Energy, Glc J/m2
Silicon	140	0.714	2.32	3	1683	1410	107	—	—	0.7	3
Silicon carbide	200	0.69	3.2	4	3110	2837	450	—	—	3-3.5	23
Diamond–Type 11A	994	0.527	3.51	1.5	4000	3727	1000	—	—	—	—
Aluminum Oxide	40	0.82	3.9	8	2323	2050	380	—	—	3	20
Beryllium Oxide	240	1.1	3	8	2700	2427	380	—	—	—	—
Aluminum Nitride	180	—	—	6	—	—	200	—	—	—	—
Silica glass	5–10	—	2.5	0.7	1100	827	70	—	—	0.5	—
Fused quartz	4	—	2.2	0.5	1935	1665	94	—	—	0.5	—
Nickel	91	0.44	8.9	13	1726	1453	214	70	400	—	—
Copper	400	0.391	8.92	16.7	1356	1083	124	60	400	—	—
Aluminum	237	0.903	2.7	23	933	660	70–80	40	200	—	—
Lead	28–35	0.17	11	29	600	327	14	11	14	—	—
63Sn–37Pb solder	50			25	183	-90	15	~10	~20	—	—
Gold	—	—	19.3	14.2	1336	1063	82	40	220	—	—
Molybdenum	140	—	—	5	—	—	—	—			
Conductive Epoxy	~0.5–1	—	1.1–1.4	30	340–380	70–110	3	30–100	30–120	0.3–0.5	0.1–0.3
Polyimide	0.35	1.6	1.4	50	580–630	310–360	3–5	—	50°90	—	—
RTV	0.31	—	0.9	260	—	—	0.1	—	30	—	—
Teflon®	0.25	1	2.3	12	510–530	240–260	0.37–0.7	—	~50	—	—

Figure 27: *Metals [17, p.526]*

Alloy	Composition	Tensile strength (MPa)	Yield strength (MPa)	Shear strength (MPa)	CTE (ppm/°C)	Range Liquidus (°C)
Sn96	0.1Pb:3.6-4.4Ag:Sn	36.3–57.6	48.8	32.1	29.3	221
Sn63	62.5-63.5Sn:0.2-0.5Sb:0.015Ag:Pb	35.4–42.2	16.1	28.5	24.7	183
Sn62	62.5Sn:0.2-0.5Sb:1.75-2.2Ag:Pb	31.0–59	17.7	27.6–37.9	27.0	179
Sn60	59-61Sn:0.2-0.5Sb:0.015Ag:Pb	18.6–28.0	14.2	24.1–33	23.9	191
Sn50	49-51Sn:0.2-0.5Sb:0.015Ag:Pb	24.2	46.5	24.2		
SnIn50	50Sn:50In	11.8		11.2		117
AgIn90	10Ag:90In	11.3		11.0		141
PbIn25	75Pb:24In	37.5		24.2		226
PbIn5	95Pb:5In	29.8		22.2		
Sn10	9-11Sn:0.2Sb:1.7-2.4Ag:Pb19.7-24.3	19.7–24.3	13.9	19.3		290
Sn5	4.5-5.5Sn:0.5Sb:0.015Ag:Pb	23.2	13.3		28.7	312
Sb5	94Sn:0.2Pb:4-6Sb:0.015Sb	56.2	38.1			240
Ag1.5	0.75-1.25Sn:0.4Sb:2.3-2.7Ag:Pb	38.5	29.9	21.0		309
Ag2.5	0.25Sn:0.4Sb:2.3-2.7Ag:Pb	26.5	16.5	17.9		304
AuSn	20Sn:80Au	198		185	16.0	280
AuSi	97Au:3Si	255–304			10–12.9	
AuGe	88Au:12Ge	233		220	13.0	356
PbIn50	50Pb:50In	32.2		18.5	26.3	180

Figure 28: *Solders, [26, p.53]*

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