Testing interface thermal resistance

Márta Rencz
Budapest University of Technology and Economics,
Budapest XI, Goldman György tér 3. H-1111 Hungary, (+36-1) 463-2727

Abstract
The paper presents some recent trends in TIM material development, and outlines the state of the art in testing interface thermal resistance values. After presenting the trends in TIM material development first the available experimental techniques are presented shortly, and then the currently available industrial methods are discussed with more details. The paper finally presents some promising developments in finding better resolution high throughput methods to solve the challenging problem of measuring very small thermal resistance values in electronics applications.

Nomenclature
- \( R_{th} \) Thermal resistance (K/W)
- \( T \) Temperature (K)
- \( A \) Area (cm\(^2\))
- \( Q \) Heat flux (W/cm\(^2\))
- \( L \) Thickness (cm)
- \( \lambda \) Bulk thermal conductivity (W/m-K)
- \( \theta \) Thermal resistance per unit area (Kcm\(^2\)/W)

Introduction
Heat dissipation of semiconductor packages has become one of the limiting factors in miniaturization. One of the biggest concerns of circuit designers is to reduce power that is continuously increasing due to increasing bandwidths. The increasing power results in increasing temperature in the chip that first just modifies, later destroys the operation of the circuit, if the heat is not appropriately lead out of the chip. The heat transfer to the outside world can be improved by better heat sinks, higher air velocities and liquid cooling if the application allows it. But the heat first has to reach the surface of the package, and the efficiency of this heat transfer depends on the conductivity of the package itself, and the interface thermal resistance that is defined as the sum of the thermal resistance of the interface material (TIM) plus the contact resistances.

Characterization of thermal properties of Thermal Interface Materials (TIMs) has gained increasing importance as the relative percentage of overall semiconductor package material thermal resistance attributed to the TIMs has increased. The development of new TIM materials has resulted in materials with very high performance and in certain instances with very thin in-situ application thickness, giving very small thermal resistance values. As the high power densities request for even better performing thermal interface materials we will soon face the challenge of measuring \( R_{th} \) values that the current technology is not able to test, or at least not with such a high throughput that would allow to apply the methodology in manufacturing testing.

These trends have placed increasing focus on the methods to characterize the thermal conductivity of TIM materials and in-situ \( R_{th} \) values, to the development of characterization equipment, and to verify the accuracy and repeatability of results.

Thermal interface material is used at several layers in complex packages - stacked die packages contain as many TIM layers as the number of stacks - but we usually distinguish TIM1 and TIM2 layers even at single die processor packages, see Figure 1 [1].

TIM1 is the biggest challenge to test, as it is in contact with the chip itself and it is normally difficult to access. On the other hand the quality of TIM1 is usually responsible for the reliability of the package and the whole operation of the chip, since any void or manufacturing problem in the TIM1 layer may result in overheating and destroying the chip during the operation. Note that although a number of very important other mechanical properties have to be achieved to have a good TIM material, in the present paper we focus our discussion only to the consideration and characterization of the thermal conductivity, as the most important parameter from the thermal management’s point of view.

In the rest of the paper first some trends in the development of TIM material is presented in order to demonstrate the challenges what does testing the thermal resistance of the TIM1 layer represent today in leading edge packaging. After this a short overview is given about the methods of testing TIM material in general. A recently developed transient methodology is discussed with somewhat more details that is used for in-situ testing the thermal resistance value represented by the TIM1 layer in electronics packages. As conclusion, some recommendations are given and the future trends in TIM characterization are summarized.

Trends in TIM material development
Common TIMs include a variety of polymer-based materials with high thermal conductivity particle inclusions, typically with diameters of 2-25 µm. The effective thermal conductivities of particle-filled polymer interface materials are...
typically about an order of magnitude higher than the polymer matrix alone, i.e. of the order of 2 W/mK. The resistance found in commercial products can be substantially larger than the anticipated values (typically 0.1 Kcm²/W) owing to resistances at the TIM boundaries and small voids. This has motivated the recent progress on using solders, which may provide conductivities in the range of 10-100 W/mK, but due to their mechanical stiffness these metallic TIMs are less attractive for TIM1 application.

Carbon nanotubes (CNTs) were expected to solve all the problems of high conductivity TIM material as their theoretical thermal conductivity was reported extremely high, but the values that could have been measured in manufactured TIM material so far have disappointed the engineering community. CNTs possess in fact an exceptionally high thermal conductivity in the axis direction according to molecular dynamics simulations and experimental measurements. For an individual single wall carbon nanotube (SWCNT), it can be as high as 5000-8000 W/mK and that of an individual multi wall carbon nanotube can reach 3000 W/mK [6]. Thus CNTs have a great potential to be employed for integrated circuit thermal management applications. As high thermal conductivity of the filler is needed in TIM1 materials for high performances CNTs with their outstanding thermal conductivity are obvious candidates. It is reported that the use of dispersed CNTs as thermal conducting fillers in polymer composites has resulted in an increase above 50% of the thermal conductivity [7],[8] achieving a measured thermal conductivity of 40 W/mK. But the enhanced values are still not satisfactory due to several problems:

- The existence of interface thermal resistances, see Figure 2,
- Non perfect crystalline structure of the CNTs,
- Non uniform dispersion of CNTs in epoxy resins,
- Weak bond between CNT and the epoxy material, resulting in increased interfacial resistance.

In order to understand the physics of TIM performance, three factors have to be known: (1) the λ, bulk thermal conductivity of the TIM; (2) the BLT bond line thickness, see Figure 2; (3) the R₀, contact thermal resistance of the TIM.

The use of nanoparticles and nanotubes is almost inevitable in finding better performing TIM material. The research and development in this field will have to focus on minimizing the total thermal resistance rather than just increasing the thermal conductivity. Minimizing the contact resistance will become a more and more important issue in realizing thin highly conducting TIMs.

**Techniques used today to characterize TIM performance**

The major challenge in TIM testing is caused by the fact that there is a significant difference between standardized lab test data and application-specific (or “in-situ”) test results in a specific set of application conditions. Standardized test methodologies are mandatory because the user has the right to a fair comparison between various TIMs from various vendors [9].

Measuring the thermal conductivity is not easy in general. The λ (or sometimes k) thermal conductivity is the intensive property of a material that indicates its ability to conduct heat. It is defined as the quantity of heat, Q, transmitted in time t through a thickness L, in a direction normal to surface of area A, due to a temperature difference ΔT, under steady state conditions and when the heat transfer is dependent only on the temperature gradient

$$\lambda = \frac{Q}{t} \cdot \frac{L}{A \cdot \Delta T} \quad (1)$$

To measure it we should know the exact values of the quantities in Eq (1), which is normally very problematic in TIMs. E.g. looking at Figure 2 it is easy to understand that the layer thickness is not uniform, consequently the temperature values along the interface will be also different, and assuring uniform heat flux along the sample is also extremely difficult. This explains why is TIM testing in the focus of academic and industrial research today, when the high quality TIM manufacturing needs appropriate measurement methods.

The extremely increased TIM material performance will be very difficult to follow by the currently available measurement techniques. The requirements here are twofold. First techniques are needed to characterize the TIM material in itself, independently from the future applications. For this purpose complex, very expensive and slow techniques are also acceptable, as these measurements do not have to be done in very high volumes. We call them now experimental methods. To characterize the TIM performance in a given electronics application, e.g. to find the R₀, value of a TIM1 layer in a processor package during manufacturing testing raises new requirements: these measurements have to be very fast in situ measurements with somewhat less demanding accuracy requirements. We call them here now industrial methods.

![Figure 2: Interfacing with TIM material](image)
**Experimental methods**

Some of the major experimental methods used today to characterize TIM performance are briefly presented below.

1. **Direct measurement of the thermal properties on special samples**

   Figure 3 presents a potential arrangement for measuring the thermal diffusivity (that is the ratio of the thermal conductivity to the volumetric heat capacity) of a dedicated sample if thermal sensors are manufactured at the interfaces.

   ![Figure 3: Direct thermal diffusivity measurement](image)

   A driving force (temperature difference, electronic potential, energetic laser pulse, etc. depending on the method) induces interactions on atomic or molecular level. This response allows to obtain insight into the physical properties of the thermal interface, allowing to measure the thermal resistance ($R_\text{th}$), the thermal conductivity/diffusivity, the interface resistance and the electrical conductivity on a continuum or sub-micron scale. The measurement techniques can be either static or transient, each of which has certain advantages with respect to sensitivity to a specific physical property (e.g. diffusivity or conductivity), resolution or applicability. The method needs special sample preparation, and maintaining uniform thickness is not easy. The cost and the accuracy of the experimental measurement are determined by the accuracy of the apparatus used for heating and measuring.

2. **Transient thermo reflectance measurement**

   The transient thermo-reflectance method (TTR) [11] is a frequently used experimental technique to determine the thermal conductivity of thin film and multilayered materials. It is a non-contact and non-destructive optical approach, both for heating a sample under test and for probing the variations of its surface temperature [10]. As the method is non-invasive, it is attractive for the measurement of the thermal properties of thin-layer materials as well.

   The basic principle of the transient thermal reflectance method is to heat a sample by laser irradiation and probe the changes in the surface reflectivity of the heated material. The source of energy in the TTR method is normally provided by a pulsed laser with short pulse duration. During each pulse, a given volume on the sample surface heats up to a temperature level above ambient due to the laser light energy absorbed by the sample. The heating area is specified by adjusting the pulsing laser aperture and the optics of the system. The depth of the volumetric heating, on the other hand, is determined by the optical penetration depth, which is a function of laser wavelength and surface material properties. After each laser pulse is completed, the sample begins to cool down to the initial ambient temperature. During this process, the probing laser light reflected from the sample surface at the heating spot center is collected on a photo detector that reads the instantaneous surface reflectivity. The influence of a pulsed laser irradiation on a given material depends both on the optical properties of that material as well as on the wavelength and pulse duration of the laser itself. This makes the technique rather complex and its everyday application for TIM testing at this moment seems rather improbable.

3. **The 3-omega method**

   The 3-omega technique was developed by Cahill [12]. It is similar to the hot-wire technique in that it utilizes radial flow of heat from a single element which is used both as a heater and a thermometer. The major difference is the use of the frequency dependence of a temperature oscillation instead of a time domain response. A narrow heating element is deposited on the sample to form a narrow line source of heat on the surface of an infinite half volume using either photolithography or evaporation through a mask. An a.c. power of controllable frequency is supplied to the heater, and the temperature response of the heater is determined from its thermal impedance. The thermal conductivity is determined from the power and the third harmonics of the voltage oscillations. Recent papers question however the accuracy of the method [13], demonstrating that complex error correction is needed to obtain accurate thermal conductivity results with the method.

   The above listed techniques are more or less applicable for the laboratory testing of thermal conductivity values of material layers, but are not applicable for in-situ industrial applications.

**Industrial methods**

The industrial methods are either standardized methods, to allow better comparison of the measured results, or they are application specific (sometimes ad hoc) methods assuring very fast measurement to allow in-line application for reliability assessment.

1. **The current primary steady state method: the ASTM D5470-01[14]**

   The ASTM D-5470 test method is a standard method to measure thermal resistance and bulk conductivity for TIMs such as pads, tapes, greases and phase change materials. The sample is placed between a hot meter bar and a cold meter bar and a steady state of heat flux is established. The ASTM test defines thermal resistance per unit area, $\theta$, to include the thermal resistance of the material ($\theta_{\text{material}}$) plus the interfacial contact resistance of the TIM to the substrates ($\theta_{\text{interface}}$):
Fourier’s Law describing one-dimensional heat flow defines the thermal resistance per unit area of a material as:

\[
\theta_{\text{material}} = \frac{\Delta T}{A} = \frac{Q}{\lambda_{\text{bulk}}}
\]

where \( \Delta T \) is the temperature difference across the TIM under test, \( A \) is the area of the meter bars, \( L \) is the thickness of the sample, and \( \lambda_{\text{bulk}} \) or \( k_{\text{bulk}} \) is the material bulk conductivity. The heat flux \( Q \) is either measured from the temperature drop along the meter bars length (requiring multiple temperature sensors in each bar) or it is identified by carefully determining the power supplied to the hot bar and by using guarding and/or insulation of the bars to eliminate any heat loss. Combining equations 2 and 3,

\[
\theta_{\text{total}} = \theta_{\text{interface}} + \frac{L}{\lambda_{\text{bulk}}}
\]

which is known to be sensitive to the testing surfaces (material type, flatness, roughness, and conditioning by previous samples), the correlation of \( \theta_{\text{total}} \) to thermal test vehicles has shown correct rank order but the ASTM test under-predicted the in-situ thermal resistance [16,17]. This difference in absolute value was attributed to the assemblies having different surface properties compared with the ASTM tester. One advantage of the ASTM test is that Equation 3 allows one to obtain \( \lambda_{\text{bulk}} \) independent of these interfacial effects, yielding a material property. The \( \lambda_{\text{bulk}} \) along with \( \theta_{\text{total}} \) measured at representative pressures and gaps can be useful in selecting candidate materials for in-situ evaluation. Depending upon the TIM under consideration, the gap in-situ, and the nature of the in-situ surfaces, the contact resistance, \( \theta_{\text{interface}} \), may be a large portion of the total resistance to the \( \theta_{\text{total}} \) heat flow. Furthermore, it should be realized that the ASTM D5470-01 is only valid under the following assumptions:

- Truly one-dimensional heat flow,
- Constant thickness during measurement,
- Thickness independent contact resistance.

The one-dimensional heat flow assumption has been investigated by modeling with the conclusion that the 1D heat flow can be ensured if the meter bars are long enough, the temperature sensing holes are far enough apart and the position of these holes is known with high accuracy. The latest version of the ASTM test addresses methods to hold constant or measure the gap during the test. If the contact resistance is a function of thickness a straight line is not obtained when plotting the data according to Equation 3, so this assumption can be tested.

The most important shortcoming of the ASTM method has been its use of high pressure during the test [9]. This pressure is useful in coalescing elastomeric TIM material layers which are stacked to obtain the thickness variation required for analysis using Equation 3. In addition, the high pressure reduces the contact resistance between solid samples and the meter bars. With grease and phase change TIMs high pressure testing will result in a lower gap settings than seen in most applications and if the \( \theta_{\text{total}} \) is only reported at this thinnest gap, the value of \( \theta_{\text{total}} \) will be lower than seen in an actual application. Most TIM vendors address this issue by publishing \( \theta_{\text{total}} \) as a function of pressure so users can estimate the \( \theta_{\text{total}} \) for their application. The next revision of the ASTM method will officially make provisions for lower pressure testing [14].

Another drawback is that even today no commercial source is available guaranteeing consistent quality. Each machine has been built uniquely for the specific user. Such a wide variety of instrumentation has led to the historic inter-laboratory error.

A final drawback of this method is that the problems associated with thermal conductivity measurements are often underestimated, even by experts, because the principle seems so easy. It is recommended that users become familiar with some recent papers, e.g. [1, 19,20] which discuss the issue and cover the technical difficulties of building reliable ASTM D5470-based equipment.

2. Transient methods

It is commonly believed that as transient methods are faster in general than steady state methods they are better applicable for industrial measurements. Two branches of the transient methods have been intensively discussed in the literature in the last years. The structure function based methods allow determining partial thermal resistances in a heat flow path [21], based on rigorous mathematical transformation of the measured heating or cooling curves [23].

Structure function based TIM testing methods

The example given below the measured sample contained stacked thermal test dies for verification purposes. The cross section of the measured packages is shown in Figure 5. In the experiment presented in details in [24] the top die was used as heater and temperature sensor. The bottom was connected to a cold plate to assure one dimensional heat flow from the top die towards the cold plate. The thermal transient

\[
\begin{align*}
\theta_{\text{total}} &= \theta_{\text{material}} + \theta_{\text{interface}} \\
\theta_{\text{material}} &= \frac{\Delta T}{A} = \frac{Q}{\lambda_{\text{bulk}}} \\
\theta_{\text{total}} &= \theta_{\text{interface}} + \frac{L}{\lambda_{\text{bulk}}} \\
4.00 & \ 3.50 & \ 3.00 & \ 2.50 & \ 2.00 & \ 1.50 & \ 1.00 & \ 0.50 & \ 0.00 \\
4.00 & \ 3.50 & \ 3.00 & \ 2.50 & \ 2.00 & \ 1.50 & \ 1.00 & \ 0.50 & \ 0.00 \\
\end{align*}
\]
measurements on the top die were done by the T3Ster thermal transient tester and software [25].

Figure 5: Cross section of the measured packages from the paper of [24]

The structure function shown in Figure 6 was constructed automatically by the measuring equipment from the measured driving point thermal impedance, referring to the top die. In this figure the horizontal axis shows the thermal resistance values measured from the heated top die towards the ambient. On the vertical axis the thermal capacitance values are shown in logarithmic scale. This curve is called the cumulative structure function. The first vertical step of the cumulative structure function refers to the thermal capacitance of the first element in the heat flow path that is the top die itself. The next element of the structure is the die attach under the top die: appearing with its high thermal resistance value in the figure and an almost horizontal section in the structure function. The next very steep section of the curve refers to the bottom die: both the thermal resistance of the next die attach and the thermal capacitance the second die can be read from the function. In a similar way thermal resistance/thermal capacitance values corresponding to further structural elements in the heat-flow path can be identified. At the end of the curve the capacitance of the lead frame and the thermal resistance from the lead frame to the cold plate can be read. As presented in the example the thermal resistance of the different TIM layers can be easily and readily read from the structure functions with very short transient measurements 21.

Figure 6: The obtained cumulative structure function of a sample of a 2 die package

Another structure function based method is presented in [21] and discussed also in [9]. The differential structure function (that is the derivative of the cumulative structure function, giving peaks at the region transitions) of the sample of Figure 7 shows a well identifiable peak at B.

Figure 7: Outline of a fixture for TIM testing. The measurement is to be done with and without the TIM sample to be tested

The peak at B shifts to the left if sample material is placed between the faces of the fixture. The shift in the location of the peak B gives the $R_{th}$ value of the sample.

The advantage of the method is its simplicity, but to increase accuracy high precision version with pressure control has to be developed.

A transient method based on the comparison of measured and simulated transient curves

Papers [9] and [27] present a method that is targeting industrial application but is still in experimental phase. In this method the experiment of the testing apparatus is compared to the 18 parameter model of the structure, and the numerical simulation helps to find optimum accuracy between the measured and simulated results.

3. Special thermal test dies

For the sake of completeness we have to mention also the specific thermal test vehicles that are more and more frequently used in the industrial development process to verify...
the measurable characteristics of the packaged circuit [28, 29]. The thermal test die used in the package of Figure 5 is a good example for using a specific thermal test vehicle. This is a die with uniformly placed heater and sensors, enabling to emulate the operation of the final device in the package in order to assure optimization of the TIM technology, and other elements of the packaging for minimal junction temperature. Of course both static and transient measurements can be used to characterize the behaviour of the TIM layer placed between 2 such thermal test dies.

Conclusions

The main objective of the paper was to summarize the current status and some future trends in TIM testing that is considered by many experts one of the major issues in thermal management in the near future. Several problems have to be solved very soon that can be listed as follows:

- The current standard the ASTM D5470-01 has to be further developed for TIM material testing
- Application specific methodologies should be standardized to enable the comparison of in-situ TIM applications
- Reference materials should be defined to allow calibration of the different methods
- A common nomenclature should be used among physicists, electrical and mechanical engineers involved in TIM characterization
- Organization of round-robin tests to compare methodologies, etc

Some good signs in these aspects may be observed already. The JEDEC 15.1 committee has placed the subject of TIM testing already on its roadmap [30], and work is going on already for a while. In Europe a special consortium has been formed and an integrated project will be sponsored by the EU called “NANOPACK” that is aimed at developing better TIM material and new methodologies to test them. With these combined efforts a burst in developing new or improved methodologies for testing TIM material is expected in the very near future.

Acknowledgments

This work was supported by the PATENT IST-2002-507255 Project of the EU and by the OTKA-TS049893 project of the Hungarian Government.

References