Basics of (PCB) Thermal Management for LED Applications

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Introduction

The reader may wonder why 'PCB' in the title is between quotes. The original objective of the paper was to lay a firm base for people who are involved in printed circuit board (PCB) design for LED applications to understand and predict the thermal behavior of their design. However, after reading the paper the basic achievement will be the notion that such a designer cannot focus on the PCB alone, she has to take into account the rest of the world too (by way of speaking of course). Hence, the paper is equally well suited to serve all designers dealing with one or more aspects of the total LED application, be it the LED itself, the thermal interfaces, the heat sinks or the luminaire.

First of all, the paper will discuss the reasons why thermal management is important, and then treat the basics of heat transfer: conduction, convection and the concept of thermal resistance. How to perform back-of-the-envelope calculations is another topic that is covered, as well as the non-trivial concept of heat spreading, required in later stages of a design phase. Before jumping to conclusions, the paper discusses thermal interface materials and the associated wrong use of thermal impedance as their characterization.

1. Why thermal management?

The first question to be addressed is why we need thermal management in the first place. As Christian Belady (formerly HP) put it eloquently in 2001:

The ultimate goal of system thermal design is not the prediction of component temperatures, but rather the reduction of thermally associated risk to the product.

Hence, if your boss asks you: "Please take care that the junction temperature does not exceed 125 °C", you may answer: "Why? Do we sell temperatures?" If you are not fired a good boss should reply: "Clever answer, but the reason is that the junction temperature is linked to three key issues that determine the quality of our LED-based products: Lifetime, Color point and Efficiency, and these features we *do* sell." Of course, the biggest problem nowadays is to find a good boss, simply because most people become boss because they fail as an engineer.

The first step in reaching the aforementioned goal is to be able to perform back-of-the-envelope calculations to get a rough idea about the feasibility of your design from a thermal point of view. What kind of knowledge do you need to enable these calculations? Determining critical temperatures is contingent upon a correct understanding of:

- Thermal conductivity k
- Heat transfer coefficient h
- The electrothermal analogue and its derivative: thermal resistance R_{th}

That's all you need for rough calculations. However, when you need more accurate answers such as in later design stages, things become much more complicated, and the best advice is to hire a thermal expert with access to dedicated computer codes.

2. Basics of heat transfer

To understand what is required for a PCB from a thermal point of view one needs to understand the meaning of thermal conduction, convection and resistance.

Thermal conductivity (W/mK)

The notion of thermal conduction is not very old. Biot (1804) and Fourier (1822) were the first to study quantitatively the heat flow through a solid piece of material. Fourier observed that the heat flow q was proportional to the temperature difference ΔT over the test piece, proportional to the cross sectional area A of the bar, and inversely proportional to the length or thickness ℓ., known as Fourier's law:

$$q = k \frac{A}{\ell} \Delta T \qquad (1)$$

The proportionality constant k is called the *thermal conductivity* in W/mK. It is a material property and a measure for the ability of a material to conduct heat. The range for engineering materials is from air (0.03W/mK), via plastics (0.2 W/mK), FR4 (0.4-1 W/mK), glass (1 W/mK), aluminium (200 W/mK) to copper (400 W/mK). Typical thermal interface material (TIM) values cover the range 0.4-4 W/mK.

Heat transfer coefficient (W/m2K)

The heat generated in an electronic device is usually transported by conduction to a heat sink or an area where the heat is transferred to a fluid, which is called convection. The fluid can be a gas such as air, or a 'real' fluid such as water. It turns out that to first order the heat that is convected away is proportional to the area A and the temperature difference between the wall and the main stream flow:

$$q = hA\Delta T \qquad\qquad (2)$$

This equation is commonly known as 'Newton's cooling law but it should be realized that it is neither a law nor derived by Newton. The famous chap did know a lot about a lot of things but unfortunately the notion of the heat flux, let alone the heat transfer coefficient, was not part of it. The proportionality coefficient h is called the *heat transfer coefficient*, in $W/m^2 K$. As a rule-of-thumb, take for natural convection h=10 $W/m^2 K$ and for fan-driven forced convection h=50 W/m^2K. It is not advised to use so-called correlations because these suggest an accuracy that is absolutely not warranted in real-life. See for more details Lasance [1].

The electrothermal analogue and the definition of the thermal resistance

The last term to discuss shortly is the *thermal resistance* which got its name thanks to the electrothermal analogue. In a DC electrical circuit, Ohm's law describes the relations between the voltages and the currents. It states that a voltage difference over a resistor causes an electrical current, which is proportional to the voltage difference: $\Delta V = I * R$.

In steady state heat transfer, a temperature difference causes a heat flow which is proportional to the temperature difference as is seen in equations (1,2). Both equations can be written in the form $\Delta T = q * R_{th}$, with R_{th} the thermal resistance (also commonly noted as R when there is no chance for misreading it as an electrical resistance). This is analogous to Ohm's law. In both the electrical and the thermal case we observe that a driving force exists (either voltage difference or temperature difference), which causes a flow (of current, or of heat) over a resistor. In more general terms, it appears that the differential equations describing current flow and heat flow are the same, hence the term *electrothermal analogue*. However, a word of caution should be issued. Differential equations alone are not sufficient, we need also initial and boundary conditions and it is here where we meet a serious problem in interpreting thermal resistances in real life.

The notion of 'thermal resistance' is deeply rooted in the vocabulary of thermal and electronic designers. Every textbook treats the fundamental analogy between electrical and thermal resistance, and most of the thermal data found in the Component Data Sheets are presented in the form of either thermal resistance from junction to case ($R_{th\ j-c}$) or junction-to-ambient ($R_{th\ j-a}$). Usually, these resistances are defined somewhere in the introduction. Of course, it is possible to define everything, and call it what you want, as long as the expressions at both sides of the equal sign have the same dimensions. There is no law that the definition should make sense from a physical point of view. And here we meet the problem. Most people are of the opinion that the definition should have a physical significance, on the grounds that an electrical resistance has certainly a physical meaning (the voltage between two points divided by the current from one point to the other), and smart professors told them that electrical and thermal differential equations are identical. Unfortunately, the conclusion ('electrical and thermal resistance are analogous') is wrong, while the proposition ('electrical and thermal differential equations are analogous') is right. Why? Mother Nature has to be blamed. Somehow, at time zero of the universe (or maybe even before that), the building stones of matter and life were arranged in such a way that what an electrical engineer calls 'insulation' is about 20 orders of magnitude away from what he calls 'conduction', while, in thermal terms, the difference between 'insulation' and 'conduction' in practice is about 3 orders of magnitude. To highlight the distinction, the thermal difference between insulation and conduction is about the difference in conduction between high-doped and low-doped Silicon in electrical terms.

A formal definition of a thermal resistance is:

The temperature difference between two isothermal surfaces divided by the heat that flows between them is the thermal resistance of the materials enclosed between the two isothermal surfaces and the heat flux tube originating and ending on the boundaries of the two isothermal surfaces (Rosten and Lasance [2]).

The essential point to understand is that a thermal resistance can never be based on measuring or calculating two *points* unless the plane is isothermal. Additionally, no heat should be lost between the two planes, see Figure *1*.
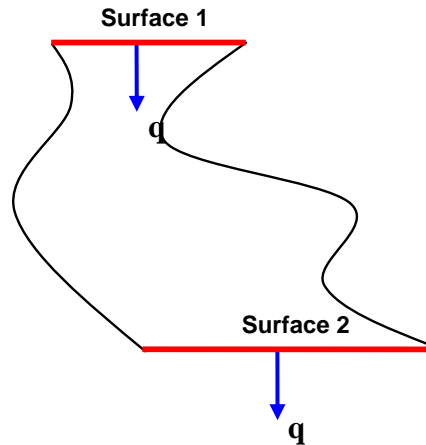
Figure 1 Two isothermal surfaces connected by a heat flux tube

Now consider at a real product.

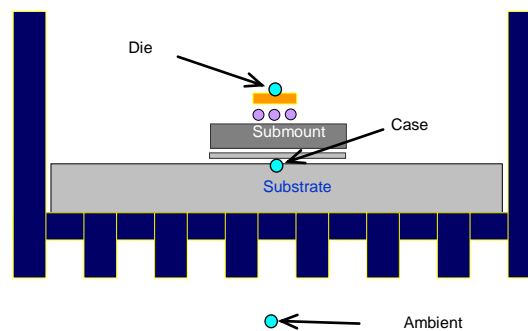Figure *2* shows the most important features of a typical LED-based product.

Figure 2 A typical LED-based product

According to the above definition, it is formally not possible to define a thermal resistance between two points, e.g. die and case. In other words, $R_{th\ die-case}$ is *only* correct provided:

- The die and case surfaces are at uniform temperature
- We know the heat flux between die and case

Regarding the first bullet point: except for high-power LEDs (e.g. > 3 W) the assumption of a uniform die temperature is correct. It is the case surface that causes severe problems because the heat spreader (or alternatively the board) cannot be a priori considered to be at uniform temperature, even not for cases where the PCB is a metal-core board. This assumption should always be checked upfront. The consequence is that the measured case temperature becomes dependent on the heat transfer coefficient *h* that describes the rate of heat transfer from the heat sink to the environment, usually including both radiation and convection.

Take the following example. For the single source case depicted at Figure 4 left a constant heat transfer coefficient h at the bottom causes a non-uniform temperature profile on this face, except in the case of h or the thermal conductivity k being infinite, or the trivial case of the source area equalling the substrate area. The average temperature could be used, but the question in practice is: how do we get this value? Usually a single thermocouple is used at the centre, but one should realise that the thermal resistance from source to thermocouple defined in this way is dependent on the boundary conditions because these determine the temperature profile over the backplane and hence influence the temperature at the location of the thermocouple. The only metric that is in accordance with the definition is the thermal resistance from source to ambient: R_{thj-a}, but this value is often useless because it includes not only the heat spreading but also the air-side part that is usually not known in practice.

The second bullet point is usually also met, but should be checked in case some heat is leaking away through the optics, either by radiation directly from the source or by conduction and convection/radiation from the top surface. However, it should be stressed that in contrast to incandescent lamps the corrections with respect to radiation are of second order.

Thermal resistances (K/W)

In general, we can write the following equation for the thermal resistance in K/W:

$$R = \frac{\Delta T}{q}$$

The thermal resistance for conduction is (see Eq. 1):

$$R = \frac{\ell}{kA}$$

The thermal resistance for convection is (see Eq. 2):

$$R = \frac{1}{hA}$$

The *unit area thermal resistance* θ (hence absolutely not *thermal impedance*, see Section 6) is equal to the ratio between thickness t and thermal conductivity k and is often used to allow for a direct comparison of the heat transfer performance of commercially available thermal interface materials (TIMs).

$$\theta = \frac{t}{k}$$

3. How to perform a back-of-an-envelope calculation

In many cases it is good practice to start by drawing a simple thermal network using the equations explained above. Figure 3 shows the basic idea. On top the most simple network: a heat source, and a thermal resistance connecting the source temperature and the ambient temperature, for example describing the convection.
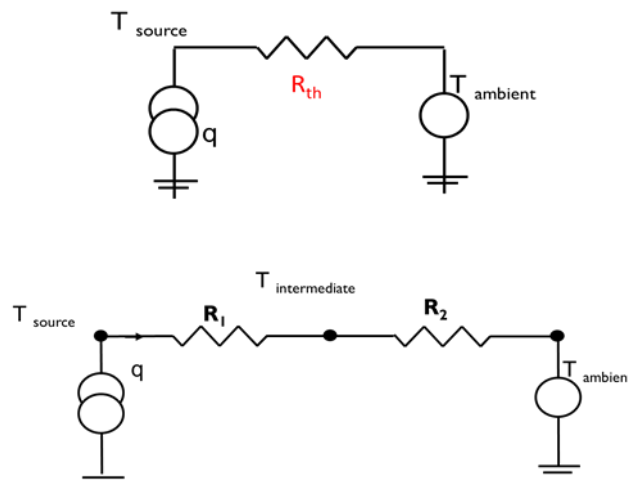

Figure 3 top: simple thermal network, bottom: two thermal resistances in series

At the bottom an often used network with two thermal resistances in series: one describing the heat flow by conduction, the second by convection. Often only the largest resistances deserve attention. ***It is the designer's job to find the largest resistance!***

It is clear that such a network can be expanded in both directions at will, adding successively more detail. In the end, there is no difference anymore between a very detailed network and a discretization method as is for example used in a Finite Volume Method.

For the series resistance network we can write for the temperature difference between source and ambient:

$$\Delta T = T_{source} - T_{ambient} = q * R_{total}$$

with: $\qquad R_{total} = R_1 + R_2$

Let's discuss a practical example. Only the philosophy is discussed here, the calculation details are covered in a Calculator available on the web [3].

Suppose the designer knows that 5W is required to realize a certain light output. Further input she got: maximum junction temperature 120 °C, maximum ambient temperature 40 °C. The chosen LED is attached to a metal core printed circuit board (MCPCB) of area 1 cm^2. How to proceed? Here are the steps to follow:

- First of all, check if the 5W can be handled by the preferred type of convection (forced or natural) and heat sink (weight, volume, size, cost). To this end, sketch a network and calculate the relevant thermal resistances.

- If it turns out that 5W is too much to handle, check which thermal resistances are dominant, then focus on them.
- If the results are not trivial (such as: no problem exists even if the data are wrong by a reasonable margin) the final step should always be a detailed analysis. Recall that often we don't talk one-dimensional heat transfer but heat spreading, which is a rather complicated issue, see Section 5.

4. The Calculator

The Calculator [3] is a spreadsheet based tool, with the following input:

- Number of LEDs
- Dimensions of LED source and PCB area
- LED thermal data from datasheets
- PCB dielectric and bulk thermal conductivity, area and thickness
- TIM thermal data between PCB and heat sink
- Area enlargement factor for heat sink
- Heat transfer coefficient to ambient air
- Maximum allowed LED and ambient temperatures
- Power dissipation

Dependent on the question, the user has a choice of options. Three examples are given below of how to estimate respectively your heat sink, convection mode and dielectric (or PCB), given a certain input.

Starting point is a given PCB area with a number of LEDs. First calculation is the area per LED. However, the user should realize that this is only valid if the dissipation of all LEDs is approximately the same. If not, you have to consult an expert.
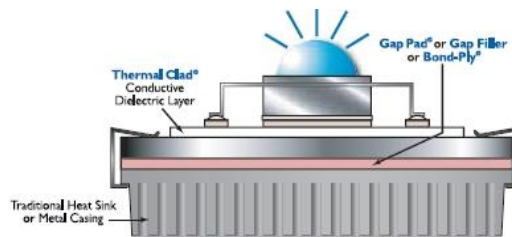
Figure 4 Layout for examples showing e.g. the dielectric layer and the TIM (in between the MCPCB)

Example 1
I need to dissipate 5W per LED for a given light output, with a prescribed LED (Luxeon Rebel in this case), a prescribed Metal Core Printed Circuit Board (MCPCB), and a prescribed thermal interface material. Per LED I have 10cm^2 PCB area.
Question: What kind of heat sink and convection mode is recommended?
Answer:
- Even with an ideal heat sink and ideal liquid cooling (R_{th} = 0) the required 5W cannot be reached.
- It is clear from the data that the LED itself is the culprit.
- In this case I need an LED with a (much) smaller thermal resistance, or I should use two LEDs.

Example 2
I need to dissipate 1 W for a given light output, with the same LED-MCPCB-TIM combination.
Question: Can I use a standard heat sink and natural convection?
Answer:
- The required heat sink thermal resistance is 63,8 K/W
- The calculated heat sink R_{th} is 5 K/W, due to the large area available.
- Reaching the goal is no problem at all, the area and/or heat sink can be made much smaller, or the power per LED can be raised significantly.

Example 3
Same as Example 2. Additionally, I want to use a cheap heat sink and no fan.
Question: What are the thermal requirements the dielectric of the MCPCB should obey?
Answer:
- The required PCB thermal resistance is 58,9 K/W.
- Suppose the thickness of the dielectric layer (the contribution of the metal part can be neglected) of the MCPCB is 0.1 mm, then it follows that a dielectric with a thermal conductivity of 0.0017 W/mK will do.
- Even cheap dielectrics have a thermal conductivity that is at least a factor of one hundred higher.

Other examples, e.g. for high-power LEDs, are also discussed in the spreadsheet examples. Based on all evidence, we may conclude the following regarding the MCPCB thermal requirements.

In the majority of the cases (say 99.9%), the thermal properties of the PCB are not important.

Hence, there is no reason to buy a MCPCB because of its better thermal performance. Of course, there may be other reasons such as CTE mismatch or breakdown voltage requirements to choose a more sophisticated PCB.

In summary, *from a thermal point of view only*, in many cases of practical interest it will turn out that the thermal performance of the PCB is relevant only for very high heat flux cases (e.g. liquid cooling) and for top-of-the-bill LEDs.

5. Heat spreading: *not* a trivial issue

As argued before, designers should know upfront if heat spreading is an issue or not. Unfortunately, no simple rules exist in order to make an early decision. Unfortunately, except for the simplest of cases, the equations describing heat spreading physics do not have an explicit mathematical solution. Hence, we have to rely on clever approximations or suitable computer codes.

The following section discusses the basics of heat spreading physics. For a more in-depth discussion the reader is pointed to Lasance [4]. A distinction is made between single source and multiple sources heat spreading.

Single source

Heat spreading is essentially area enlarging: the larger the area, the more heat can be removed at the same temperature difference (subject to certain limits). Contrary to what is believed by many designers: heat spreading is *not* a trivial issue. Consider the simple configuration shown in Figure 4. A square source with zero thickness of size A_s centrally located on a square plate of size A, thickness d and thermal conductivity k dissipates q W. The top and sides of the plate are adiabatic (insulated), the bottom 'sees' a uniform heat transfer coefficient h (W/m^{2}K).
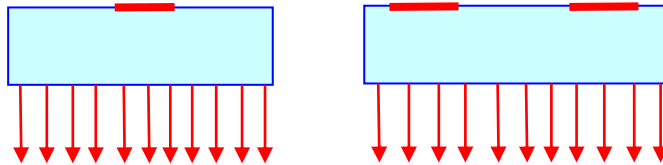

Figure 4 Heat spreading from single source (left) and two sources (right)

The remarkable thing is that even for this simple configuration no explicit solution is known for the description of heat spreading. Observing the exact *implicit* solution of the governing differential equations reveals the source of the complexity of heat spreading: it is *not* possible to separate the convection and conduction parts. In other words, changing the heat transfer coefficient changes also the value of the spreading resistance. Consequently, it is *not* possible to write the problem in terms of one conduction resistance describing the heat spreading inside the solid and one convection resistance describing the boundary condition because the two are dependent. There is one exception: the analysis becomes much more straightforward when the temperature gradients over the area that is in contact with the environment can be neglected. In other words, when a uniform temperature may be assumed. Such is often the case with relatively small heat sinks and spreaders, and when the thermal conductivity is relatively high everywhere.

A final complexity stems from the fact that decreasing the thickness of the plate does *not* automatically result in a decrease in temperature, caused by the fact that a smaller thickness also implies a decrease in spreading capability. Hence, for a certain combination of thickness and thermal conductivity given the boundary conditions and the dimensions a minimum in the total thermal resistance may be found.

Multiple sources

Multiple sources add another layer of complexity because the coupling between the sources is not only dependent on the dimensions and physical properties but also on the boundary conditions and, worst of all, on the dissipation of the sources themselves. Even the definition of thermal resistance is lost when more than one source is present, because the second condition for a correct definition, the fact that the same flux has to enter and leave the resistance, is violated. The essential point to understand is that when dealing with multiple sources the concept of thermal resistance becomes meaningless, except in the situation where the multiple sources/spreader assembly is subdivided into many resistances, for each of which the definition holds, being mathematically similar to a finite volume discretization.

How to address heat spreading

In growing order of complexity, we may distinguish the following four approaches to calculate heat spreading:

- 1D series resistance network with or without a geometrical correction factor
- Analytical solution-based approximate equations
- Software based on analytical solutions
- Conduction-only finite volume/element based codes

All four approaches are extensively discussed in ref… For the purpose of this paper the following summary is sufficient.

For situations where one is dealing with a single source, predominantly one-sided heat transfer, and one heat spreading layer, the analytical solution-based approximate equations (easy to embed in a spreadsheet) demonstrate an order of magnitude higher accuracy over the 1D series resistance network approach.

For situations where double-sided heat transfer plays a role, or multiple sources, or multiple layers, the problem becomes intractable from an approximate analytical point of view and we have to rely on computer codes. Implicit solutions are known for multi-layer cases with multiple sources and uniform boundary conditions, even when time is a parameter. User-friendly software exists that is based on these solutions [5], with the big advantage that also people with little background in heat transfer can get insight in the physics underlying heat spreading by simply changing a few parameters. An additional advantage is that no mesh generation is required. Another recommended source of information can be found on the website of the University of Waterloo [6]. One of their papers (Culham and Yovanovich [7]) contains a couple of graphics showing clearly the errors a designer may encounter by using a simple series resistance approach. However, the user should be aware of the limitations. For more practical cases for which layers consist of more than one material or for which the boundary conditions cannot be considered uniform, more advanced conduction-only codes should be used.

Figure *3* shows some cases that can and cannot be handled by the analytical software discussed in this section.
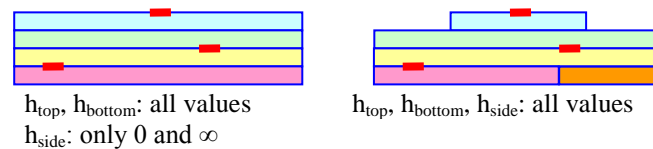

h_{top}, h_{bottom}: all values h_{top}, h_{bottom}, h_{side}: all values
h_{side}: only 0 and ∞

Figure 3 Left: cases that can be solved analytically. Right: cases that cannot be solved analytically

When one is dealing with cases that resemble the case shown in Figure 5, right, one has to rely on more sophisticated codes. In principle, all Finite Volume/Finite Element/etc. codes can be used that solve the energy equation. In practice, in most cases only user-friendly codes are recommended that enable a designer to get results in an hour or so. Some popular Computational Fluids Dynamics codes used in conduction-only mode are examples of such a code. It is recommended to validate the model in an early stage by comparing the results with those obtained analytically using the software described in this section.

In summary, the author is of the opinion that using analytical solutions, including the 1D series resistance network, in one way or another has its main merits in getting insight, hence is second to none from an educational point of view. However, when accuracy is at stake in the final design stages the recommended approach for solving real-life problems is in using a 3D conduction solver.

6. The role of TIMs in LED thermal management

The thermal budget of many LED applications consists to first-order approximation of three parts: 1) the thermal resistance of the ensemble LED-PCB, 2) the thermal interface resistance that is defined as the sum of the thermal resistance of the interface material plus both contact resistances, and 3) the convective heat transfer to the outside world, including the heat sink. The problem in a nutshell is that in high-performance applications the interface thermal resistance can easily account for 80% of the allowed total resistance.
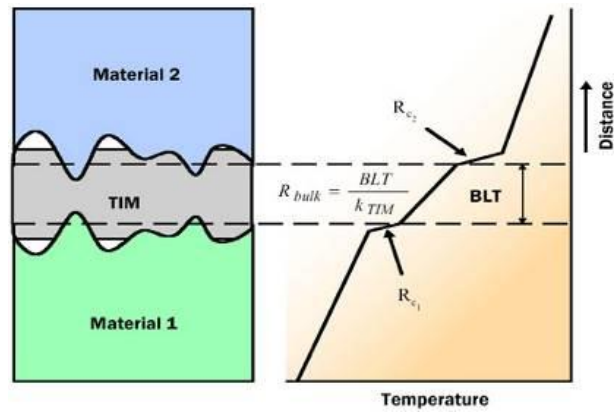
Figure 6 Sketch of interface between two materials

Figure 6 shows a TIM between two materials, and it is clear that the effective thermal resistance consists of the TIM plus two contact resistances. The effective material thickness is called the *bond line thickness* (BLT). To enable an optimal choice the thermal performance of TIMs should be known with certain accuracy. The main problem is the often unknown contact resistance. Measurements are in fact the only choice because no theory exists that predicts the value with the required accuracy despite serious progress in the science of contact resistance.

Lasance [8] and Lasance et al. [9] discuss the main problem with TIM characterization: the often significant difference between standard tests performed by TIM manufacturers and real-life tests. It is instructive to summarize the parameters that are application-specific and may influence the thermal behaviour of the TIM in the final product.

- In factory assembly applications, the inability to measure the thickness and actual TIM material quantity applied with materials such as thermal greases,
- Flatness and surface conditions of both heat sink and component,
- Pressure applied. The current ASTM D5470-01 standard prescribes a pressure of 3 MPa, far above what is used in practice (0.1 MPa) (in the next revision the standard will permit for lower pressure testing),
- Clip clamping force or screw torque,
- Clip installation,
- Time-dependent phenomena, e.g. reduction in clamping force, warpage, ageing of TIM, pump-out of silicones or other fluids or carrier constituents,
- Non-uniform surface heating,
- Thermocouple placement. The best but also most difficult method is to measure the case temperature of the package at the hottest spot,
- Presence of manufacturing machining oils, solvents, washing agents, plastic injection molding release agents, or other contaminants present on volume-manufactured components,
- Problems increase with higher thermal conductivity (the future direction), because the influence of the contact resistances becomes larger.

The conclusion is that it is very difficult or even impossible to reproduce *operational* contact resistances in a standardized test method, for the simple reason that the vendor cannot possibly know what the application will be. However, the conclusion should not be that henceforth the standard test should not be performed. After all, the vendors are responsible for the characterization of their materials, which should include information of some reproducible contact resistance. It is the responsibility of the user to address the application-specific contact resistance issue.

Reliable vendor data should be interpreted as the *minimum* value a customer can possibly acquire, given a certain pressure. It is the responsibility of the designer to estimate the operational value and judge the relative magnitude of the TIM and contact resistance contributions.

In a paper from 2005, Maguire et al. [10] did a series of tests with a high-power amplifier on an extruded heat sink and demonstrated clearly the huge differences between vendor data and field data. Greases, gap pads, PCMs and some homemade compounds were compared. The vendor data and the field tests showed differences of a factor of two. Even the ranking was different. In all cases, the vendor data underestimated the real-life interface resistance.

Thermal impedance???

It is important that all people involved use the same terminology to define the performance of TIMs. The problem is that part of the people (mostly vendors) uses the word 'thermal impedance' as shorthand for 'unit area thermal resistance'. This violates the electrothermal analogy commonly in use because of two reasons. First, in the electrical world 'electrical resistance' and 'electrical impedance' have the same unit, namely Ohm.

Consequently, 'thermal impedance' should have the dimension K/W, not K m^2/W. Second, 'electrical impedance' is a time-dependent quantity. In limiting cases, for frequency zero or large enough times approaching steady state, the impedance becomes equal to the resistance. Sticking to the current definition of 'thermal impedance' will cause a lot of confusion in the future, because the use of dynamic test methods is the obvious choice for application-specific tests, one output of which is thermal impedance. When quoting the performance of a TIM per area, we propose to use *'R-value' (*universally accepted in the building field)*, 'unit area thermal resistance'* or simply *'unit thermal resistance'*.

Conclusions

Regarding thermal management of LED applications it is demonstrated that the designer needs at least a first guess about the thermal behavior of the whole system, even if she is only responsible for a single part, such as the PCB or the heat sink. After discussing the essentials of heat transfer, a spreadsheet-based Calculator is demonstrated to facilitate the assessment of the dominant thermal resistances in a series network comprising the thermal path from junction to ambient. When accuracy of temperature prediction is required in later design stages the designer has to rely on more sophisticated tools, for example to judge if heat spreading plays a role. Finally, the important role of thermal interface materials is treated, including the reasons for the often doubtful thermal data published by the vendors, and concluded that their use of the word 'thermal impedance' should be forbidden by law.

References

[1] *Lasance C*. Sense and Nonsense of Heat Transfer Correlations Applied to Electronics Cooling, Proc. Eurosime 6, pp.8-16 (2005)

[2] *Rosten H. and Lasance C.*, "DELPHI: the Development of Libraries of Physical Models of Electronic Components for an Integrated Design Environment", in Model Generation in Electronic Design, Eds. J-M. Berge, O. Levia and J. Rouillard, Kluwer Academic Press, pp. 63-90 (1995

[3] http://www.saturnelectronics.com/thermal-transfer-calculator.htm

[4] *Lasance C*., How to Estimate Heat Spreading Effects in Practice, J. Electron. Packag., **132,** pp.   (2010)

[5] THERMAN, by Micred, Hungary

[6] http://mhtlab.uwaterloo.ca/RScalculators.html

[7] *Culham J. and Yovanovich M*.,   Factors affecting the calculation of effective conductivity in printed circuit boards, Proc. ITHERM '98, Seattle, pp.46-467 (1998)

[8] *Lasance C*. "The urgent need for widely accepted test methods for thermal interface materials", Proc. SEMITHERM XIX, March 2003, San Jose, pp.123-128.

[9] *Lasance C., Murray C., Saums D., Rencz M.,* Challenges in Thermal Interface Material Testing Proc. SEMITHERM XXII, March 2006, San Jose

[10] *Maguire L, Behnia M., Morrison G*., Systematic Evaluation of Thermal Interface Materials - Case Study in High Power Amplifier Design, Microelectronics Reliability vol.45, pp.711-725, 2005

MCPCBs for LED Applications

Thermal Management Based Material Specifications

- Yash Sutariya
  - V.P. Saturn Electronics Corporation (www.saturnelectronics.com) Rigid PCB Manufacturer
  - President/Owner Saturn Flex Systems (www.saturnflex.com) Flex & Rigid-Flex PCB Manufacturer
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Purpose

Defining your needs

To break down your needs for thermal management materials, specifically metal core printed circuit board (MCPCB), in LED Applications by *technical requirements* in order to make more effective callouts.

Controlling the process

The end result should be shorter lead times, lower cost, and more reliable product.
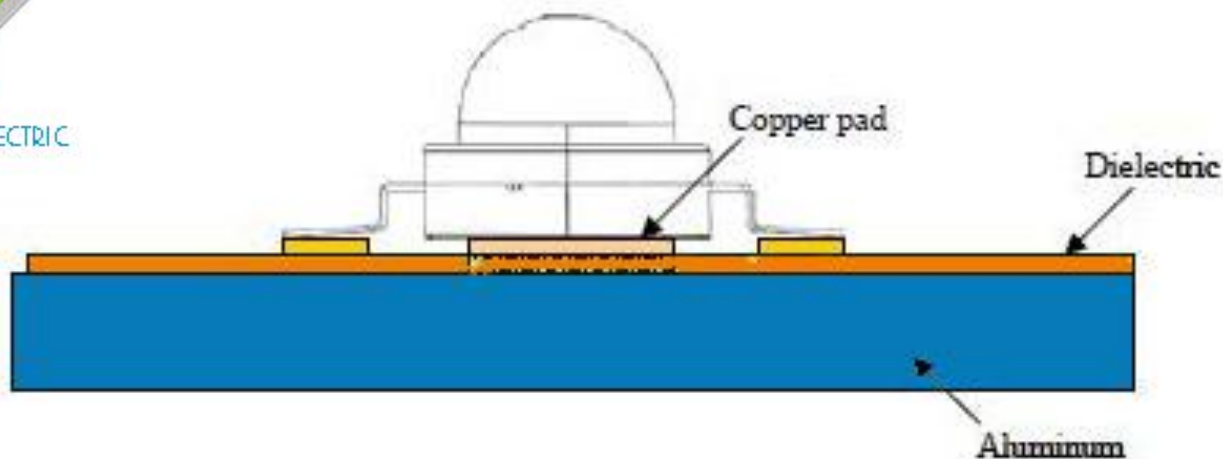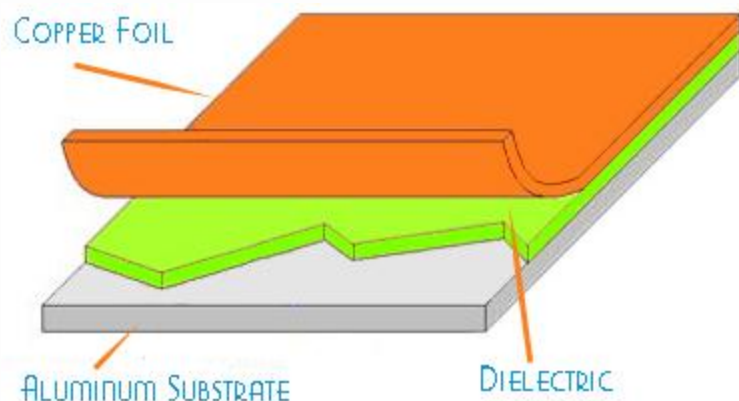
Non-browning soldermasks

Introduce new non-browning white LED soldermasks.
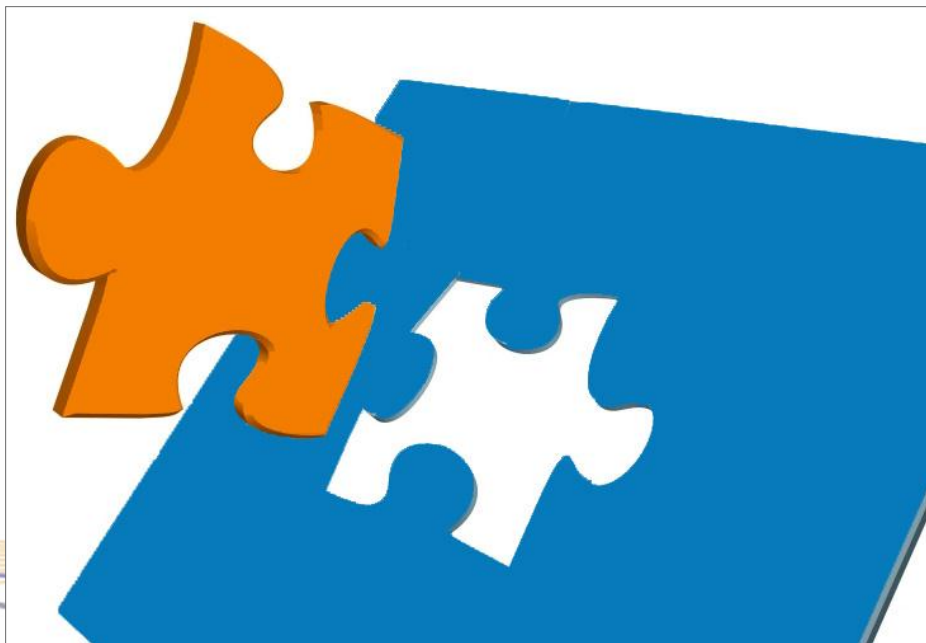
Metal Core Boards

Definition

The MCPCB commonly consists of a metal core layer (typically aluminum or copper), a continuous dielectric layer and a copper circuit layer.

Survey Question

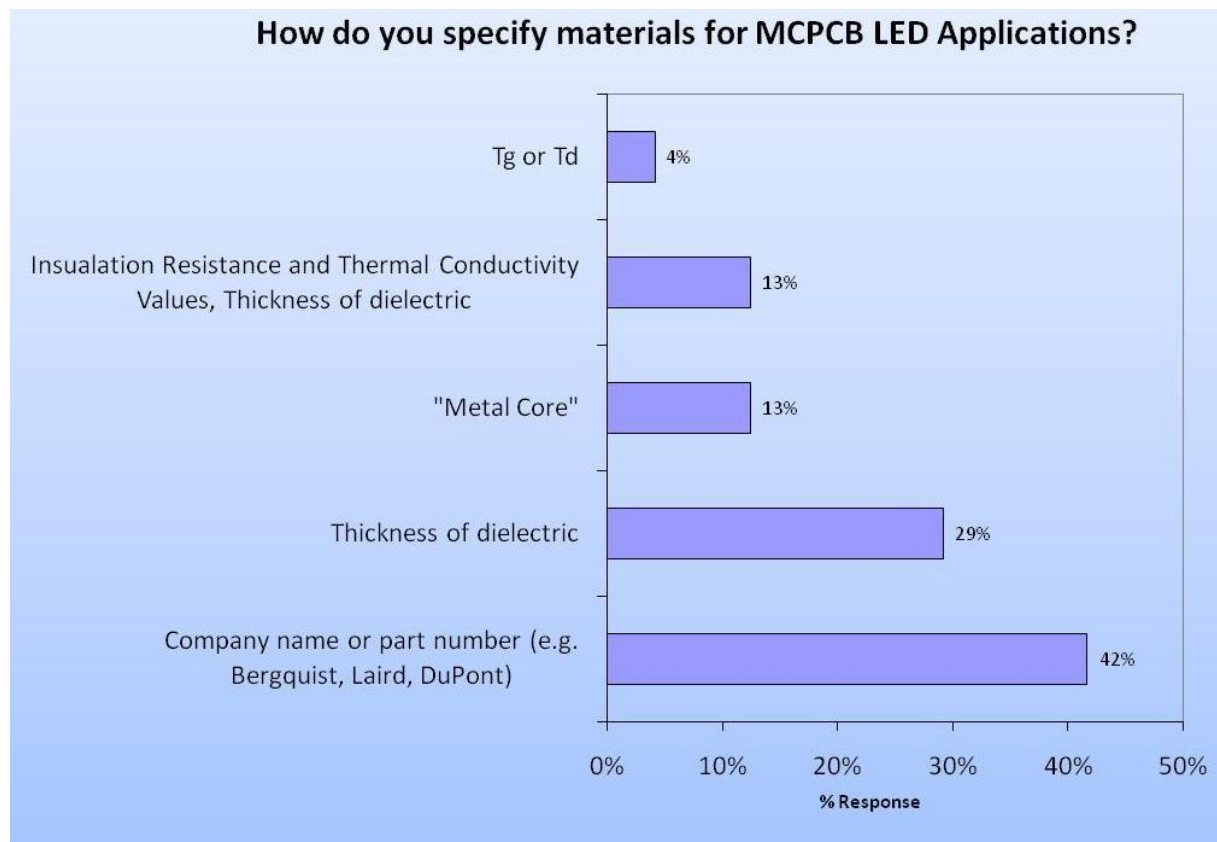**How do you specify materials in MCPCB LED applications?**
a) Company Name and/or Part Number (e.g. Bergquist, Laird, DuPont, etc.)
b) Thickness of dielectric
c) T_g or T_d
d) "Metal Core"
e) Insulation Resistance & Thermal Conductivity Values

Survey Results

of respondants = 120

How do you specify materials for MCPCB LED Applications?

Category	% Response
Tg or Td	4%
Insualation Resistance and Thermal Conductivity Values, Thickness of dielectric	13%
"Metal Core"	13%
Thickness of dielectric	29%
Company name or part number (e.g. Bergquist, Laird, DuPont)	42%

% Response

Survey Answer

How do you specify materials in metal core LED applications?

a) Company Name and/or Part Number (e.g. Bergquist, Laird, DuPont, etc.)

Comment
Specifying by brand name locks you into a particular product produced by a particular manufacturer.

Risks Include:
• Locked into pricing
• Subject to lead times
• Preventing new materials from being used on your product

Survey Answer

How do you specify materials in metal core LED applications?

    b)   Thickness of dielectric,
    c)   Tg,
    d)   Td

Specifying only these items may not fully address your needs.
- Does not address thermal conductivity
- Does not address electrical insulation resistance
- Does not address type of dielectric

Answer

> **How do you specify materials in metal core LED applications?**
>
> e) "Metal Core"

Comment:
Specifying "metal core" does address anything whatsoever.

Answer

How do you specify materials in metal core LED applications?

    f)   Insulation Resistance & Thermal Conductivity Values

Comment:

You are a rock star! This is the whole point of our presentation.

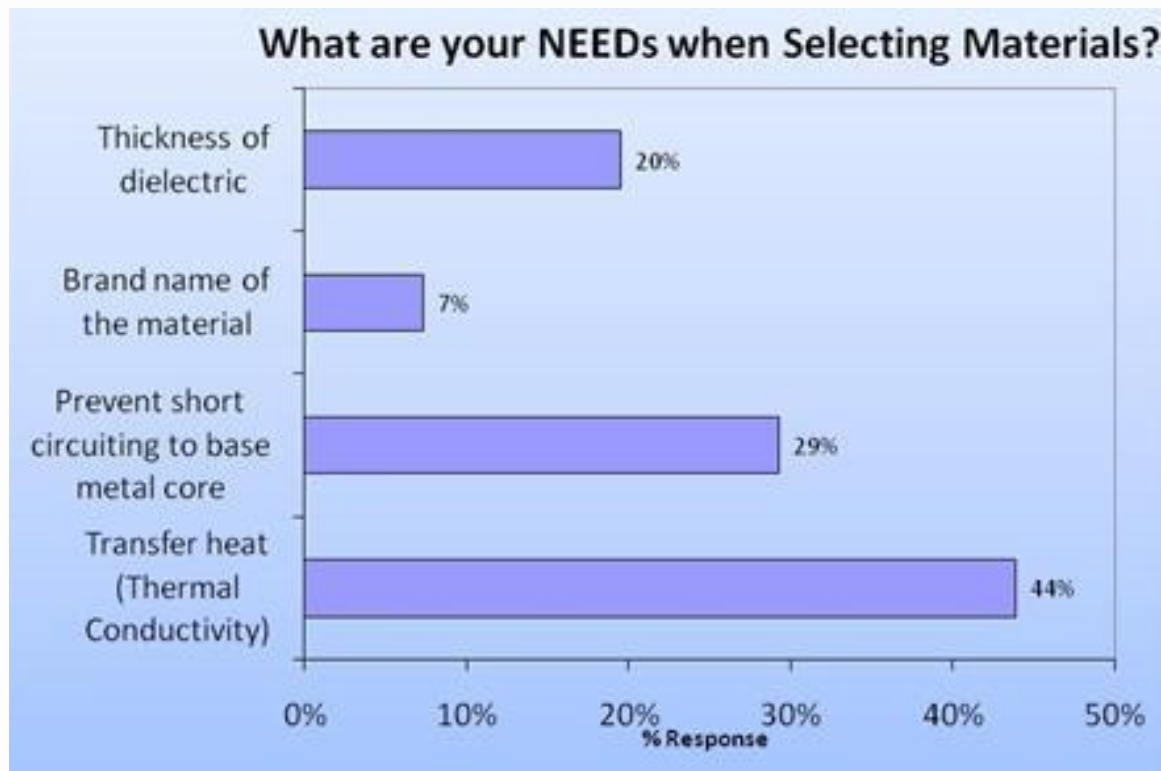Consider *your needs* when bringing the bare board into the equation

Survey Question

What Are Your Needs When Selecting Materials? (Choose all that apply)
a) Transfer heat (Thermal Conductivity)
b) Prevent short circuiting to base metal core (Electrical Insulation Resistance)
c) Thickness of dielectric
d) Brand name of the material?

Survey Results

# of respondants = 120

Cost Drivers For MCPCBs

Dielectric Substrate

The # 1 cost component of the MCPCB is the dielectric substrate between the copper traces and the metal heatsink / core.

Definition

An electrically insulating medium which occupies the region between two conductors.   In this case, the copper circuits and the metal core heat sink.

Copper Foil

Aluminum Substrate

Dielctric substrate between copper traces and metal core / heatsink
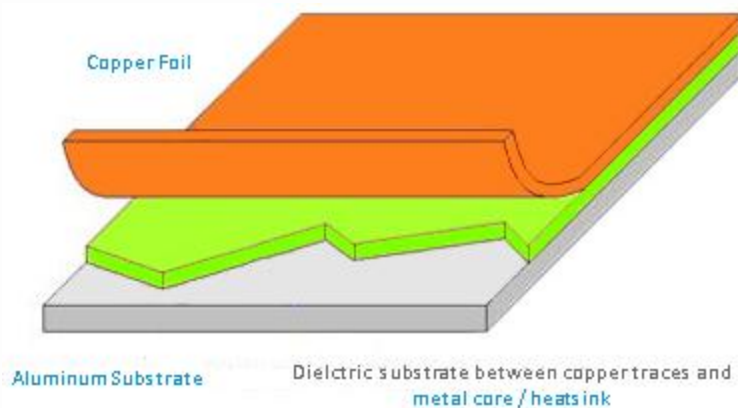
Cost Drivers For MCPCBs (cont.)

Introducing competition

The most effective way to reduce cost of dielectric is to introduce competition:

- ❑ Laird
- ❑ Bergquist
- ❑ Dupont
- ❑ Uniplus
- ❑ Iteq
- ❑ Insulectro
- ❑ Plus future innovators

Definition and Applications

Thermal Transfer

Product Application

Electrical Insulation

Product Reliability

Purpose #1

Transfer Heat

Common Callouts include Thermal Impedance or (Unit Area) Thermal Resistance (°C in^2/W,) and Thermal Conductivity (W/m-K).

Notes:

- The use of 'Thermal Impedance' is not recommended, will be discussed later
- The use of °C in^2/W is not recommended, preferred is K-m^2/W, in line with W/m-K

Thermal Management for LED Applications

What is the role of the PCB?

Presented by Clemens Lasance

Clemens is a former Principal Scientist Emeritus with Philips Research, the Netherlands, with a 30 year + focus on thermal management of electronic systems.

He is now a consultant for *Somelikeit Cool*, contact info: lasance@onsnet.nu

Motivation

Providing the right information the first time

The goal is to provide the LED application engineer with the right information to select the most optimal MCPCB from a ***thermal*** point of view. Thus, ensuring the best decision is made for a specific application in regards to thermal performance and cost.

Main Goal of Thermal Management

The Calculation of application-specific junction temperatures

Reasons / Key Issues

- Lifetime
- Color point
- Efficiency

All these key issues are significantly dependent on the junction temperature.

Basics of Heat Transfer

Fundamentals of Critical Temperature Calculation

Determining critical temperatures is contingent on a critical understanding of:

- The electrothermal analogue
- Thermal conductivity k
- Heat transfer coefficient h
- Thermal resistance R_{th}

Electro-Thermal Analogue

$$\Delta T = q * R_{th} \qquad \rightarrow \qquad \Delta V = I * R$$

Temperature drop (°C) $\rightarrow$ Voltage drop (V)

Power dissipation (W) $\rightarrow$ Current (A)

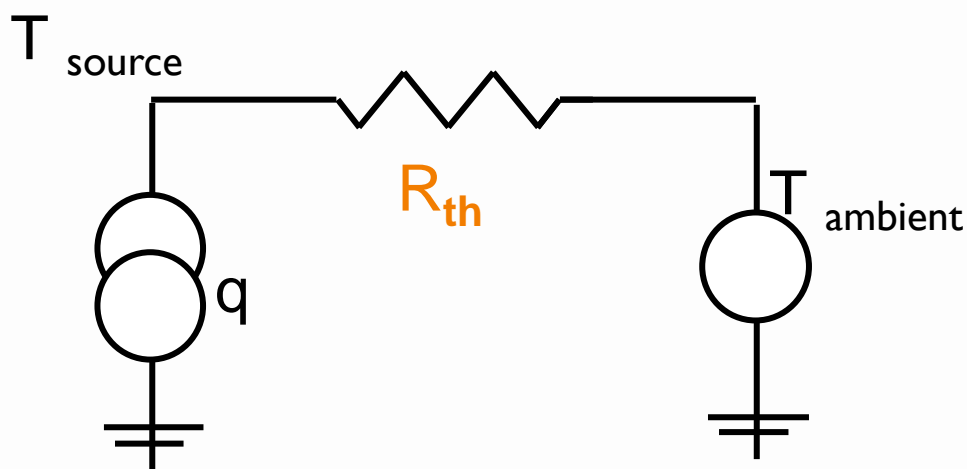Heat flux (W/m²) $\rightarrow$ Current density (A/m²)

Thermal resistance (K/W) $\rightarrow$ Resistance (Ohm)

Electro-Thermal Analogue

A heat transfer path can be described by an electrical network
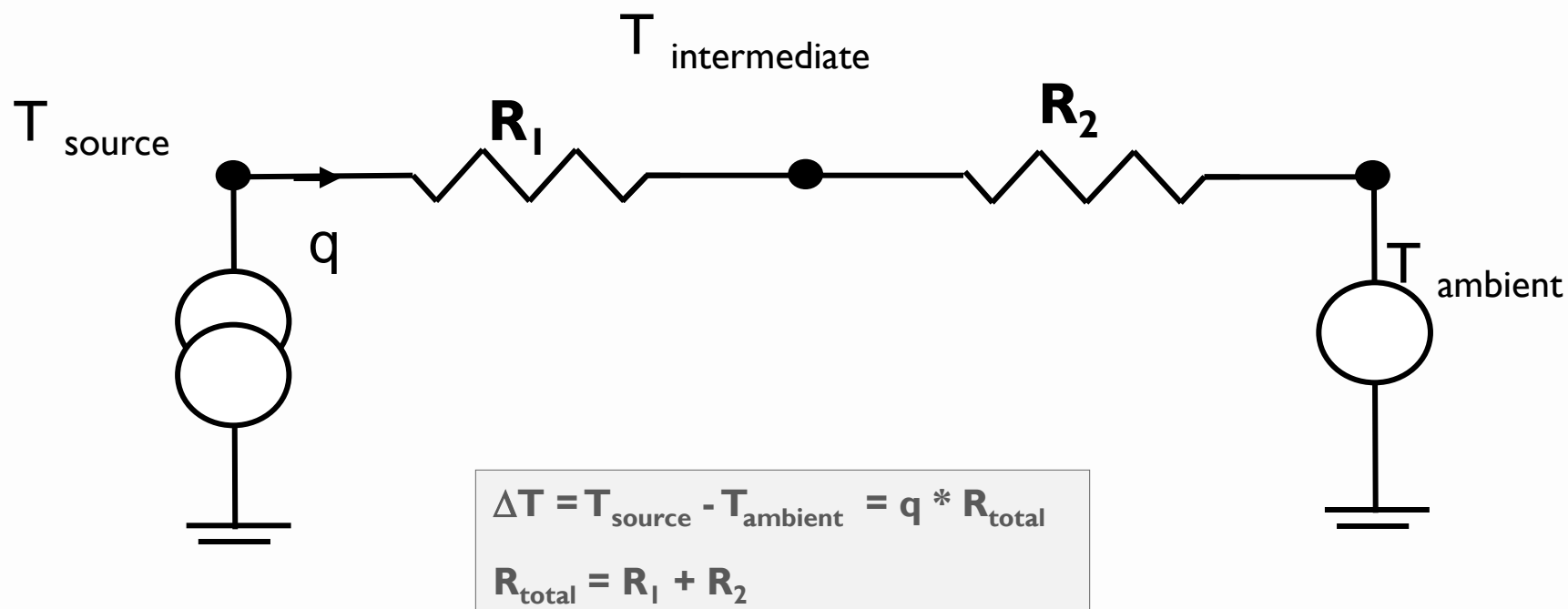

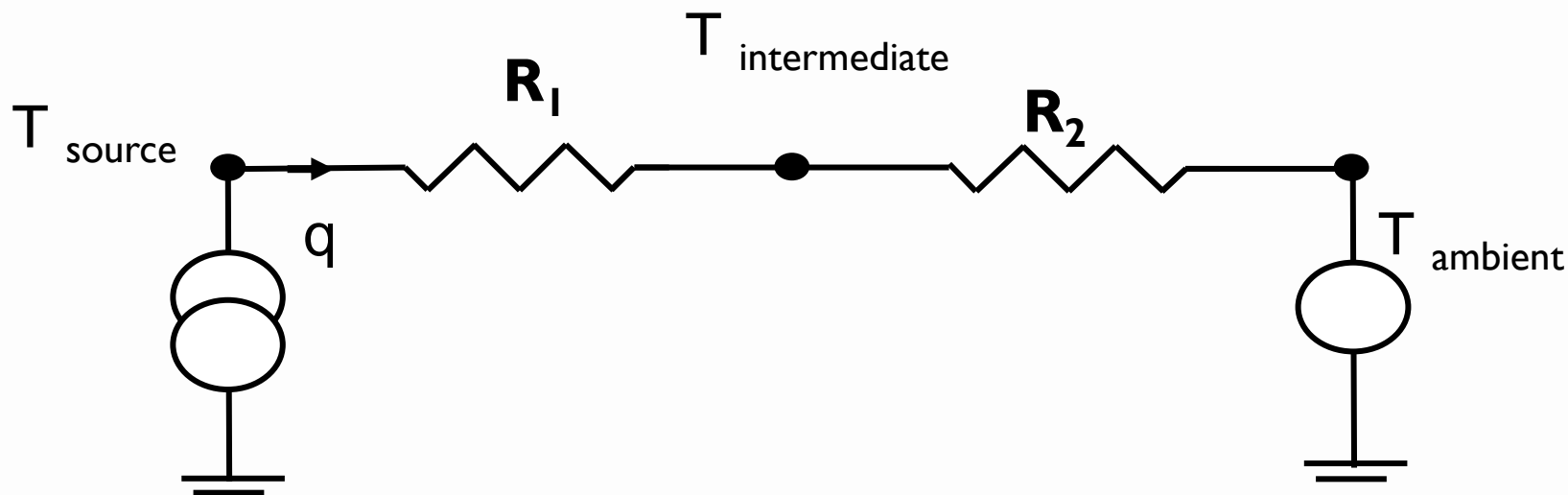$\Delta T = T_{source} - T_{ambient}$

R_{th} (K/W) = thermal resistance

Series Circuit

Example for two resistances in series

$$\Delta T = T_{source} - T_{ambient} = q * R_{total}$$
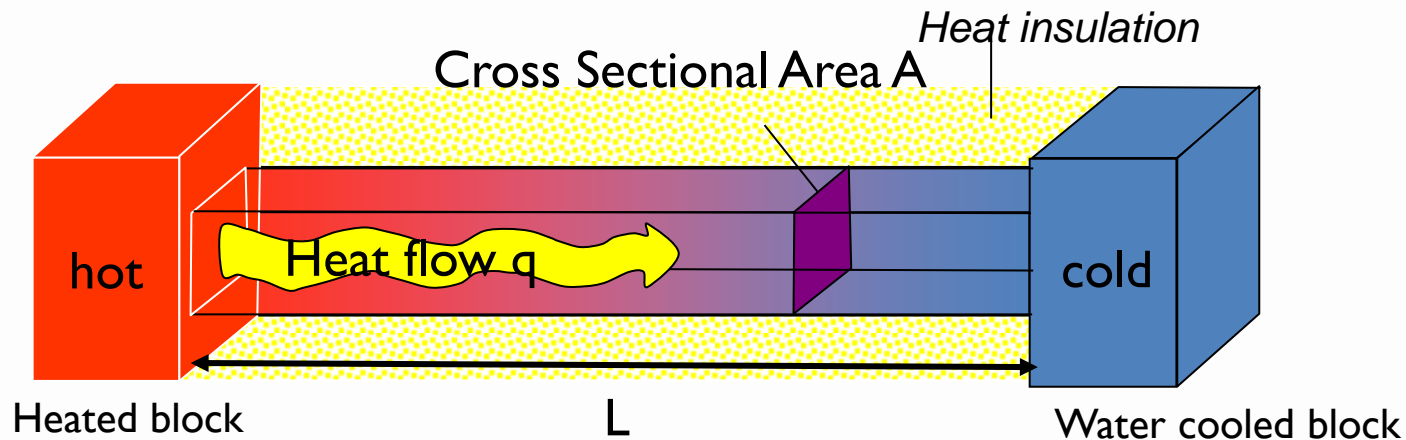
$$R_{total} = R_1 + R_2$$

Consequence of Series Circuit

Often only the largest R is relevant!

Designer's job: find the largest resistance!

Thermal Conductivity: Fourier's Experiment (1822)

Heat insulation

Cross Sectional Area A

hot

Heat flow q

cold

Heated block

L

Water cooled block

Result of Fourier's experiment:

$q \sim \Delta T = T_{hot} - T_{cold}$
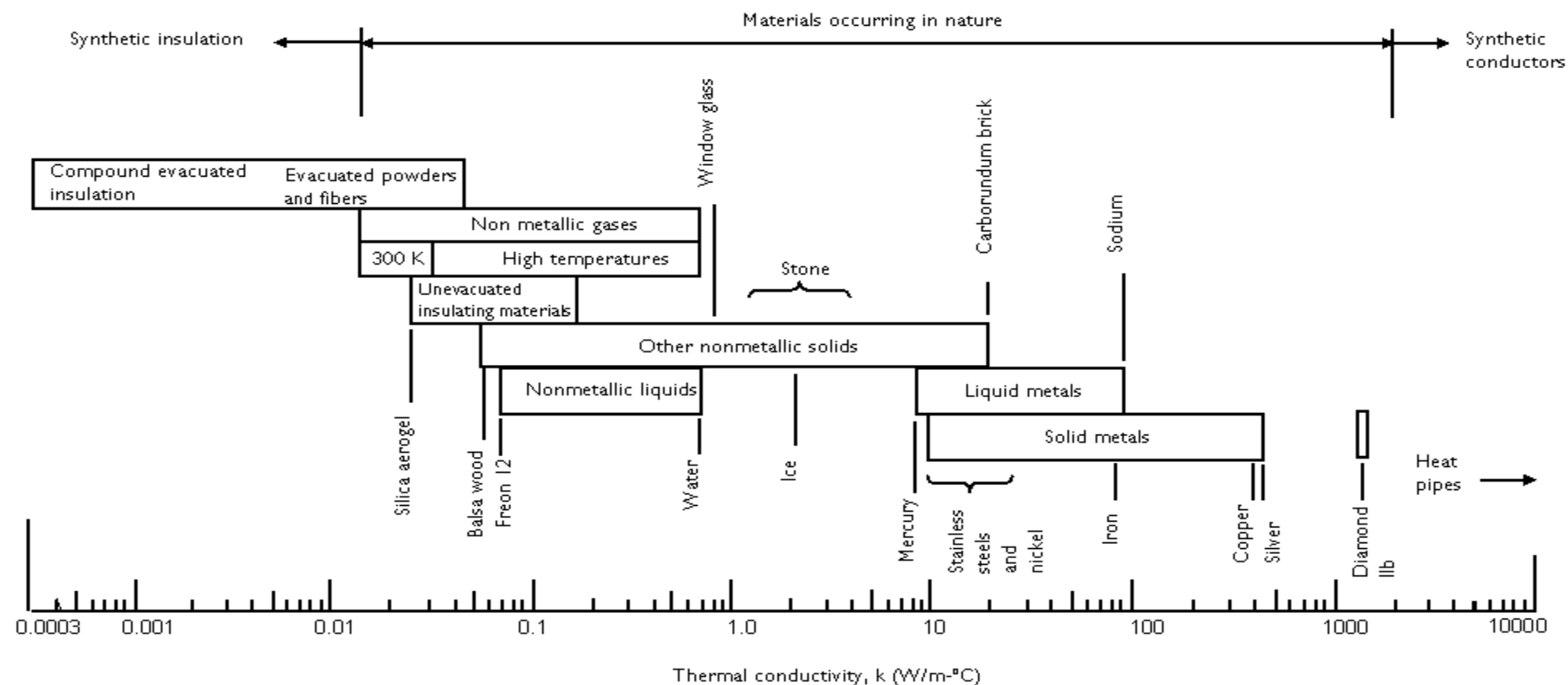
$q \sim A$ = cross-sectional area

$q \sim L^{-1}$

$$q = k \cdot \frac{A}{L} \cdot \Delta T$$

The proportionality constant *k* is called the *'thermal conductivity'*

Typical Thermal Conductivity Values

Approximate ranges of thermal conductivity for various substances
(All values are in the neighborhood of room temperature unless noted)

The Heat Transfer Coefficient *h*

The heat transfer from a solid wall into a fluid (air, water) is called convection, and to first order this heat transfer is proportional to the area and the temperature difference between the wall and the fluid:

$$q = h \cdot A \cdot \Delta T$$

The proportionality constant *h* is called the
'heat transfer coefficient'

Typical values:
Natural convection: 10 W/m²K
Forced convection: 50 W/m²K

Practice (1)

Suppose a Designer needs 5W to reach a required light output

What procedure is most optimal?

$$q = \frac{\Delta T}{R_{th-total}}$$

Information required for first order guess:

- Maximum junction temperature: e.g. 120 °C

- Maximum ambient temperature: e.g. 40 °C

- An estimation of all thermal resistances in the total heat transfer path

Practice (2)

Next steps

- Check if required power is manageable by suitable heat sinks & convection

- Check which thermal resistances are dominant

  - Then focus on these to reduce the total thermal resistance

- Final step should always be a more detailed analysis

  - Recall that often we don't talk one-dimensional heat transfer but heat spreading, which is a rather complicated issue

    - For more information please see accompanying paper and

      Heat Spreading, Not a Trivial Problem in the May 2008 issue of **ElectronicsCooling**
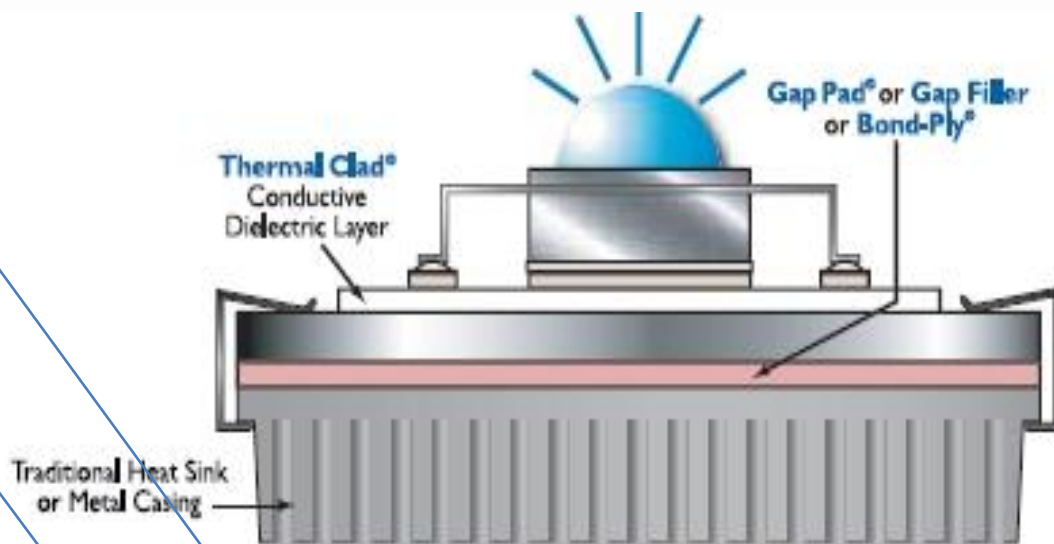
Practical Example

$$q = k \cdot \frac{A}{L} \cdot \Delta T$$

$$R_{th} = \frac{L}{k \cdot A}$$

$$q = h \cdot A \cdot \Delta T$$

$$R_{th} = \frac{1}{h \cdot A}$$

Gap Pad® or Gap Filler or Bond-Ply®

Thermal Clad®
Conductive Dielectric Layer

Traditional Heat Sink or Metal Casing

Relevant thermal resistances, assume 1 cm² PCB per LED

	K/W	
R_{th}-LED	16	Luxeon Rebel
R_{th}-MCPCB	0.5	t = 100 µm, k = 2 W/mK
R_{th}-TIM	1	t = 100 µm, k = 1 W/mK
R_{th}-heatsink	50	A = 20 cm², h = 10 W/m²K
R_{th}-heatsink	2	A = 100 cm², h = 50 W/m²K
R_{th}-heatsink	1	A = 1 cm², h = 10000 W/m²K

Practical Example

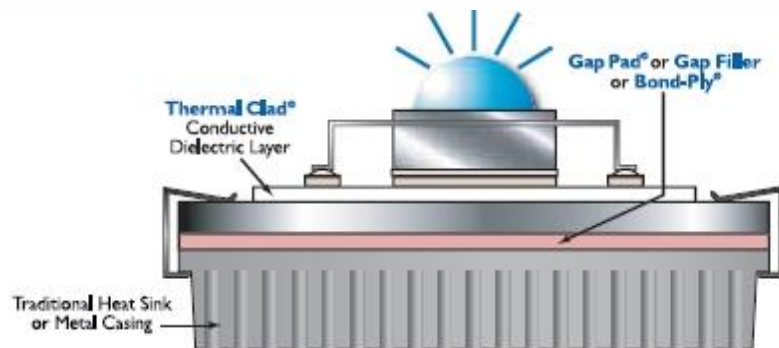We need *5W* for our light output

Can we find a suitable heat sink?

We have:

$T_{junction}$ = 120 °C

$T_{ambient}$ = 40 °C

R_{th}-LED + R_{th}-MCPCB + R_{th}-TIM = 17.5 K/W; R_{th}-heatsink = ?

$$q = \frac{\Delta T}{R_{th-total}}$$

Can we dissipate 5W? No way:

q = 80 / (17.5 + R_{th}-heatsink)

Conclusion:

Even with an ideal heat sink (R_{th}-heatsink = 0) we cannot dissipate the required 5W. In this case we need an LED with less thermal resistance.
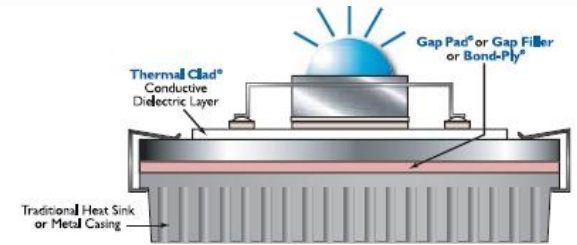
Practical Example

We need *1W* for our light output

We have again:

$T_{junction}$ = 120 °C

$T_{ambient}$ = 40 °C

R_{th}-LED + R_{th}-MCPCB + R_{th}-TIM = 17.5 K/W; R_{th}-heatsink = ?

$$q = \frac{\Delta T}{R_{th-total}}$$

Which heat sink is OK?

q = 80 / (17.5 + R_{th}-heatsink) ; R_{th}-heatsink = 62.5 K/W

Conclusion:
We can use a simple heat sink with natural convection.

We found earlier:

A=20 cm^2, h=10 W/m^{2}K → R_{th}-heatsink = 50 K/W

.

Practical Example Conclusion

Thermal resistance of the MCPCB does not play *any* role
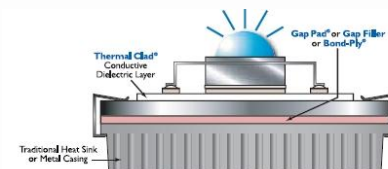
- In our first case, the *LED thermal resistance* was dominant; while in the last case, the *convective resistance* was dominant.

- Hence, *from a thermal point only*, you can choose MCPCBs with a much lower thermal performance (e.g.: lower thermal conductivity) and, hence, lower cost.

- **The thermal performance of the PCB is relevant only for very high heat flux cases (e.g. liquid cooling) and for top-of-the-bill LEDs.**

Nomenclature

The confusing situation regarding *'thermal impedance'*

Fact:

'Electrical impedance' is historically reserved to describe time-dependent electrical resistance. In the limit of steady state, thermal impedance equals thermal resistance → hence, units should be the same!

Hence,

'Thermal impedance' , as used by U.S. vendors, violates the electro-thermal analogy:

- Unit does not correspond (K/W vs. m^2K/W)

- Definition does not correspond (time-dependent vs. steady state)

Is this a problem?
Yes, because time-dependent (dynamic) test methods will be increasingly used, one output of which is the 'correct' thermal impedance.

Proposal:
Use unit area thermal resistance, or unit R_{th}

Product Reliability

Simplified LED
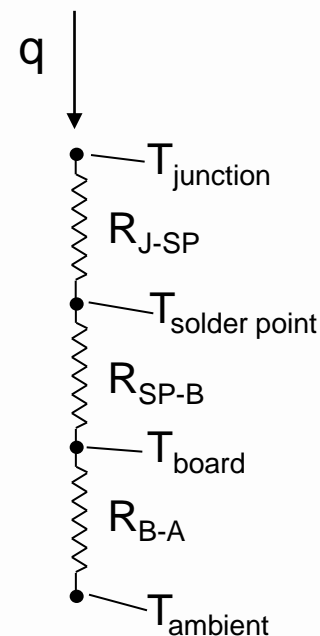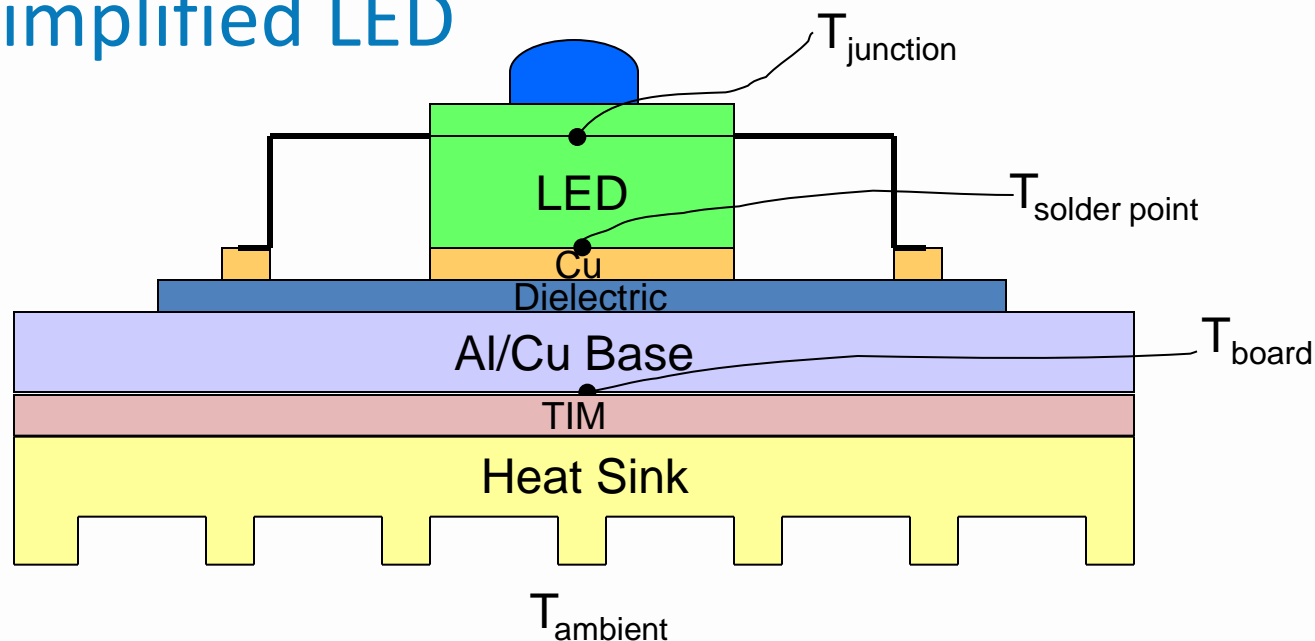
Big concern: what is T$_{junction}$?

Why?

Lower T $_{junction}$: More Light

Increased relative luminous flux for lower junction temperature

Relative Flux vs Junction Temperature (I_F = 350 mA)

The following graph represents typical performance of XLamp MC-E LEDs with all four LEDs driven in series at 350 mA.

Cree® XLamp® MC-E LED
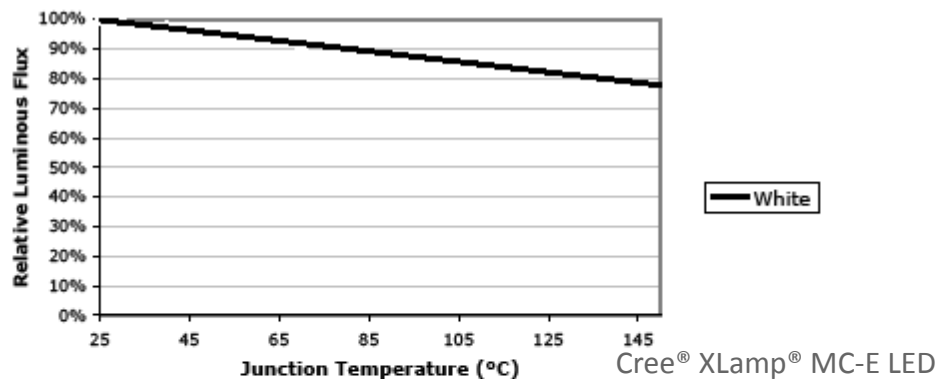
Luxeon® Rebel
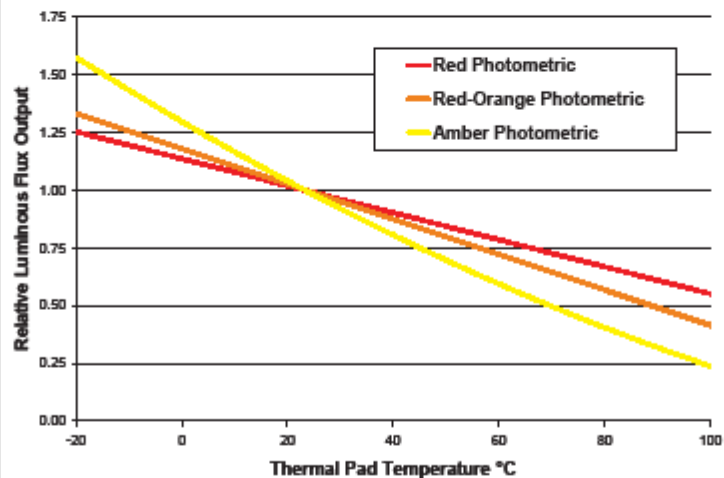
Figure 7. Relative light output vs. Thermal Pad temperature for Red, Red-Orange and Amber.

Figure 8. Relative light output vs. Thermal Pad temperature for White, Green, Cyan, Blue and Royal-Blue.

Lower T $_{junction}$: Increased Lifetimes

Luxeon®
Rebel

Figure 7. Expected (B50, L70) lifetimes for InGaN LUXEON Rebel.

Figure 11. Expected (B50, L70) lifetimes for AlInGaP LUXEON Rebel.
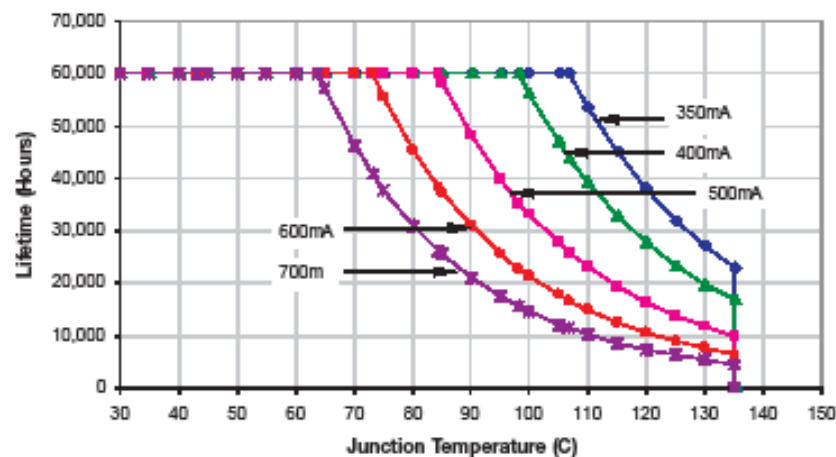
Solid-State Lighting **Mid- and High-Power LEDs**

Moonstone™ Family

Moonstone™ Emitter

Moonstone™ Star 1
Module (MCPCB)

Moonstone™ Star 2
Module (MCPCB)

Description

Avago´s Moonstone™ high-power LED-family has the widest high power offering on the same platform (0.5W, 1W, and 3W). The industry-proven power transistor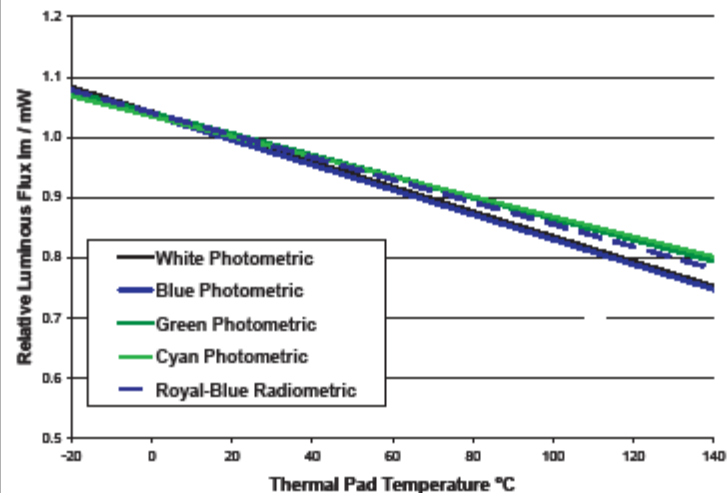 package grants a robust and reliable performance. The exposed pad design has excellent heat transfer from the package to the motherboard.

Typical Applications

- Portable lighting – flash light, bicycle headlight & miner light
- Safety / security lighting – exit and emergency sign light
- Task lighting – reading light, spot light, track light
- General lighting – street lighting, interior lighting
- Decorative lighting – cove lighting, contour lighting and garden lighting
- Billboard backlighting – sign backlighting

Features

- Power: 0.5 Watt, 1 Watt, and 3 Watt
- Low profile (3.3mm height), footprint is 10mm x 15.85mm
- Direct heat transfer from the metal slug to the mother board
- Option with electrically isolated metal slug is available (only for InGaN colors)
- Wide viewing angle: 110° / 120°
- Low thermal resistance: 10°C/W min *
- Can be driven at stringent operating condition: LED Junction Temperature 145°C max *
- Operating temperature: -40°C to +120°C max *
- Long operating life due to silicone encapsulation
- Energy efficient: Power Dissipation starts at 525mW
- Helps lower design cost due to:
  - Compatible with reflow soldering process
  - Non-ESD sensitive (threshold > 16kV)

* Refer to Data Sheet for details

Smell Test

Input data					
Tjunction	**Tambient**	**Dissipation**	Area PCB	Number of LEDs	Area per LED
°C	°C	W	cm2		cm2
145	40	3	10	10	1

Calculation of thermal resistances	Comments	Thickness	Thermal conductivity	Area		Rth
		mm	W/mK	cm2		K/W
LED	From data sheets					10
(MC)PCB	dielectric layer	0.5	2	1		2.5
(MC)PCB	metal layer	1.6	160	1		0.1
TIM	between PCB and heatsink	0.1	1	1		1
Rth of LED-PCB-TIM combination						13.6
heatsink	tbd					
convection	tbd					
Total Rth						?

$$R_{th} = \frac{L}{k \cdot A}$$

Maximum dissipation
W
7.72

$$q = \frac{(T_{junction} - T_{ambient})}{R_{th}}$$

Looking good so far. The LED to TIM part of the total thermal resistance path allows me to dissipate the heat to the heat sink.

Now, let's find an effective heat sink package….

Heat sink Calculation

Input data		
Tjunction	Tambient	Dissipation
°C	°C	W
145	40	3

Calculation of thermal resistances	Comments	Thickness	Thermal conductivity	Area	h	Ext.	Rth
		mm	W/mK	cm^2	W/m^{2}K		K/W
LED	From data sheets						10
(MC)PCB	dielectric layer	0.5	2	1			2.5
(MC)PCB	metal layer	1.6	160	1			0.1
TIM	between PCB and heatsink	0.1	1	1			1
Rth of LED-PCB-TIM combination							13.6
heatsink	standard					20	
convection	natural				10		50.0
Total Rth							63.6

Req. Max. total thermal resistance	Req. heat sink thermal resistance (max)
K/W	K/W
35.0	21.4

$$R_{th\_heat\,\sin\,k} = R_{th-total} - R_{th\_LED\,/TIM\,/PCB}$$

$$R_{th} = \frac{(T_{junction} - T_{ambient})}{q}$$

No Go Joe. A heat sink with Natural Convection generates too much thermal resistance to effectively cool the LED junction. Let's try something else....

Heat sink Calculation

Input data		
Tjunction	Tambient	Dissipation
°C	°C	W
145	40	3

Calculation of thermal resistances	Comments	Thickness	Thermal conductivity	Area	h	Ext.	Rth
		mm	W/mK	cm^2	W/m^{2}K		K/W
LED	From data sheets						10
(MC)PCB	dielectric layer	0.5	2	1			2.5
(MC)PCB	metal layer	1.6	160	1			0.1
TIM	between PCB and heatsink	0.1	1	1			1
Rth of LED-PCB-TIM combination							13.6
heatsink	standard					20	
convection	forced				50		10.0
Total Rth							23.6

Req. Max. total thermal resistance	Req. heat sink thermal resistance (max)
K/W	K/W
35.0	21.4

$$R_{th\_heat\,\sin k} = R_{th-total} - R_{th\_LED\,/TIM\,/PCB}$$

$$R_{th} = \frac{(T_{junction} - T_{ambient})}{q}$$

Bam! A heat sink with Forced Convection reduces the thermal resistance enough to meet your needs.

However, the data show that you do have a cost savings opportunity!

Heat sink Calculation

Input data

Tjunction	Tambient	Dissipation
°C	°C	W
145	40	3

Calculation of thermal resistances

	Comments	Thickness	Thermal conductivity	Area	h	Ext.	Rth
		mm	W/mK	cm^2	W/m^{2}K		K/W
LED	From data sheets						10
(MC)PCB	dielectric layer	0.5	0.4	1			12.5
(MC)PCB	metal layer	1.6	160	1			0.1
TIM	between PCB and heatsink	0.1	1	1			1
Rth of LED-PCB-TIM combination							23.6
heatsink	standard					20	
convection	forced				50		10.0
Total Rth							33.6

Req. Max. total thermal resistance	Req. heat sink thermal resistance (max)
K/W	K/W
35.0	11.4

$$R_{th\_heat\,sin\,k} = R_{th-total} - R_{th\_LED\,/\,TIM\,/\,PCB}$$

$$R_{th} = \frac{(T_{junction} - T_{ambient})}{q}$$

Time for some non-government style cost cutting. Based on the calculations, you may actually be able to substitute your expensive thermally conductive dielectric with FR4!

Don't take calculations in a vacuum

Heat Spreading

The previous calculations are for *one-dimensional* heat transfer only. Heat *spreading* is a different, and much more complex, issue that cannot be modeled into a one size fits all calculation.

See accompanying paper for more details.

Calculate the effects of other cost drivers

MCPCB metal substrate

Using copper? Try plugging in Aluminum at almost 1/4 of the cost

Heatsink

Adjust the size of your heat sink to optimize performance vs. cost

Try different materials (PGHT) that offer superior thermal conductivity so that they can have a smaller footprint

Break out of the box!!!

Toss the MCPCB!

Use 2 layer flex and mount directly to heatsink using TIM or Thermal Grease. *Note: Filled flex materials conduct heat better than unfilled materials*
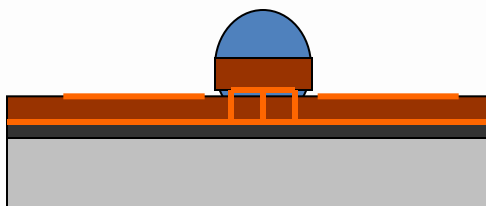
Use no flow prepreg and mount LED base directly to metal core substrate
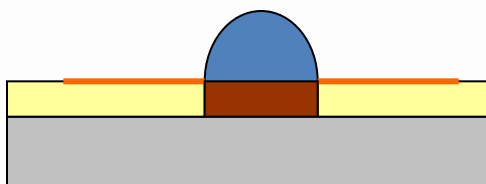
Suggested Fabrication Notes

Taking Control of Your Design!

Suggested Fabrication Notes

Purpose of Fab Notes

Take *your* requirements for each characteristic that *you* deem most important and specify (values for thermal conductivity and electrical insulation resistance).

We also suggest including a list of pre-approved materials.

Suggested Fabrication Notes (cont.)

Example of a Fab Note

Copper Weight: 2 oz.

Metal Core: 0.060" Al 5051

Dielectric:

    Thermal Resistance: Maximum 0.9 (°C in^2/W)

    Electrical Insulation: Must meet or exceed 2,000 VDC

    *Any other characteristic you feel is important: **XYZ***

    Currently Approved Materials:
- ❑   Bergquist HT-07006
- ❑   Bergquist LTI-06005
- ❑   Laird T-lam SS 1KA06
- ❑   DuPont CooLam

Suggested Fabrication Notes (cont.)

Benefits of Fab Notes

Allows supplier to quote **multiple vendors**.

Subsequent Results
- Lower Cost
- Quicker Lead Times
- Adaptability to take advantage of new technologies down the road
- Introduce competition from the raw materials and finished PCB suppliers

Materials Chart

Thermal Dielectric Material Selection Chart

Brand		Thermal Characteristics		Dielectric Characteristics / Insulation			Other		
Material Manufacturer	Material Type	Resistance (°C in²/W)	Conductivity (°W/m-K)	Typical Proof Test (VDC)	Breakdown (kVAC)	Permitivity (Dk)	Glass Trans (°C)	UL Index (°C)	Peel Strength (lb/in)
Bergquist	HT-04503	0.05	2.2	1500	6.0	7	150	140 / 140	6
Bergquist	HT-07006	0.07	2.2	2500	11.0	7	150	140 / 140	6
Bergquist	LTI-04503	0.05	2.2	1500	6.5	7	90	130 / 130	6
Bergquist	LTI-06005	0.09	2.2	2000	9.5	7	90	130 / 130	6
Bergquist	MP-06503	0.09	1.3	1500	8.5	6	90	130 / 140	9
Bergquist	CML-11006	0.21	1.1	2500	10.0	7	90	130 / 130	10
Laird	T-lam SS 1KA04	0.05	3	1200		4.3 / 4.1	105	110	4.5
Laird	T-lam SS 1KA06	0.08	3	2500		4.3 / 4.1	105	120	4.5
Laird	T-lam SS 1KA08	0.11	3	3500		4.3 / 4.1	105	130	5
Laird	T-lam SS HTD04	0.072	2.2	4000+	2.5	5.1 / 4.9	168	150	6.5
Laird	T-lam SS HTD06	0.107	2.2	6000+	3.5	4.9 / 4.7	168	150	7
ISI	Zeta Bond 1.0 mil						> 300°		
ISI	Zeta Bond 1.5 mil			1000			> 300°		
DuPont CooLam	LX03517016	0.05	0.8	2500		5.5	225	130	14
DuPont CooLam	LX07022016	0.065	0.8	4000		5.5	225	130	14
UniPlus	UP-HTC-P075016	0.09	1.3	1500	8.3	4.8	135	140 / 110	9.5
Iteq	IT-858T (80 um)	0.128	2.2	> 6000	>4.0		159		
Iteq	IT-858T (100 um)	0.128	2.2	> 6000	>4.0		159		
Iteq	IT-859GT (80 um)	0.126	2.2	> 6000	>4.0		156		
Iteq	IT-859GT (100 um)	0.126	2.2	> 6000	>4.0		156		
Taconic	TacLED-4	0.19	0.4	> 3000	>3.0	3.05	327		12
Taconic	TacLED-10	0.13	1		>6.0	4.6	136		9.5
Taconic	TacLED-20	0.06	2		>6.0	5.2	125		8.4

Part Two

Non-browning White Soldermask

White Soldermask

Current Resin Systems

- Focus on initial thermal shock, not constant heat

- Tend to Brown over time

- Not developed to be a Reflecting Surface for LEDs

White Soldermask (cont.)

Desired Resin Systems

- Remain white through Assembly and Lifespan of LED final product

- Have high reflectivity to enhance LED performance
    - Some believe high reflection soldermask results in lower power consumption for same light output

What are the Solutions?

New White High Temperature Liquid Photo-Imageable Soldermasks

- Past three years a number of "LED" white soldermasks have been introduced
    - Unfortunately we have not seen improvements in all of them

- Through numerous studies we have so far found two offerings that show significant improvement:
    - Peters *(SD2491SM TSW)*
    - Sun Chemicals *(CAWN 2589/2591)*
    - Electra *(EMP110/5076) – available in spray on format*

What are the Solutions? (cont.)

New White High Temperature Thermal Soldermasks

If *Bright* white soldermask is the objective, these solutions may not suffice

- Suggest base coat of LPI White then topcoat of High-Temp thermal white soldermask

- After numerous thermal whites, one does not brown after multiple cycles *(Peters SD2496TSW)*

- This is the formula behind "proprietary" white soldermasks offered by other PCB vendors

Cost Expanders

New White High Temperature Liquid Photo-Imageable Soldermasks

- To date, we've seen cost increases over standard soldermask price of 30% - 100%
    - Approximately .20 to .30 cents per panel (18" x 24")

New White High Temperature Thermal Soldermasks

- To date, we've seen cost increases over standard soldermask price of > 100%
    - Approximately $1 per panel (18" x 24")
    - Includes labor and set up for secondary application process

How do I specify White Soldermask?

"White" covers a range of hues and conformity is very judgemental

Goal is to specify in such a way to remove human judgement and create a measureable specification

- One suggestion is to specify by acceptable Pantone codes, that are measurable through instruments
    - Acceptable Pantone codes:

        196, 250, 256, 263, 2706, 2707, 290, 2975, 304, 317,
        324, 331, 332, 337, 344, 420, 427, 428, 434, 441,
        453, 454, 4545, 468, 4685, 4755, 481, 482, 489, 503,
        5035, 5165, 517, 5175, 524, 5245, 531, 5315, 538, 544,
        545, 5455, 5513, 5517, 552, 5523, 5527, 559, 5595, 565,
        566, 5665, 571, 572, 573, 5803, 5807, 621, 622, 628,
        629, 635, 642, 643, 649, 650, 656, 657, 663, 664,
        670, 671, 677, 678, 684, 691, 698, 705, 706, 719,
        …or any others you feel are acceptable

Sample Pantone Measurement

Thermal Webinar Conclusion

SPECIFY your needs for thermal performance of the dielectric

SPECIFY your needs for the electrical performance of the dielectric

SPECIFY your needs in context of entire product, not just PCB (when applicable)

KNOW that you have white soldermask choices

but keep your fab notes open to take advantage of future developments