Thermal Design Challenges at the PCB Level: Identifying the Cause

Thermal management of high-power electronic components (single chips, multi-chip modules, IC's, high power, high frequency transistors, etc.) with high heat dissipation ratings demands careful design using all available techniques to be successful. The most important goal in electronic cooling is to maintain junction temperature (T_j, the temperature) from rising above prescribed levels, since the junction temperature is good predictor of the useful life of the component. From a thermal standpoint, the junction temperature is affected, as with many other electronic components and systems, by the heat generation levels, heat sinking (high conductivity materials, convection cooling, extended surfaces, heat spreading, heat pipes, etc.), ambient temperature, applied interface materials, applied pressures (clamping to reduce thermal contact resistance), among others.

Thermal management for components and PCB (Printed Circuit Boards) boards can range from the application of natural convection to the use liquid cooling loops that allow for far higher heat removal rates than the use of gases as the cooling medium. wIn the case of using water instead of air, the difference can be staggering (air and water are used here as an example; many other liquids and gases can be effectively applied for thermal management of electronics.) *Table 1* shows the relative effectiveness of various convective heat transfer methods. Air natural and forced convection have been up to recently the cooling methodology of choice when cooling with a fluid. As seen on *Table 1*, water natural convection has approximately the same heat transfer effectiveness as forced air convection and forced water convection has 10 times the effectiveness of air forced convection. Therefore, if the heat transfer requirements are such that air is no longer effective, then liquid cooling must be considered (for example signage applications or Video/TV applications.) Single phase liquid cooling can be effected using natural convection or forced convection. Both modes of convective heat transfer have their application, however, the main obstacle to the implementation is the fact that a pump or liquid along with a heat exchanger are necessary for a forced convection liquid cooling loop.

Mechanism	Typical Heat Transfer Coefficient (W/m^2-K)	Relative Effectiveness	Achievable Density	Complexity
Natural Convection (air)	10	0.1	Low	Very Low
Forced Convection (air)	100	1.0	Medium	Low
Natural Convection (liquid)	100	1.0	Medium	Medium
Forced Convection (liquid)	1000	10.0	High	High
Phase Change (liquid) Heat Pipes	5000	50.0	High	High

Table 1 Relative Effectiveness of Thermal Control Methodology. [Doane, D. A. and Franzon, P. D., "Multichip Module Technologies and Alternatives: The Basics," Van Nostrand Reinhold Publishers, New York, 1993]

Thermal Characterization for Electronics Cooling Design

In order to simplify thermal design, we need to define several concepts: Junction Temperatures and the Thermal Resistance Concept. In most electronic systems, junction temperature is the point in a component (the die where most of computations are carried out, for example) where the highest temperatures are reached. For an LED system, for example, this temperature resides in the p-n junction.

One methodology used to simply calculate the efficacy of a particular simple heat sinking system is the thermal resistance concept. This concept is based on the fact that layers, connections, heat sinks, interface materials possess a resistance to heat flow between two points in a component/board system, for example, the heat flow between the diode and the epoxy board. In general, between two points, say, junction and board, the heat flow from junction to board would be:

Heat Dissipated = Temperature Difference/Resistance

Or

R = Heat Dissipated/ΔT

If the thermal resistance is very low, then for moderate power dissipation, the temperature difference will be small. For the case of the simple heat sink system (see *figure 1*), a thermal resistance network can be devised to aid in the calculation and assessment of the thermal management performance of the cooling strategy. The goal is to reduce the thermal resistance (high thermal conductivity materials have lowest thermal resistance, for example) using an equivalent thermal resistance network. Moreover, since wherever two materials are in contact (underside of the diode and the board), the contact is not perfect (the two sides are not fully touching because surface finish imperfections), a contact thermal resistance will exist that needs to be reduced by applying a higher contact pressure, better clamping, better surface finish or an interstitial material such as thermal paste or glue.

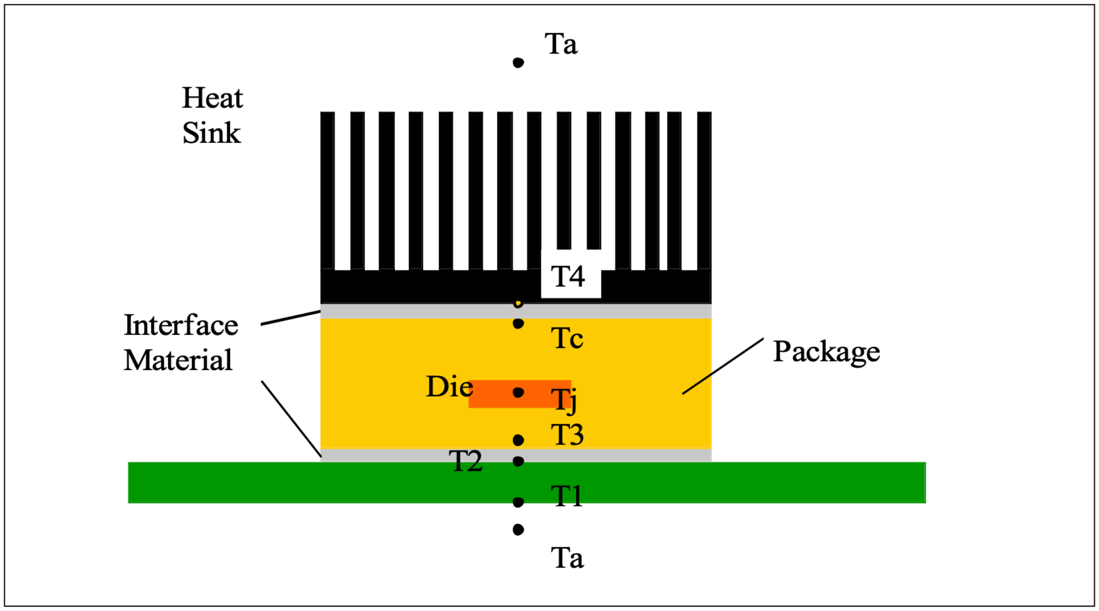

Figure 1 Typical Heat Sink Arrangement with Temperature Nodes for Thermal Resistance Network

Ways to Increase Thermal Effectiveness/Efficiency of PCB and Components

As can be seen in *Figure 1*, thermal management of PCBs and its components is essential if reliability is to be achieved and a measure of reliability is maintaining junction temperatures under a set limit. Most systems require the junction temperatures be kept at 125 C or lower.

Several methods and technologies can be implemented to increase heat flow and reduce overall temperatures and hot spots. Here is a brief review/description of these techniques.

HEAT SINKS
A typical application of thermal interface materials is the use of heat sinks. After a thermal analysis is completed and the cooling/heating loads determined for the chip/board/system/enclosure have been determined, we then need to match the right cooling devices to the system. One of the most common devices are heat sinks that are added to single hot components such as chips, IC's, power electronics. Some are added to the outside/inside of enclosures (for example modems, transceivers, etc.) See *Figure 1* for a typical plate fin heat sink.

Heat sinks are mostly made of metal (or a very high thermal conductivity material), and they are designed to perform in natural or forced convection. They are many manufacturers of heat sinks, and most of them offer performance curves with their off-the-shelf heat sinks. Most of these manufacturers provide customers with thermal characterization curves that allow for the correct matching of heat sinks to the application on hand.

Most heat sinks are characterized using the thermal resistance, defined as follows:

$$\text{Thermal Resistance} = \frac{\text{Temp. Diff. between Base and Air}}{\text{Heat Dissipated (transferred)}}$$

One needs to keep in mind that this value is fluid specific. That is, since the heat transfer mechanisms involve a fluid to remove the heat from the heat sink, the fluid and other flow parameters need to be included. Furthermore, as *Figure 2* shows, the thermal resistance for a heat sink changes as function of air flow speed (for forced convection); and a function of heat dissipation levels (for natural convection.)

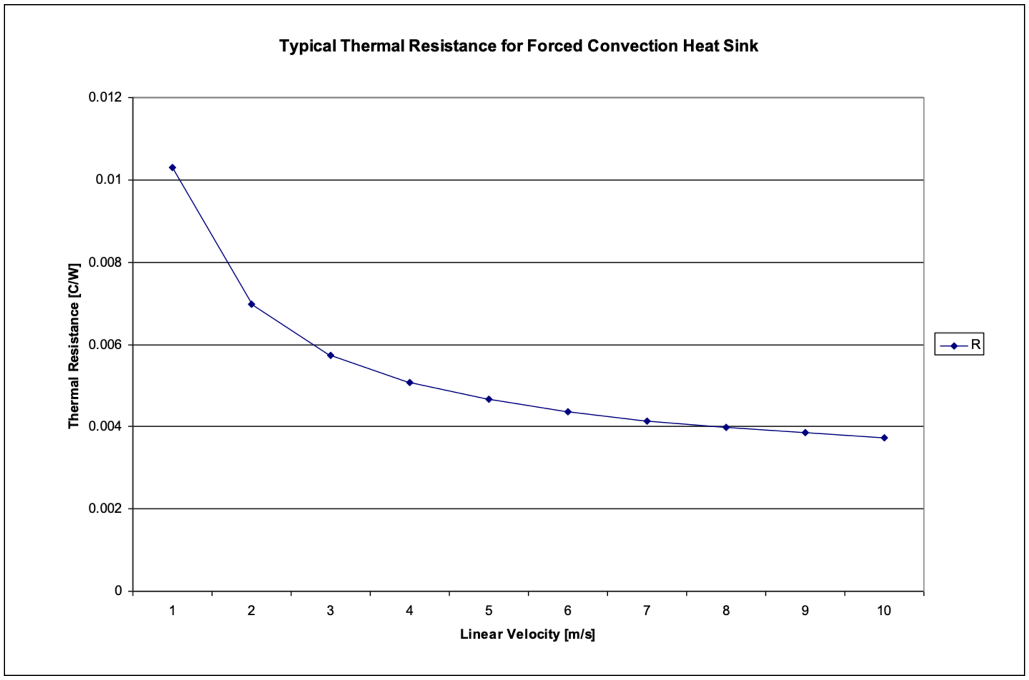

Figure 2 Typical Thermal Characterization of Air Forced Convection Heat Sink

Heat sinks need to be attached to the hot component in some thermally conductive way (see in *Figure 1* between T_2 and T_3 where a layer of material is added). These layers are called interface materials. These materials thermally conduct in several ways:

1. Mechanically – by contact under pressure (clip)
2. Thermally conductive grease or glue
3. Phase Change materials (newest)

For all, the performance is rated the same way:

$$\text{Thermal Resistance} = \frac{\text{Temp. Diff. across interface material}}{\text{Heat Dissipated (transferred)}}$$

Each component in the heat sink system has a particular thermal resistance, and the overall or total resistance for the package will be obtained using the electrical analog (series/parallel.) For example, for heat sink example (this example can apply to any electronic package) there are several ways to reduce the overall thermal resistance for electronic systems; for example, the board can be made with a metal core (metal clad boards), or high conductivity thermal glue or paste can be applied to the underside of the diode, or a heat sink can be added to the bottom of the board. Natural convection or forced convection can be applied to the underside of the board or the top of the diode through a heat sink. However, all these techniques have to take into account the overall system in which the board is located.

HEAT PIPES

Heat pipes are closed vessels in which a liquid is made to evaporated at one side and re-condense at the other end. Although they do no cooling (does not dissipate to the air), they can transfer large amounts of heat from one area to another. These heat pipes can be used as single tubes that connect the hot component to a metal heat sink or that can be incorporated into plates, heat exchangers, etc. *Figure 3* shows an illustration of a typical horizontal heat pipe.

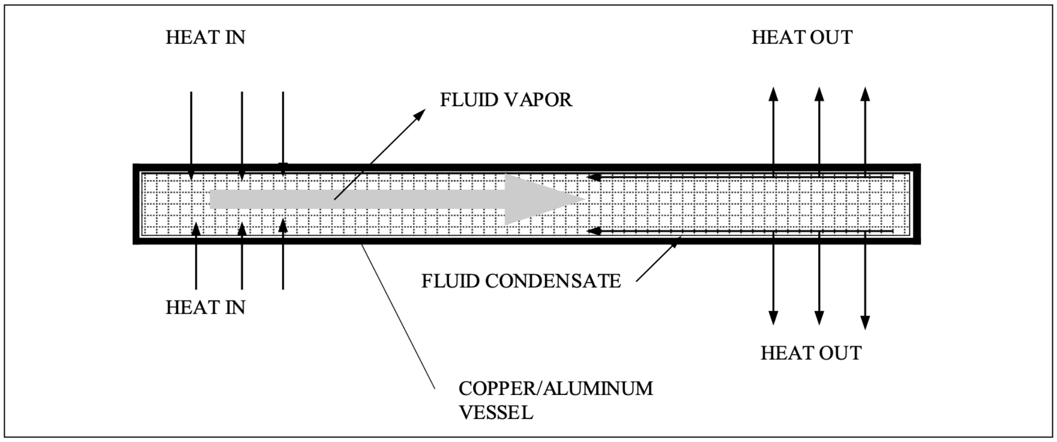

Figure 3 Typical Horizontal Heat Pipe

FORCED CONVECTION

Most electronic housings (enclosures, etc.) are primarily cooled using fans or blowers located on the perimeter of the system. Fans nowadays come in all sizes and capabilities. From small ones that deliver 1-5 cfm up to blowers that deliver 500-1000 cfm. Fans can be axial or radial fans. The subject is vast, and we are just covering a short part of it. Fans are considered low-volumetric flow/low-pressure drop air movers Blowers are considered high-volumetric flow/high-pressure drop air movers. Air movers can be either axial or radial. This is based on how flow is induced. The fans can be either intake or exhaust.

THERMAL INTERFACE MATERIALS

Since the surface morphology of the various layers is not perfect, then heat sinks, heat spreaders, etc. need to be attached to the hot component in some thermally conductive way:

Here are several ways this is being performed:

1. Mechanically--by contact under pressure
2. Thermally conductive grease, glue, or material
3. Phase Change materials (newest)
4. Adding a soft, compliant metal such as Indium

For all, the performance is rated the same way:

$$\text{Thermal Resistance} = \frac{\text{Temp. Diff. across interface material}}{\text{Heat Dissipated (transferred)}}$$

In general, when 2 surfaces meet (such as layers in a PCB board or the underbelly of a component and its board), the surfaces are not perfect, mirror-like. For example, *Figure 4* shows the temperature distribution across two surfaces that are not mirror-like. If the surfaces were perfectly flat, then, there would be no temperature gradient across the surfaces since each surface would perfectly touch each other. For example, *Figure 5* shows an illustration of an actual typical surface morphology for two meeting surfaces.

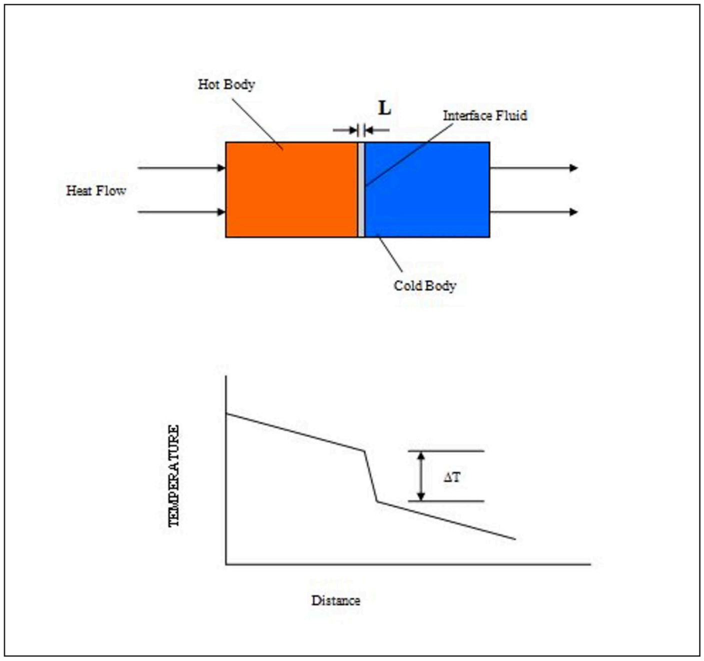

Figure 4 Temperature Distribution Across Two Meeting Imperfect Surfaces Due to Surface Morphology

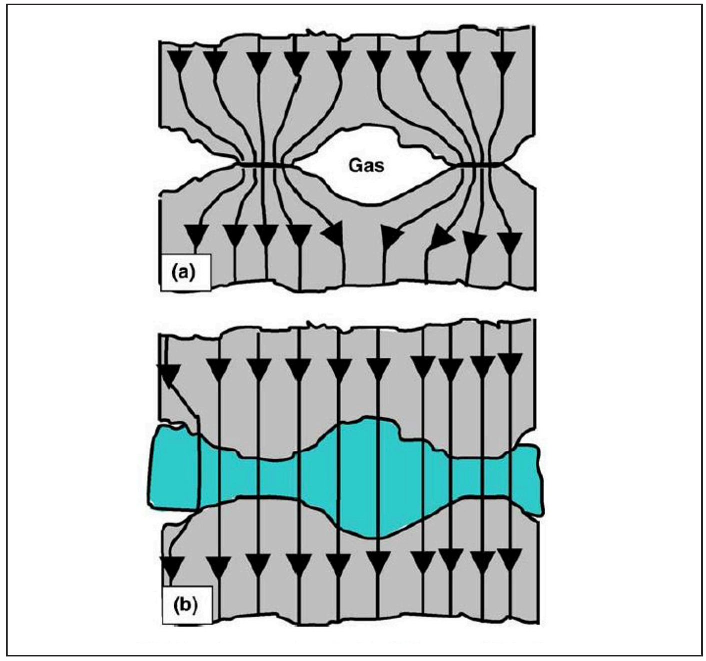

Figure 5 A schematic of two contacting bodies: (a) in direct contact and (b) separated by a thermal interface material. The arrows denote the heat flow across the interface.

Figure 5 Heat Flow Lines for Two Meeting Surface Due to Surface Morphology. Side a) Shows the Case of The Void Filled with a Gas and Side b) Shows the use of an Interstitial Material (a Thermal Interface Material, of TIM.) [Grujicic, M.; Zhao, C.L.; and Dusel, E.C., "The Effect of Thermal Contact Resistance on Heat Management in the Electronic Packaging," Applied Surface Science 246, 2005, pp 290-302]

There are several kinds of TIM with different target applications that the design engineer has at his/her disposal to achieve proper thermal management of components and boards:

- Thermal paste: Mostly used in the electronics industry, it provides a very thin bond line and therefore a very small thermal resistance.
- Thermal adhesive: A Thicker bond layer.
- Thermal gap filler: It could be described as "curing thermal paste" or "non-adhesive thermal glue".
- Thermally conductive pad: As opposed to previous TIM, a thermal pad does not come in liquid or paste form, but in a solid state (albeit often soft).
- Thermal tape: It adheres to surface, requires no curing time and is easy to apply. It is essentially a thermal pad with adhesive properties.
- Phase-change materials (PCM): These are similar to thermal management materials that take advantage of latent heat of fusion to absorb heat, but they just change phase only once to allow for the material to fill up all nooks and crevices.
- Metal Interface Materials: These are soft metals that conform to the two surfaces of interest. Indium is a typical thermal interface material.

Thermal management of high-power electronic components with high heat dissipation ratings demands careful design using all available techniques to be successful. The most important goal in electronic cooling is to maintain junction temperature (T_j, the temperature) from rising above prescribed levels, since the junction temperature is good predictor of the useful life of the component. Several techniques were described here to reduce temperatures, with emphasis on thermal interface materials. A Part 2 to this paper will cover in detail the selection and application of thermal interface materials to the thermal management of components and PCB boards.