Basics of Thermal Management Materials for Microelectronics – theory and practise

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Abstract—**Due to the increasing need for product functionality and the reduction in device size, thermal management has become a key design criterion for electronic systems. An understanding of the key fundamentals of thermal management, and, more practically, the materials commonly used for heat transfer are key tools for engineers in today's fast moving design environment. This paper presents an overview of the basics of passive thermal management, focusing on the materials and techniques commonly employed. Materials such as thermal gap pads, phase change materials, thermal greases and thermal putties are discussed. A series of key questions that the thermal engineer needs to consider to fully optimize the design are also presented.**

Index Terms—**thermal management materials, TIMS, thermal grease, phase change materials, thermal putty, gap fillers**

I. Introduction

The past few decades have seen an escalation of power densities in electronic devices [1], and in particular in microprocessor chips. Together with the continuing trend of reduction in device dimensions this has led to dramatic increase in the thermal issues within electronic circuits [2]. Thermal management is therefore becoming increasingly more critical and fundamental to ensuring that electronic devices operate within their specification.

Although a thermal management system may make use of all modes of heat transfer to maintain temperatures within their appropriate limits and to ensure optimum performance and reliability, conductive heat transfer is typically used to spread the heat out from its point of generation and into the extended surface area of a heat sink. To minimize the contact resistance, thermal interface materials (TIMs) are often introduced to the joint to fill the air gaps and are an essential part of an assembly when solid surfaces are attached together [3].

In general, various interfaces will exist between the high power, heat generating component and the eventual heatsink. Some of these interfaces will consist of permanent bonds, such as solders or adhesives, but often a non-permanent interface will form part of the heat transfer path, e.g. where a component is bolted to a heatsink or between an assembled module and a chassis. When these surfaces are attached together there will almost always be only a small area of actual mechanical contact between the two surfaces at this interface, due to the micro-scale surface roughness and waviness of the surfaces [4].

This will have an impact on the heat conduction across the interface, as there will be gaps filled with low thermal conductivity air [5]. The irregularity of real surfaces is therefore a primary cause of thermal contact resistance. In order to minimize the thermal contact resistance, filler materials, known as thermal interface materials (TIMs) are therefore generally required to enhance the contact between the mating surfaces [6]. The surface flatness, or waviness, is determined by comparing the variance of the height in a specimen to that of a reference standard. For heatsinks, the attachment face should have flatness less than 4 µm per cm to be considered satisfactory. Surface roughness (finish) is defined as the average deviation from the mean surface height. In general for very low thermal resistance, a surface finish in the range of 1.27-1.5µm is recommended [7].

The effective total thermal resistance at the interface between two materials is the sum of the resistance due to the thermal conductivity of the TIM and contact resistance between the TIM and the two contacting surfaces [8]. In order to fully understand this it is necessary to define a few basic concepts. Thermal conductivity (k) is the intrinsic property of a material which relates its ability to conduct heat. Heat transfer by conduction involves transfer of energy within a material without any motion of the material as a whole. Conduction takes place when a temperature gradient exists in a solid (or stationary fluid) medium. Conductive heat flow occurs in the direction of decreasing temperature because higher temperature equates to higher molecular energy or more molecular movement. Energy is transferred from the more energetic to the less energetic molecules when neighboring molecules collide.

Thermal conductivity (k) is the time rate of steady state heat flow through a unit area of a homogeneous material induced by a unit temperature gradient in a direction perpendicular to that unit area, W/mK:

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

Where,

L – Thickness of the specimen (m)
T – Temperature (K)
q – Heat flow rate (W/m2)

Thermal resistance, R, is the temperature difference, at steady state, between two defined surfaces of a material or construction that induces a unit heat flow rate through a unit area, and is defined as Km^2/W. Therefore, the value of the thermal resistance can be determined by dividing the thickness by the thermal conductivity of the specimen:

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

Where A is the cross sectional area.

Thermal resistance can, therefore, be shown to be directly proportional to thickness and makes the basic assumption that the material is homogeneous. For non-homogeneous materials the relationship may not be linear.

However, because true surfaces are never perfectly smooth the contact between surfaces can also contribute to the resistance of heat-flow. This is referred to as surface contact resistance and can be a factor in correctly determining heat flow.

The thermal impedance (Z) of a material is defined as the sum of its thermal resistance plus the thermal resistance of contacting surfaces:

$$Z = R_{material} + R_{contact}$$

Considerations such as flatness, clamping pressure, surface contamination etc need, therefore, to be taken into consideration.

Proper and effective thermal management and heat dissipation for electronic devices from computers to LED lighting and solar panels are critical for performance and reliability [9]. Thermal conductivity of a thermal interface adhesive or compound is commonly used as a "gauge" of how good it may be in helping to dissipate heat from a device. This should not be the only measure for the potential effectiveness of a material as a thermal interface for as other parameters are of equal importance

II. TYPES OF THERMAL INTERFACE MATERIALS

In applications where heat is generated from components of various heights and there is a need to dissipate the heat to a heat-sink or an external metal casing, thermal interface pads are employed. These products are soft, conformable sheets in thickness from 0.125 mm to 10 mm or thicker that can be compressed to give a good thermal interface.

A. Thermal Interface Pads

The softness of the gap fill pads helps eliminate air gaps between components and the heat-sink while conforming to the curvature and warp of the mating surfaces. Generally, these are soft and easily of compressible to accommodate the different profile heights of multiple components and remain stress- free whilst providing outstanding mechanical shock absorption. Gap pads offer a good combination of thermal performance, cost-effectiveness and ease of manufacture. They can be supplied in many forms, such as sheets, tubes, moldings, rolls or die cut parts.

Thermal interface pads are traditionally made using a silicone filled with a thermally conductive filler material, which may be either $Al2O3$ or. However, for more demanding applications, where silicone outgassing could be an issue, acrylic or epoxy based formulations are commonly employed.

The thermal conductivity of a particle filled thermal interface materials is given by [10]:

$$K_{tim} = \int k_f, k_m, \theta, R_b$$

Where:

$K_{(f)}$ is the thermal conductivity of the filler
k_m is the thermal conductivity of the matrix
Θ is the filler volume fraction
R_b is the contact resistance between the fillers and the matrix

For spherical filler particles, up to approximately 35% loading, a Maxwellian model can be used to predict the thermal conductivity. However, beyond this percolation occurs and a modified Bruggeman model can be used [11]:

$$k_{tim} = k_m \frac{1}{(1-\theta)^{3(1-\alpha)(1+2\alpha)}}$$

Where α is given as:

$$\alpha = \frac{R_b K_m}{d}$$

Where

R_b is the thermal interface between the filler and the particle
d is the diameter of the particle

B. Phase Change Materials

Phase Change Materials (PCMs) are solid materials at room temperature that melt at operating temperatures forming intimate contact on the mating surfaces to produce a low thermal resistance. Generally, PCM materials are used as a replacement for grease, which can be messy in a production environment and has been shown to exhibit migration, or pump out issues, particularly under conditions where thermal cycling occurs.

Generally the phase change occurs at a temperature of 50 – 70^{0}C. This is chosen so that the material will flow when the device is initially powered up but will not flow during transportation or storage. Typically these materials are composed of a mixture of organic binders, thermally conductive fillers, and an optional substrate such as polyimide or aluminium to give additional functionality and ease of handling.

In use the PCM material will initially perform like a dry joint. However, as the operating temperature increases the material will flow under the pressure of the clips used to attach the heatsink. As the material flows it displaces the interstitial air and this lowers the thermal resistance. The next time the device is powered up there will not be this delay in achieving good thermal management as the thermal joint has already been established.

The thermal conductivity of the PCM is limited by the volume of ceramic particles that can be added to the material without adversely affecting the viscosity of the PCM whilst the thickness of the interface formed will be a function of clamping pressure, surface roughness and the rheological properties of the PCM. It is for this reason that it is essential that adequate clamping pressure should be applied to PCM materials via screws or spring clips.

C. Thermally Conductive Insulators

Thermally conductive insulators are thin, thermally conductive materials designed for a wide range of applications where good thermal transfer and electrical isolation are required. One of the most critical parameters for insulators is the dielectric breakdown voltage.

The dielectric breakdown voltage is defined as the maximum electrical field strength that the material can withstand without breaking down and losing its insulation properties.

The dielectric strength of a material is an intrinsic property of the bulk material and is dependent on the configuration of the material as well as the rate of applied voltage. Defects in the material mean that the actual breakdown strength will also be a proportion of the theoretical maximum value. Typically dielectric breakdown voltages are measured with reference to ASTM-D149-09.Thermally conductive insulators can be supplied in sheet, tube, rolls or die-cut form depending on the end application.

D. Thermally and Electrically Conductive Materials

Where electrical conduction is needed as well as thermal conductivity it will be necessary to use a thermally and electrically conductive material. For solid pads these materials are predominantly graphite based whilst electrically conductive greases and pastes are often based on a silicone matrix filled with electrically conductive particles or fibres. Generally these products are used for high power electrical applications, power switches, circuit breakers and grounding semiconductor components.

E. Thermally Conductive Adhesive Tapes

Thermally conductive adhesive tapes are used to mechanically and thermally bond electronic components to heat sinks. These tapes allow for easy joining of many substrates with light pressure in just seconds at room temperature. These tapes are permanently tacky consisting of a pressure sensitive adhesive (PSA) film filled with ceramic particles. These particles allow thermal conduction through the tape. The tape provides an excellent combination of thermal conductivity, electrical isolation and adhesion. The product formulation means there is no carrier layer, which allows for superior gap filling between the bonded surfaces. This improved surface contact results in higher bond strength and lower thermal resistance. The PSA properties of these tapes make them easy to handle and apply and are also repositionable and reworkable during assembly, and the final bond is permanent, eliminating the need for clamps and screws.

F. Thermal Greases

Thermal greases are low viscosity, thermally conductive materials which can be used to transfer heat between a heatsink and a heat source. These materials are used to provide a very thin bond line thickness (BLT) which optimises the thermal transfer.

BLT minimisation is a primary goal of thermal management. BLT is a function of application pressure and material formulation. Equations have been derived that give an approximation of the BLT for particle filled TIMS [12]:

$$BLT = 1.31 \, x \, 10^{-4} \left(\frac{\tau_y}{P}\right)^{0.166}$$

Where:
τy is the yield stress of the TIM
P is the applied pressure

The practical application of this equations means that as the yield stress increases with filler content the bond line thickness will also increase. Thus, there will always be a trade-off between the maximum thermal conductivity achievable with the bond line thickness.

G. Thermal Gels

Thermal gels are one or two part systems which are cured in place to give a permanent and durable thermal interface. In the uncured state, these materials are soft enough to assemble components under low force and then cure to a harder state.

H. Thermal Putties

Of all the TIMs commercially available, thermal putties are perhaps the most interesting and offer the designer the most opportunities for low total cost of ownership thermal management. These products are one-part, fully cured thermally conductive materials which can be applied to a surface using a number of means. These materials are supplied fully cured but have a viscosity which allows them to be dispensed or printed in the same way as a conventional grease.

These materials are ultra-soft, transfer little or no pressure between bonded surfaces and are more viscous than grease or phase change materials so many of the problems associated with these classes of materials are removed.
These materials are especially useful for filling large gaps or for areas where there is significant variation in surface height or roughness.

III. Selecting The Best TIM

Choosing the best thermal interface material (TIM) will depend on the specific application, manufacturing process and operating conditions. Some of the various factors that affect the selection of thermal interface materials include:

A. Thermal conductivity.

A TIM's bulk thermal conductivity determines its ability to transfer heat across the interface and as such has a significant impact on its thermal performance. However this parameter should not be the overall driving force for selection.

B. Hardness

The hardness of a TIM, which is measured using one of three Shore hardness scales, is critical for TIM performance as this will determine how easily the TIM fills in micro-asperities and voids. This is turn will have a pronounced effect on the effectiveness of the heat transfer.

C. Thermal resistance

This should ideally be as low as possible to maintain the device below its maximum working temperature

D. Phase change temperature.

The phase change temperature is the temperature at which for PCM materials the transition from solid to liquid occurs and the interface material fills the gaps, ensuring that all the air is expelled. It is therefore important that the transition temperature is below the maximum operating temperature of the device so that it can effectively transfer heat across the interface, but as high as possible to avoid a phase change occurring during shipping.

E. Viscosity

The viscosity of a PCM (above its phase change temperature), grease or putty should be high enough to prevent the interface material from flowing when placed in a vertical orientation as this could result in dripping or draining of the TIM out of the assembly.

F. Operating temperature range

It is important that the TIM selected works over the entire operating temperature range of the device. Most silicone based TIMs operate from approximately -40 – 200C. Acrylic based materials tend to have a lower operating temperature range and can therefore not be used in more demanding applications.

G. Pressure

Mounting pressure due to clamping can make a significant difference in TIM performance and its ability to conform to surfaces to minimise contact resistance. A soft silicone based gap filler will provide conformability at low pressure whereas, a glass reinforced insulating pad will require a higher mounting pressure in order to effectively reduce contact resistance

H. *Outgassing*

This phenomenon is the release of volatile gases when materials are exposed to elevated temperatures and/or low atmospheric pressures. Most polymers, including elastomers, silicones, etc., outgas to some degree. This can be a concern in aerospace applications where outgassing is accelerated due to reduced pressures and may also cause problems within sealed cavity packages. For applications where this is deemed critical a non-silicone gap filler maybe the preferred solution.

I. *Surface finish*

Some TIMs fill large gaps in irregular surfaces better than others and the interaction of filler particles with the microscopic projections at the adjoining surfaces influences the level of compaction and wetting at the interfaces.

J. *Ease of application/installation*

Depending on the material, control of the amount of TIM applied e.g. grease, gel or putty is important. Selecting a material which can be dispensed, printed or applied using readily available commercial equipment may greatly reduce the total cost of ownership of the TIM

K. *Mechanical properties of the material*

TIMs in paste or liquid state could need to be dispensed or printed. Although a higher filler volume fraction increases the thermal conductivity it also increases the viscosity of the mix making it more difficult to dispense. A higher volume loading of filler could also have a detrimental effect on the lifetime of any pumps used to dispense the material so this needs to be factored into any cost of ownership calculations.

L. *Long term stability and reliability*

The TIM is required to perform consistently throughout the lifespan of the device. Electronic devices such as microprocessors are designed to survive typically for seven to ten years, whereas avionics and telecommunication devices are expected to survive for decades. It is important to consider the working temperature, the pressures applied to the TIM and any vibrations that the device will endure during its lifetime.

There is a complex relationship between the variables outlined here which will determine the choice of TIM and ultimately, performance, cost and manufacturability concerns dictate the trade-offs that are made during TIM selection for a particular application.

IV. Conclusions

Selection of the appropriate thermal interface material for effective electronic cooling depends on a number of parameters. It is necessary to consider not only the type of TIM but also the overall design of the system and the environment in which it will be used. Failure to consider the overall system, and focus on one parameter of the TIM, such as thermal conductivity, can be detrimental to product life time and result in a significantly reduced lifetime.

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