Thermal Management
In Microelectronic Circuits

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Biography

Prakash Bhartia graduated with a B.Tech (Hons) from the ITT of Bombay and obtained his MSc and PhD degrees in Electrical Engineering from the University of Manitoba (Canada). He served as an Associate Professor and Assistant Dean of Engineering at the University of Regina, Saskatchewan. Over a 25-year career in the Canadian Department of Defence, he held four Director level positions and served as Director General of the Defence R&D Laboratories in Halifax and Ottawa over the past ten years.

Dr. Bhartia has published extensively with over 200 publications, 9 books and 5 patents to his credit. He was appointed to the Order of Canada in October 2002 and is a Fellow of the Royal Society of Canada, the IEEE, the Engineering Institute of Canada, the Canadian Academy of Engineers and the Institute of Electronic and Telecommunication Engineers. He was awarded the IEEE McNaughton Gold Medal for his outstanding contributions to Engineering. He has also served on many boards and senior level committees in Canada and internationally.

Thermal Management in Microelectronic Circuits

The increased trend to the use of hybrids/multichip modules (MCMs) brings about a requirement for improved thermal management methods in order to maintain system performance and reliability over a broad range of environmental conditions. Temperature changes affect characteristic parameters of both active and passive devices and result in performance degradation or even total failure. Some hybrids and MCM circuits have a built-in design to compensate for temperature variations, besides using other aids such as thermal die attach, heat spreaders, substrate-to-package attach, heat sinks, fans, micro-channel cooling, peltier coolers, etc. In this article, we discuss some fundamental heat transfer mechanisms and basic management techniques.

All microelectronic circuits are composed of different materials that expand, contract and transfer heat at different rates. So when dissimilar materials are soldered or bonded together, and subjected to the repeated operational heat cycles of the device or component, after time, heat sink bending, solder joint failure, ceramic warping, failure or cracking are possible. Thus, it is important to choose materials with as similar coefficients of thermal expansion (CTE) and thermal conductivity (TC) as possible. The table below gives the values of these two parameters for some of the most commonly used materials.

Table 1: Coefficient of Thermal Expansion and Thermal conductivity for some Common Microelectronic Package Materials.

Metals		
MATERIAL	**CTE** 10^{-6}/@25°C	**W/mK** @25°C
Kovar (FeNiCo)	5.5	17
Copper	17	400
Molybdenum	5.2	139
Nickel	14	90
Semiconductors		
Silicon	2.8	145
Gallium Arsenide (GaAs)	5.7	33
Germanium	5.8	60
Ceramics (substrates)		
Alumina	6.7	24
Beryllia	8.0	298
Aluminum Nitride	4.5	160
Silica	0.8	2
Organic Material (substrates)		
FR-4 (epoxy-glass)	16	0.1
Polyimide	30-60	0.1-0.2

Heat Transfer Mechanisms

In most devices, heat transfer occurs through conduction, convection and radiation and the thermal analysis can be performed by using an electrical circuit model with the thermal resistance Ø analogous to the electrical resistance R and thermal conductivity K, analogous to electrical conductivity σ. When different materials are stacked in series as is typical in a microelectronic circuit, the total thermal resistance is the sum of that of each individual element (see Fig. 1) i.e.,

$$R = R_1 + R_2 + R_3 + R_4 + R_5 \quad (1)$$

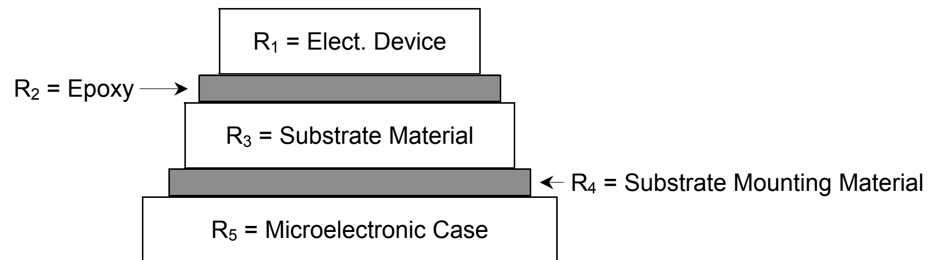

Fig. 1 – Illustrative material stack with analog resistance.

The thermal resistance of a particular material (R_m) is obtained from:

$$R_m = {}^{t}/KA \quad (2)$$

where t is the thickness of the material, K is the thermal conductivity in W/(ºC-in) and A the cross-sectional area of the material (in^2).

The temperature at a junction can be calculated from:

$$T_{i,i-1} = T_{hs} + S_k \sum R_{i-hs} \quad (3)$$

where $T_{i,i-1}$ is the temperature at interface of layers $_i$ and $_{i-1}$, S_k is the heat produced by the source attached to a heat sink of constant temperature T_{hs} and R_{i-hs} is the sum of the thermal resistance from interface of layers $_i$ to $_{i-1}$, to the heat sink.

For small heat sources, heat spreaders such as copper, molybdenum, aluminum nitride, etc. are commonly used and care is required to ensure that contact and bonding material thermal resistances of the heat spreader do not mitigate the gain afforded by the spreader.

Heat transfer also occurs by convection in fluids, by the mixing of the fluids and one can define a convective surface thermal resistance R_s given by:

$$R_s = 1/h_cA_s \qquad (4)$$

where h_c is the convection heat transfer coefficient in W/in^3-ºC and A_s is the surface area.

Convection cooling is either natural or forced and both methods are commonly used in the microelectronic industry.

Finally, all objects above 0ºK transfer heat by electromagnetic emission and this can be considered a surface related phenomenon and the emissivity (E) of a material defines its ability to radiate heat. Thus, a black body or perfect emitter has an emissivity of 1.0 and a perfect reflector – 0. The rate of emission of radiant energy from the surface of a body R is given by:

$$R = Q/A \quad W/in^2 \qquad (5)$$

where Q is the heat transferred in watts and A is the radiating surface area in in^2.

The Design Process

A microelectronic package may be very simple or quite complex. Fig. 2 shows a picture of a command and control hybrid of a satellite technology system that incorporates both power and signal circuits in one package. Since the heat generated in such a typical microelectronic package or semiconductor device flows through several layers, i.e., die attach, substrate attach, package, etc., one must perform a heat flow analysis to ensure proper and safe operation of the device or package. Computer-based techniques using the Finite Element method or finite Difference Technique are commercially available for this purpose.

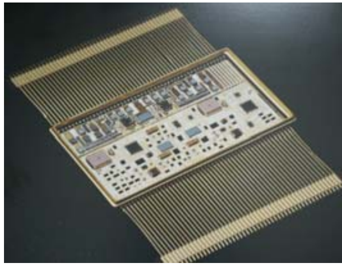

Fig. 2 – Command and Control Hybrid
(Photo courtesy of Natel Engineering Co., Inc.)

To start the thermal design, the designer must determine the total power to be dissipated from all of the components using quantitative methods or simulation programs. Further, knowledge of the environmental specifications and size and weight and available cooling mechanisms must be determined. A thermal analysis is then performed for each point and as required, components may be moved, materials changed and heat paths adjusted. Through this iterative process, an optimal design is established and a prototype built and evaluated for thermal performance.

For thermal management, one resorts to heat sinks, the most common type being a finned heat sink typically fabricated from a high thermal conductivity material. In many cases, additional air cooling using more surface area or fans may also be required. For best results, air gaps need to be avoided and, as appropriate, spaces should be filled with solder, thermal grease, elastomers, thermal conductive tape, etc. Other techniques for cooling should also be considered depending on the heat management problem. Amongst these are flow-through, cold wall, immersion, micro-channel cooling, etc., and in certain cases, one may have to resort to special methods such as thermoelectric coolers, heat pipes, etc.

<u>Conclusion</u>

In summary, heat management in microelectronic circuit packages is as much an art as it is a science and requires the use of proper modeling tools and knowledge base in designing an adequate regime. While some fundamentals have been discussed here, details are available in many handbooks.