Thin Film Thermal Management Design

In order to understand the design challenges facing engineers in the electronics industry, we need to first look at the way heat moves or flows through a material system, and to do this we need to look at the forces that govern that movement. Heat has always been an issue for system designers, but only recently has the problem become so severe that thermal management solutions can no longer be introduced as an afterthought. Heat flux must be looked at from the beginning of the design process. Heat flowing through a material will always create a temperature gradient across that material and will do so in a continuous manner as it flows from one material to another.

Designing in a thermal management system today is a cumbersome exercise where the means for moving the heat and the manner and location in which we reject the heat must be considered early in the design cycle in order to avoid causing severe problems at the system level. This is an important consideration because at the system level the thermal operating space is more restricted with the temperatures that can be tolerated and any thermal conducted at the system level is likely to be more expensive than one implemented at the chip level.

Unfortunately the management of heat in a system is at times a lot like pushing jelly. You can press it down in one direction but it will just flow in another. To see why this is so, we will look at the rules for heat flow in a material system.

Heat Flow in a Material System

The heat equation is an important partial differential equation describing the distribution of heat (or variation in temperature) in a given region over time. For a function u (x, y, z, t), which is a measurement of the temperature T, of three spatial variables (x, y, z), and the time variable t, the heat equation is

$$\frac{\partial u}{\partial t} - k\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2}\right) = 0$$

u = u(t, x, y, z) is temperature as a function of time and space; or equivalently

$$\frac{\partial u}{\partial t} = k\nabla^2 u$$

Here k is a constant.

The other important governing equation is

$Q = U + W$

Heat flow is equal to the work on the system plus the change in internal energy of the system. Hence, in thermodynamics, the change in heat is equivalent to the heat flowing into the system. Combining these two equations and in the absence of any work being performed, Q is proportional to the change in temperature. We won’t provide the derivation here since it is to be found everywhere in the literature but we then arrive at:

$Q = k\Delta T$

Hence for passive systems, cooling by the conduction of heat is a linear function of temperature and a constant related to the material properties of the solid. This constant k may be a function of many variables including T, P, and V.

Passive Cooling

The primary systems used for passive cooling of electronic and optoelectronic systems are materials configured as thermal interface materials (TIM), heat spreaders and heat exchangers. Each perform a different function for removing heat from a system.

Heat exchangers may be an environment (e.g. liquid or air) or object that absorbs and then dissipates heat while in physical or thermal contact. This may occur in different ways including direct and radiant transfer of heat. A heat exchanger’s performance is a function of material, geometry, and the overall surface heat transfer coefficient along with the temperature of the heat sink. Generally, forced convection heat sink thermal performance is improved by increasing the thermal conductivity of the heat exchanger materials and increasing the surface area.

Thermal interface material (TIM) is used to fill the gaps between thermal transfer surfaces, such as between microprocessors and heat sinks, in order to increase thermal transfer efficiency. These gaps are normally filled with air, which is a very poor conductor of heat. The most common TIM is thermal grease, typically silicone oil filled with aluminum oxide, zinc oxide, or boron nitride.

Heat spreaders, most often simple metal plates, have high-thermal conductivity. Carbon-based heat spreaders having anisotropic characteristics are also being used. They act as a heat exchanger moving heat between localized heat and a secondary heat exchanger that is larger in area.

For all the passive components described above, heat will move through them as described by the general rules below:

1. There has to be a temperature difference; heat will only flow if there is a temperature difference
2. Heat always flows from a higher temperature to a lower temperature
3. The rate of flow is proportional to the difference in temperature
4. The flow of heat may be caused or assisted by both active and passive means

Active Cooling and Package Size

As overall sizes of electronic devices shrink, the size of the thermal management system must also shrink. Given that passive heat removal is only a linear function over distance of the temperature difference, work must be put into the system to obtain a greater rate of cooling and yield a smaller device.

One such example for optoelectronics of the continuing reduction in package size is shown below in Figure 4. In some instances, designers choose to place the cooling device outside the package because it is too large to be placed inside.

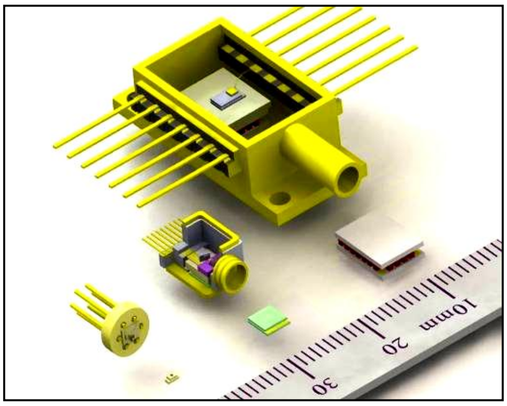

Figure 4: Size comparisons of optoelectronic packages and thermoelectric modules. From left to right, TO-56, TOSA and butterfly package

An active thermal management device, such as a thermoelectric module (TEM), has been employed to provide this additional heat pumping and temperature stabilization capability. A simple example of the type of heat pumping and temperature control offered by a TEM and its ability to cool a device is shown in Figure 5.

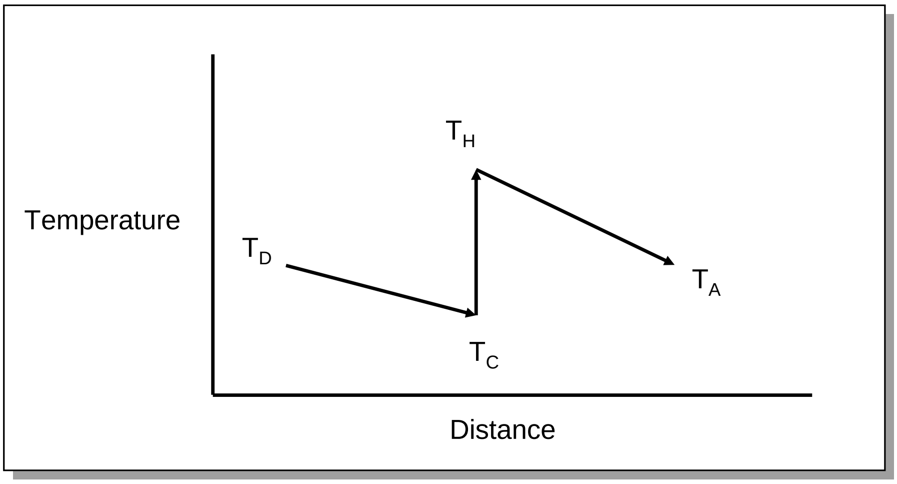

Figure 5: T_D is the temperature of the device to be cooled; T_C is the temperature of the cold side of the TEM; T_H is the temperature of the hot side of the TEM; and T_A is the temperature of the ambient or surrounding environment where the heat is to be dumped.

A Comparison of Active and Passive Cooling

As shown above, thermal management solutions for electronics may be divided into two types of systems: active and passive. With the exception of fans, which are usually combined with heat sinks, most of today's thermal management systems are passive types. Conduction-based thermal management systems, such as thermal interface materials (TIMs), are used to improve the flow of heat from one location to another and greatly enhance the efficiency of the overall thermal management system. However, convection-based systems have the drawback of allowing heat to flow in an uncontrolled manner from one level to the next.

These systems have served the industry well but have the drawback of removing not only the heat that is limiting device performance but also any of the heat from the surrounding area which likely is not limiting the device or system performance.

One solution is to apply an active device as a localized thermal management solution. This could be applied inside the electronic package. To reduce the cooling needed at the system and building levels, we need to reduce the amount of heat extracted from the die. Die are typically cooled to keep their operating frequency near its peak. However, this peak frequency is typically limited by the temperature within one of the hot spots on the die and not the temperature across the entire die.

If instead of extracting the heat from the die as a whole, we are able to extract the heat from the hot spot only, we will create a smaller system-level problem to deal with and subsequently have a smaller building thermal management problem.

Design Considerations

One of the drawbacks of thermoelectric devices is that in order to cool, they consume power. This power adds to whatever power is being pumped out of the cooling zone, so at the larger, system level more heat has to be dissipated with a TEM in operation than without one.

If TEMs are applied to cool devices in the same manner as passive thermal components, then the heat dissipation becomes a much larger problem at the system than at the chip level. A more cost-effective and efficient approach — and one that is only possible with TEMs — would be to cool only what is necessary. In other words, scale the thermal management system to the size of the heat problem.

This can be illustrated by looking at the coefficient of performance (COP) of a TEM, which is defined as:

$$COP = \frac{Q_{pumped}}{P_{in}}$$

A TEM will pump a certain amount of heat, Q, and add an additional amount of heat, Q*COP to move this heat. This is a result of the inherent inefficiency in all engines. As a result, bulk TEMs are often sold as systems that include the TEM and a heat transfer mechanism such as a fan and heat sink or liquid heat exchanger. The value of the TEM in this case is that it can deliver sub-ambient temperatures and provide active temperature control but at the cost of increasing the system level heat transfer problem.

Because heat in the passive case flows linearly, any thermal resistance between the TEM and the heat source will have a temperature drop across it. This will act to increase the temperature difference that the TEM must pull. As already mentioned, the TEM is a heat pump removing heat in a manner whose efficiency depends upon the temperature difference it is required to generate. Minimizing this temperature difference will improve the efficiency of the TEM and reduce the additional heat added at the system level.

Integration of a TEM close to the heat source is the key to improving a TEMs operational efficiency. Adding an additional heat transfer system defeats the purpose of the integration. As such, careful attention has to be paid to the characteristics of the heat transfer problem, the design of the thin film solution and also the design of the device package. When these three issues are addressed in tandem; ideally at the time of product design and development, significant performance improvements can be achieved.