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# Improved method for thermal conductivity measurement of polymer based materials for electronic packaging

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## Abstract

The increasing demand on higher packaging density, higher frequency and higher power of electronic devices is a challenge for contemporary engineers to be able to simulate and prototype the thermo-mechanical problems. The heat dissipation problem is becoming nowadays a crucial issue and requires application of materials with high thermal conductivity and novel packaging methods. The lacking knowledge on precise thermal conductivity properties of most polymer materials used in electronic packaging (adhesives, underfillers etc.) is a basic problem referring to simulation of temperature distribution in modern electronic packages. The main problem in precise measurements thermal conductivity is thermal contact resistance and its non-linear properties. The high thermal contact resistance reduces the amount of heat, which can be transmitted from the heat source to the heat sink and the same raises the device temperature and reduces the overall reliability of the package due to thermo-mechanical stresses. In this paper, enhanced method for thermal conductivity measurement of polymer based materials used in electronic packaging is presented. It minimizes influence of thermal contact resistance on measurement accuracy.

## 1. Introduction

All microelectronic devices require power for their use. The resistance to the flow of electrical current through the leads, poly-silicon layers and transistors comprising a semiconductor device, results in significiant internal heat generation within an operating microelectronic component. In the absence of cooling – that is heat removal mechanism – the temperature of such an operating component would rise at a constant rate until it reaches a value at which the electronic operation of the device ceases or the component loses its physical integrity. The reliability of a system is defined by the probability that the system will meet the required specifications for given period of time. For may package categories, temperature is the strongest contributor to the loss of reliability. In such systems, thermal management is critical to the success of the electronic system. Placing the device in contact with a lower temperature solid or fluid, facilitates heat flow away from the component. Due to this cooling, the temperature rise is moderated as it asymptotically approaches an acceptable steady-state value.

The heat transfer from its source to the ambient air outside the system and/or heat sink is accomplished by the three basic transport mechanisms: conduction, convection, and radiation. The first level of packaging (single chip or multichip modules) is primarily concerned with conducting heat from the chip to the package surface and then into the printed circuit board. At this packaging level, reduction of the thermal resistance between the silicon die and the outer surface of the package is the most effective way to lower the chip temperature. The convection seems to be important for assembled packages while the radiation is rather out of the temperature work-range of electronic products. [1]

## 2. Heat transfer

### 2.1. Heat transfer through conductance

The general transient heat transfer equation can be written as follows:

$$\lambda \ \nabla^2 T - c \ \rho \ \frac{\partial T}{\partial t} + q_v = 0 \tag{1}$$

where $T$ is a temperature, $\lambda$ is a coefficient of thermal conductivity, $c$ is a specific heat, $\rho$ is density of a material, while $q_v$ stands for other inside and outside heat sources or phenomena.

The above equation consists of three components of which the first one is responsible for heat conductance, the second for heat accumulation, while the third for the internal heat generation or outside heat dissipation.

In case of heat conduction, the above equation can be rewritten as:

$$\frac{dQ}{dt} = -\lambda A \frac{dT}{dx} \tag{2}$$

where $Q$ is quantity of heat energy [J], $t$ is time [s], $\lambda$ is a thermal conductivity [W/mK], $dT/dx$ is a temperature gradient in the heat flow direction [K/m], $x$ is direction of heat flow [m], $A$ is the area of the cross-section [$m^2$].

The equation 2 can be solved as long as the material property referenced by thermal conductivity $\lambda$ is known. Thermal conductivity is usually treated as a constant value but in fact it is a multi variable dependent material property with non-linear behaviour.

## 2.2. Thermal Resistance

With analogy to the electrical conductivity the thermal resistance can be represented by a resistor of a defined material properties and geometry and the thermal resistance can be define as:

$$\Theta_\lambda = \frac{l}{\lambda \cdot A} \tag{3}$$

where $\Theta_\lambda$ is thermal resistance of a thermal conductor [W/mK], $l$ is length of thermal conductor. However there is an essential difference between thermal and electrical conduction when oxide films or other contaminants are present within the contact area. They are usually isolative for the electric current flow, but thermally they produce considerable short circuits in the surroundings of contact areas.

The total thermal resistance in a “thermal circuit”, sometimes represented as a chain of resistors, can be summed using the same concepts of series and parallel resistances as in an electrical circuit (**Figure 1**).

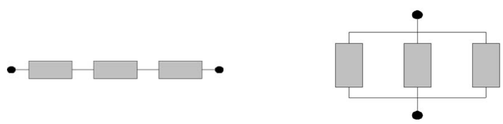

Fig. 1. The basic resistor network configuration.

Thermal resistance of multilayer solid in the steady state conditions ($\Theta_{\lambda s}$) and for a parallel heat flow systems ($\Theta_{\lambda p}$) are:

$$\Theta_{\lambda s} = \frac{1}{A}\left(\frac{l_1}{\lambda_1} + \frac{l_2}{\lambda_2} + \cdots + \frac{l_n}{\lambda_n}\right) \quad ; \quad \Theta_{\lambda p} = \frac{1}{A} \cdot \left(\frac{\lambda_1}{l_1} + \frac{\lambda_2}{l_2} + \cdots + \frac{\lambda_n}{l_n}\right)^{-1} \tag{4, 5}$$

## 3. An approach to measurement and evaluation of the thermal conductivity

An experimental setup (**Figure 2**) of thermal conductivity measurement consists of: heater, heat sink, pair of contact members (cylinders with known thermal conductivity $\lambda$), as well as temperature sensors [7]. The whole setup is placed in high vacuum environment in order to minimize the effect of heat dissipation through convection. The radiation is out of the temperature work-range therefore is neglected and the heat conduction is a dominating factor in transport heat energy. When the experimental setup reaches the steady state then by extrapolating the readings of the temperature sensors it is possible to find out the temperature drop $\Delta T$ at the contact interface [4], which is shown in **Figure 2**.

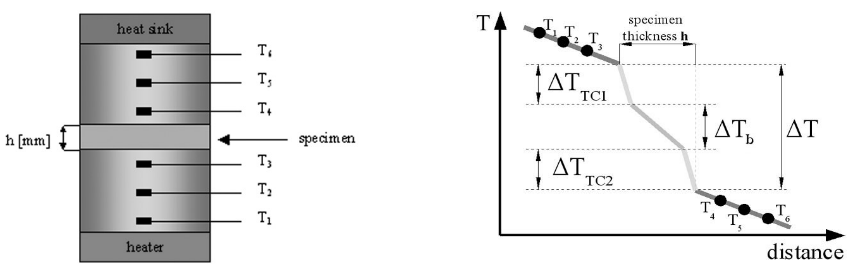


Fig. 2. An experimental setup and thermal distribution in steady state.

The difference between the traditional experiment setup and the applied one is reflected by the temperature profile, which is presented in **Figure 2**. Due to existing serial thermal contact resistance the total thermal resistance [8, 10, 11] can be defined as:

$$\Theta_T = \Theta_{TC1} + \Theta_b + \Theta_{TC2} \tag{6}$$

where $\Theta_b$ thermal resistance of measured sample and $\Theta_{TC1}$, $\Theta_{TC2}$ are thermal contact resistances on both sides of sample. Most often it is assumed that both thermal contact resistances are equal, which leads to:

$$\Theta_T = 2\Theta_{TC} + \Theta_b \tag{7}$$

To eliminate influence of thermal contact resistance on accuracy of calculating the thermal conductivity of tested material it is necessary to perform at least two measurements with different thickness of specimens. Changing thickness of sample causes increase of thermal resistance of material but the thermal contact resistances remain unchanged. The temperature profiles and equivalent "thermal circuits" [10] for samples with different thicknesses are shown on **Figure 3.**

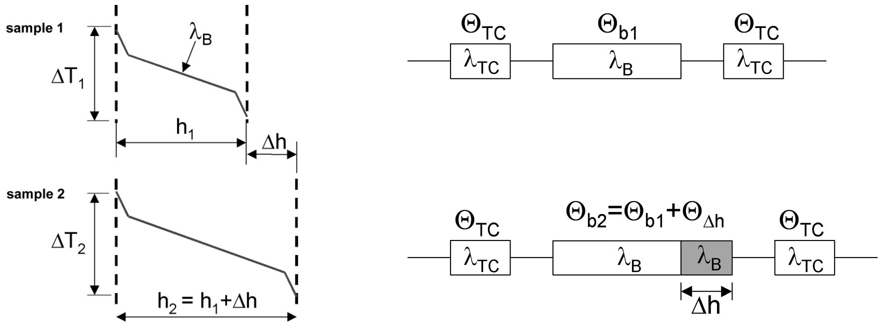


Fig. 3. Temperature profiles and equivalent thermal circuits for samples with different thicknesses; $\lambda_{TC}$ is thermal conductivity of thermal contact; $\lambda_B$ is thermal conductivity of tested material

Basing on equations 2, 4 and 7 it is possible to extract the thermal conductivity of tested material:

$$\lambda_B = \frac{1}{A} \cdot \frac{\Delta h}{\frac{\Delta T_2}{q_2} - \frac{\Delta T_1}{q_1}} \tag{8}$$

where $q_1$ and $q_2$ are heat flows evaluated basing on equation 2 taking into account temperature gradients and thermal conductivity $\lambda$ of the contact members for both samples.

## 4. Results of the experiments

The verification of the described approach to evaluation of the thermal conductivity of the polymer based materials used in electronic packaging was done on a test samples: samples B and C – polymer based materials. To verify the method for materials of greater thermal conductivity than polymer materials was used sample A made of lead based alloy. Results of measurements are gathered in **Table 1**.

Tab. 1. Results of measurements

| | **Sample A** | | **Sample B** | | **Sample C** | |
|---|---|---|---|---|---|---|
| A [m$^2$] | 2827,43e-6 | | 2827,43e-6 | | 2827,43e-6 | |
| h [m] | 3,85e-3 | 2,65e-3 | 4,20e-3 | 2,80e-3 | 2,66e-3 | 1,87e-3 |
| q [W] | 78,48 | 78,85 | 23,36 | 23,62 | 56,75 | 84,54 |
| ΔT [K] | 6,35 | 5,70 | 65,94 | 61,52 | 102,25 | 112,45 |
| **λ* [W/m K]** | **16,829** | **12,965** | **0,526** | **0,380** | **0,522** | **0,497** |
| **$\lambda_B$ [W/m K]** | **49,218** | | **2,269** | | **0,592** | |
| **$\Theta_T$ [K/W]** | **0,081** | **0,072** | **2,823** | **2,605** | **1,802** | **1,330** |
| **$\Theta_b$ [K/W]** | **0,028** | **0,019** | **0,655** | **0,436** | **1,588** | **1,116** |
| **2$\Theta_{TC}$ [K/W]** | **0,053** | | **2,168** | | **0,214** | |

where $\lambda^*$ – thermal conductivity measured without assuming existence of thermal contact resistances, $\lambda_B$ – thermal conductivity measured according to proposed method, $\Theta_T$ – the total thermal resistance (sample and thermal contacts), $\Theta_b$ – thermal resistance of measured sample (bulk material resistance), $2\Theta_{TC}$ – sum of both thermal contact resistances

In standard method of measurement thermal conductivity a thermal contact resistances are usually neglected but it may cause an error in calculations. In Table 1 was shown how the thermal contact resistance influences on calculated value of thermal conductivity.

To reduce the influence of specimen roughness on the thermal contact resistance between specimen and contact members was given additional layer of thermal silver paste, therefore the resistance $\Theta_{TC}$ is actually a sum of resistances of silver paste and thermal contacts.

There are enormous differences between thermal conductivity measured without assuming existence of thermal contact resistances ($\lambda^*$) and calculated from **equation 8** ($\lambda_B$) for samples A and B. In these cases thermal contact resistances $2\Theta_{TC}$ are much greater than resistance of measured material $\Theta_b$. When the thermal contact resistances are smaller then resistance of tested material as it takes place in the case of sample C, the difference between $\lambda^*$ and $\lambda_B$ is not significant. Nevertheless for thin layers the thermal contact resistance can play main role in heat transfer through a specimen and it cannot be neglected.

## 5. Conclusion

Basing on the presented results it can be concluded that the thermal contact resistance in comparison to the total resistance of a tested material becomes an important factor. In case of microelectronic packages where the polymer thickness layer is of the order of micrometers the thermal contact resistance may play a vital role in heat dissipation [8]. Due to enormous influence of thermal contact on measurement accuracy it seems that propose method is more effective than normally used methods.

The elaborated experimental setup allowed for measurement of the both: polymer layer and polymer bond thermal conductivity. It can be noticed that thermal conductivity of materials and thermal contact properties are usually non-linear and depend on many factors such as temperature, therefore that method should be supplemented with numerical simulation [8-11].

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