# A STUDY OF THE THERMAL CHARACTERIZATION OF A HIGH – PERFORMANCE FLIP CHIP PACKAGE

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## ABSTRACT

This paper describes a systematic experimental and numerical study of the thermal characterization of a flip-chip package. A cold-plate based test method is used for thermal characterization and internal thermal resistance is used as the basis of all comparisons. Experiment results are presented for three flip-chip packages. Test parameters such as thermocouple wire, attachment, thickness of interface material (grease) between the package lid and the cold plate and power dissipation are presented. Using a detailed numerical model [1], of the package, a parametric study of the experimental method is presented. The parametric study shows the variation in package thermal resistance due to different thermocouple bead sizes, thermocouple attachment parameters, different thermal grease thicknesses and different chip-lid thermal interface material (TIM1) properties. All the numerically predicted values are within the experimental range.

## NOMENCLATURE [2]

| | |
|---|---|
| u | velocity |
| $\rho$ | mass density |
| g | acceleration due to gravity |
| t | time |
| p | pressure |
| T | temperature |
| $\mu$ | dynamic viscosity |
| $C_p$ | specific heat capacity |
| k | thermal conductivity |
| $S^r$ | radiation source term in energy equation |
| $Q^{///}$ | chip volumetric heat generation rate |
| Tj | chip junction temperature |
| Tc | copper lid temperature |
| $\Theta$ | package internal thermal resistance |
| P | power dissipation |

## INTRODUCTION

Thermal characterization of electronic packages helps in determining their thermal resistance. Thermal resistance of an electronic package is a measure of the package's ability to transfer the heat generated by the chip to the printed wiring board (PWB) or to the ambient. For a high performance flip-chip package, the primary heat transfer path for most applications is through a heat sink or cold plate attached to the package lid. Hence, a test method that evaluates the heat transfer path from the chip to the lid is the most relevant one. In this study, $\Theta$ is the internal thermal resistance of the package. It is also called thermal resistance from junction to case and is similar to the JEDEC standard being currently developed. Junction refers to the chip temperature and case refers to the temperature at a specified point on the outside surface of the package (center of copper lid). It is calculated using equation 1:

$$\Theta = \frac{(T_j - T_c)}{P} \tag{1}$$

## PACKAGE DESCRIPTION

Figure 1 shows cross-section of the flip-chip package. A semiconductor chip is soldered to the top side of the laminate composite. A stainless steel stiffener in the shape of a picture frame is attached to the laminate around the chip site. A copper lid is attached to the back side of the chip using a high conductivity thermal adhesive. The stiffener is also coupled to the copper lid using adhesive. Calmidi et al have discussed that direct attachment of the lid and its coupling to the stiffener enhances the thermal performance [1].

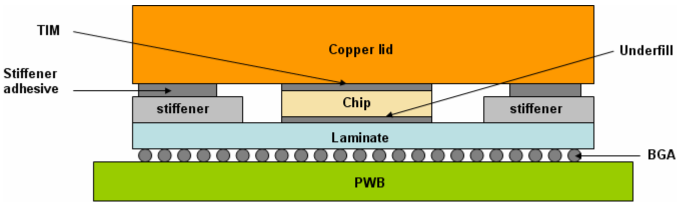


Figure 1: Schematic of high performance flip chip package.

On the other side of the laminate ball grid array (BGA) interconnections are provided for the electrical interconnections to the board. The size of the board is 125 mm x 130 mm. There are two power planes inside the board of thickness 1.4mil. Dimension, thickness and material properties of package components are summarized in table 1.

| Layer | Dimension | Thickness | Material | kxy (W/mK) | kz (W/mK) |
|---|---|---|---|---|---|
| Substrate | 55 mm | 0.018" | Composite | 20 | 0.7 |
| Stiffener | 55mm (outer)<br>24.9 mm (inner) | 0.020" | Stainless steel-400 | 23.4 | 23.4 |
| Chip | 18.9 mm | 0.029" | Silicon | ~100 | ~100 |
| TIM | 18.9 mm | 0.002" – 0.003" | Silicone | 2 | 2 |
| Stiffener adhesive to lid | 2mm wide ring | 0.0155" | Silicone (filled) | 1 | 1.2 |
| Underfill | 18.9mm | 0.004" | Filled epoxy | 0.6 | 0.6 |
| Stiffener adhesive to substrate | Same as stiffener | 0.004" | Polyimide | 0.17 | 0.17 |
| Copper lid | 53mm | 1mm | Ni plated copper | 380 | 380 |
| BGA | 1mm pitch<br>22mil ball sphere | ~0.15 collapse | Sn/Pb solder | 0.06 | 3 |

Table1: Dimensions, thickness and material properties of package layers.

## EXPERIMENTAL MEASUREMENTS

Figure 2 shows module mounting arrangement of the test, which is similar to the method described in [4]. The module on the PWB is placed lid down on the cold plate.

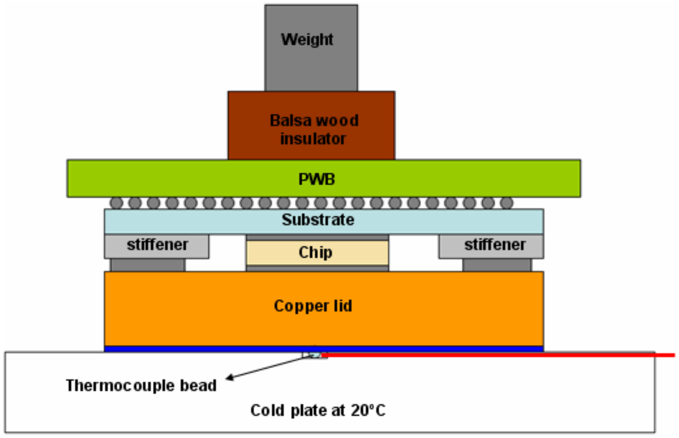
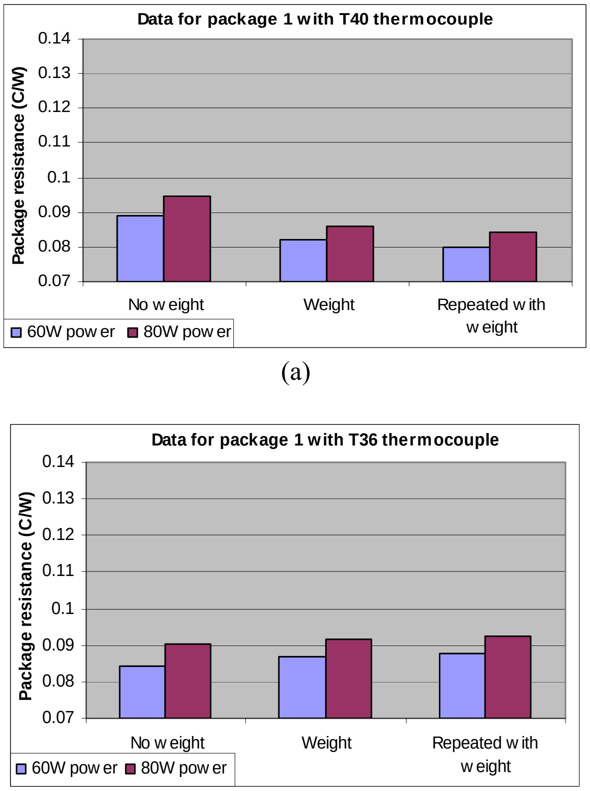


Figure 2: Module mounting arrangement for the test

Thermocouple bead is placed at the center of the copper lid to measure the case temperature. The bead is firmly attached to the lid using conductive silver epoxy. An additional non-conductive epoxy is used to cover the silver epoxy to secure the bead in place [5]. A thin layer of thermal grease is applied between the module lid and cold plate for efficient heat transfer. The cold plate is maintained at a uniform temperature of 20ºC using re-circulating chilled water. A balsa wood insulator is placed behind the PWB to minimize heat losses to the ambient. A dead weight is used to vary the thickness of thermal grease.

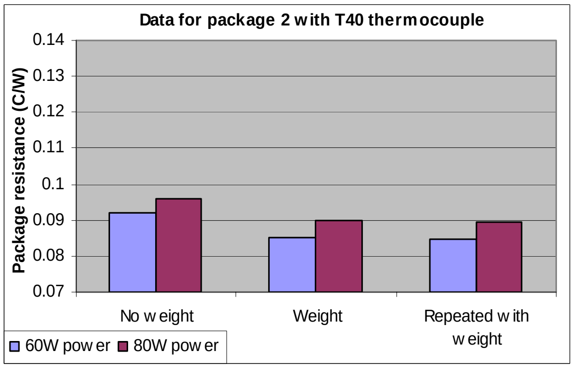
Measurements were taken simultaneously on three similar flip chip packages. Two T-type thermocouple wires with different diameters 40 and 36 gauges respectively (T-40 & T-36) are used for two set of measurements for each package. Each set of measurement was taken at 60W and 80W power dissipation. To understand the effect of thermal grease thickness, measurements were taken with and without a dead weight (3.5 kg) placed on the wood insulator. Measurement with the dead weight was repeated to understand the repeatability of the data collection. Although the actual thickness of the grease interface was not measured, it is expected that the use of a normal force on the package will reduce the bondline thickness of the interface.



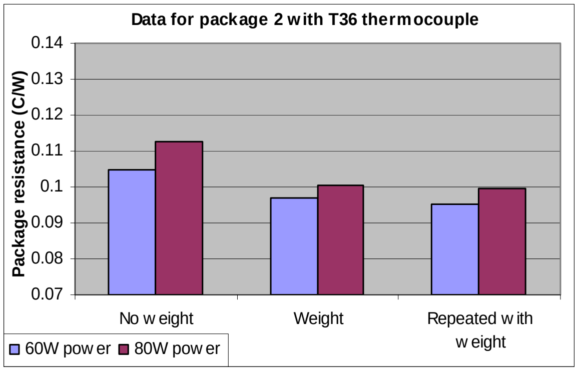
(a)

(b)

Figure 3(a): Thermal resistance for package 1 with (a) T-40 thermocouple (b) T-36 thermocouple

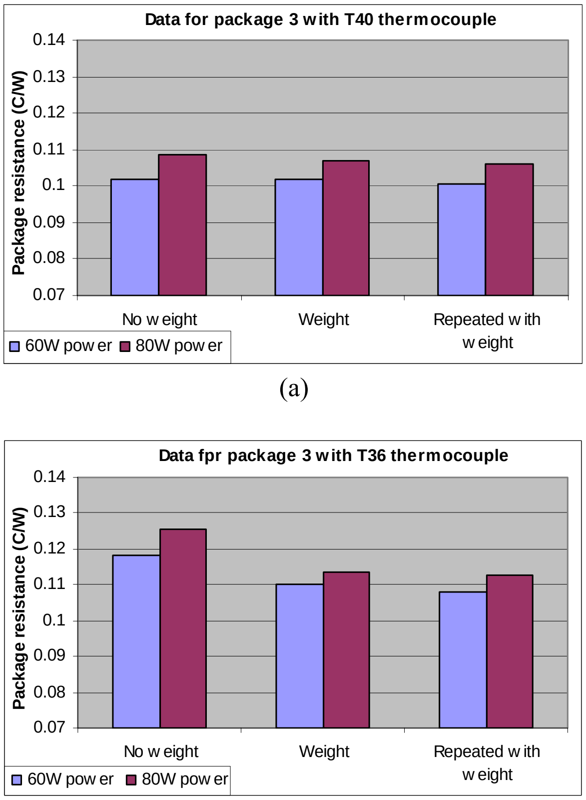


(a)



(b)

Figure 3(b): Thermal resistance for package 2 with (a) T-40 thermocouple (b) T-36 thermocouple



(a)

(b)

Figure 3(c): Thermal resistance for package 3 with (a) T-40 thermocouple (b) T-36 thermocouple

Considering all the measurements for packages 1, 2 and 3 separately, mean internal resistance for package 1 is 0.087 ºC/W, package 2 is 0.096 ºC/W and package 3 is 0.11 ºC/W. This variation in package resistance values is primarily due to the different TIM1 thickness between the three packages (refer to figure 1). The TIM1 thickness is known to vary between 2 and 4 mils from package to package. Due to varying thermal impedance offered by different interface thickness, the package resistance varies. Variation in package resistance due to the variation in thermal interface material thickness is investigated numerically in the following section of the paper.

Now we consider all the packages together for separate power dissipations i.e. 60W and 80W respectively. For 60W, minimum measured package resistance was 0.08 ºC/W; maximum measured package resistance was 0.12 ºC/W; and mean measured package resistance was 0.095 ºC/W. For 80W, minimum measured package resistance was 0.084 ºC/W; maximum measured package resistance was 0.13 ºC/W; and mean measured package resistance was 0.1 ºC/W. On an average for all the cases, there is about 5% increase in package thermal resistance when the power dissipation was increased from 60W to 80W. This increase in package resistance with the increase in power dissipation is likely due to a systematic variation in the package structure caused by internal thermal gradients.  A physical understanding of this effect is beyond the scope of this work and is being investigated in a separate study.

Now we consider all the packages together for separate thermocouple wire attachments with different diameters i.e. 40 gauge (T-40) and 36 gauge (T-36) respectively. For thermocouple with 40 gauge diameter (smaller), measured mean package resistance was 0.093 ºC/W with standard deviation of 0.009 ºC/W. All the values are within 2 standard deviations from the mean. For thermocouple with 36 gauge diameter (larger), measured mean package resistance was 0.1 ºC/W with standard deviation of 0.012 ºC/W. All the values are within 2 standard deviations from the mean. Hence smaller diameter thermocouple wire (T-40) is experimentally shown to have lower variability in data.

Another parameter which affects the measurement is the thickness of thermal grease between the lid and cold plate. To measure the package resistance values for two different grease thicknesses all measurements were taken for two cases (i) no weight placed above balsa wood insulator (ii) Weight placed above balsa wood insulator. For the case with no weight placed above balsa wood insulator mean thermal resistance for all the packages was calculated as 0.1 ºC/W with the data standard deviation of 0.004 ºC/W. For the case with weight placed above balsa wood insulator mean thermal resistance for all the packages was calculated as 0.096 ºC/W with the data standard deviation of 0.003 ºC/W. By putting weight above the insulator the thermal grease squeezes allowing better contact of package lid with the cold plate, hence the package resistance reduces by ~5%. Also case with no weight is shown to have a slightly higher variability in data as indicated by standard deviation values.

Finally the measurements for all the packages are considered to investigate the variation in data due to repeatability. Hence two cases considered for all the packages are (i) set up with weight and (ii) set up with weight repeated. For the case with weight, minimum measured package resistance was 0.082 ºC/W; maximum measured package resistance was 0.11 ºC/W; and mean measured package resistance was 0.096 ºC/W. For the case with weight repeated, minimum measured package resistance was 0.08 ºC/W; maximum measured package resistance was 0.11 ºC/W; and mean measured package resistance was 0.095 ºC/W. Hence there is less than 1% difference in measured values due to repeatability. Also both the cases had similar variability in the measured values because the standard deviations for both the data are 0.003 ºC/W. Hence the experiments were very well controlled and repeating the experiments under similar conditions did not change the measured values considerably.

## NUMERICAL MODELING

Based on the data given in table 1, a detailed numerical model of the flip chip package is generated. Commercial computational fluid dynamics (CFD) code IcePak 4.2.6™ is used as a simulation tool. IcePak™ solves complex three-dimensional Navier Stokes equation coupled with the energy equation. Note that even though heat transfer from the package to the cold plate is primarily by conduction, the experimental setup is such that there is convective heat transfer between objects. One, there is heat loss (convection and radiation) from the backside of the PWB. Two, there is heat transfer (convection and radiation) from the portion of the PWB around the package and the cold plate. These effects were explicitly included in the numerical model in order to evaluate their relative importance. The governing equations for steady state laminar flow and heat transfer are written as follows [1-2]:

$$\nabla.\rho u = 0 \tag{2}$$

$$\frac{\partial \rho u}{\partial t} + (u.\nabla)\rho u = -\nabla p + \mu \nabla^2 u + \rho g \tag{3}$$

$$\frac{\partial \rho C_p T}{\partial t} + (u.\nabla)\rho C_p T = \nabla^2 kT + S^r + Q''' \tag{4}$$

All the solid objects, representing different layers of the package are modeled as solid cuboids with appropriate thermal conductivity. Air is assumed to be nonparticipating in radiation calculations. Top surface and bottom surfaces of the board and bottom surface cold plate are defined as radiating surfaces with emmisivity value of 0.8.

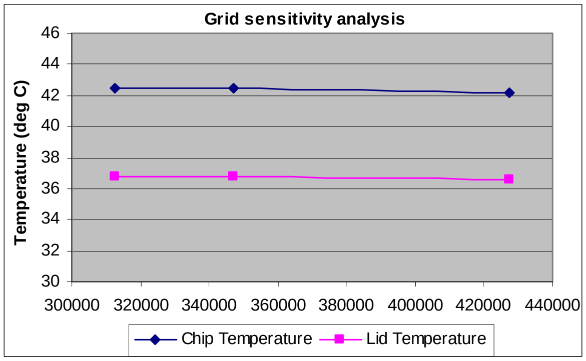
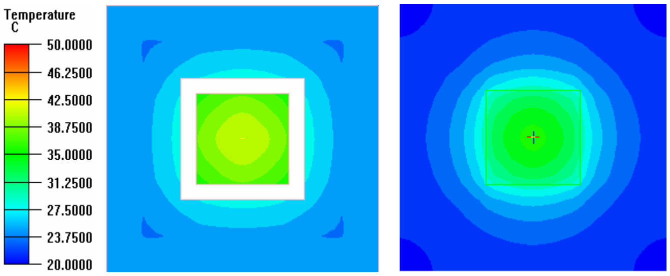


Figure 4: Grid sensitivity analysis for the numerical model.

Prior to parametric runs, mesh sensitivity analysis was carried out to obtain the grid independent temperature distributions. Figure 4 is a plot for chip and lid temperatures over the range of grid sizes.

## BASELINE CASE

Baseline cases have 7.5 mil thickness thermal grease thickness between the lid and the cold plate. The effect of thermocouple bead is not included in the models. The baseline case is solved for 60W and 80W power dissipation. Figure 5(a) shows temperature contours for the baseline case with 60W power dissipation.



(a) (b)

Figure 5(a): Temperature contours for the flip chip package for 60W power dissipation at (a) chip and stiffener surfaces (b) copper lid surface

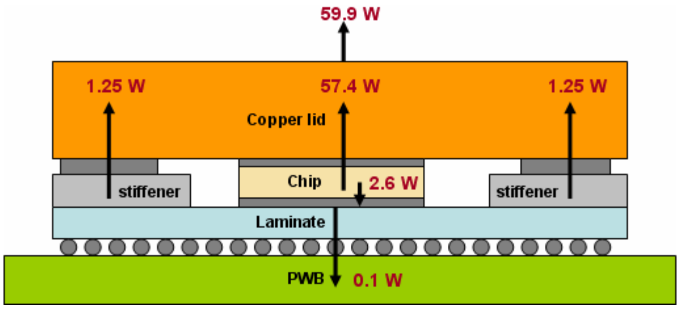
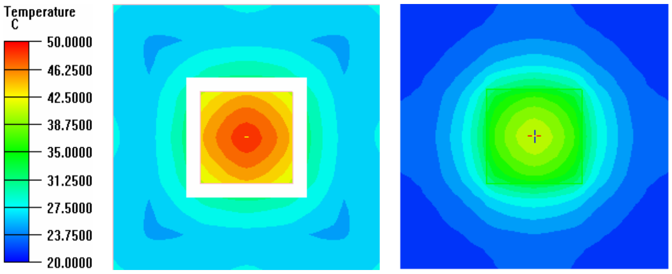


Figure 5(b): Heat dissipation path schematic for various layers of the flip chip package with 60W power dissipation

Figure 5(b) is schematic showing path for heat dissipation for the flip chip package with 60W power dissipation. Chip dissipates 57.4 W of heat from its top surface and 2.6W of heat from its bottom surface. Out of 2.6W of heat flowing down through underfill layer, 2.5W of heat is picked by the stiffener. Remaining 0.1W of heat flowing down gets dissipated from the BGA into the board. For the heat flowing upwards, 57.4W of heat is conducted into the copper lid through the thermal interface material. Additionally 2.5W of heat is conducted into the copper lid by stiffener layer. Hence a total of 59.9W of heat is dissipated from the top of the copper lid.

Figure 6(a) shows temperature contours for the baseline case with 80W power dissipation.



(a) (b)

Figure 6(a): Temperature contours for the flip chip package for 60W power dissipation at (a) chip and stiffener surfaces (b) copper lid surface

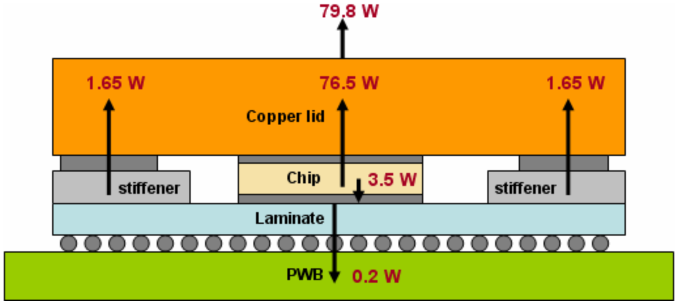


Figure 6(b): Heat dissipation path schematic for various layers of the flip chip package with 80W power dissipation

Similarly, figure 6(b) is schematic showing path for heat dissipation for the flip chip package with 80W power dissipation. Chip dissipates 76.5W of heat from its top surface and 3.5W of heat from its bottom surface. Out of 3.5W of heat flowing down through underfill layer, 3.3W of heat is picked by the stiffener. Remaining 0.2W of heat flowing down gets dissipated from the BGA into the board. For the heat flowing upwards, 76.5W of heat is conducted into the copper lid through the thermal interface material. Additionally 3.3W of heat is conducted into the copper lid by stiffener layer. Hence a total of 79.8W of heat is dissipated from the top of the copper lid.

Hence the thermal analysis of the high-performance flip chip package reveals that chip typically dissipates about 5% of the heat from its bottom surface. Out of this 5% heat flowing through the underfill 95% of the heat is conducted back to the copper lid through stiffener. Hence less than 1% of the heat is dissipated into the board through the BGA.

For the two baseline cases presented above, temperatures were monitored at the chip center (Tj) and at the lid center (Tc). For 60W power dissipation the package resistance was calculated as 0.093 ºC/W. For 80W power dissipation the package resistance was calculated as 0.094 ºC/W. Hence the numerical model indicates that there is negligible variation in package resistance due to variation in power. However experimental results indicate higher package resistance for higher power. This paper does not deal with the structural analysis of the package components; hence the thermal model predicts negligible variation in thermal resistance of the package due to power dissipation. However ongoing study focuses on variation in package thermal resistance with increasing power dissipation.

## PARAMETRIC STUDY

### Effect of epoxy bead on package for thermal resistance calculations:

To investigate the effects of thermocouple attachment, an epoxy bead is placed at the center of the copper lid. Based on dimension measurements during the experiment study, the epoxy bead is modeled as a cube of dimension 2.58 mm sitting above another cube of dimension 1.292 mm. The smaller cube (1.29 mm) has a thermal conductivity of 1 W/m-K (conductive silver epoxy). The bigger cube has thermal conductivity of 0.15 W/m-K (non conductive epoxy). The cold plate hole that accommodates the epoxy bead is modeled as a cube of dimension 3 mm. Epoxy bead sits inside the cold plate hole. Since the epoxy bead is smaller than the cold plate hole, there is a small clearance between the cold plate hole and the epoxy bead. Whether grease or air fills the clearance, it is uncertain. So simulations were carried out with cold plate hole having properties of air and thermal grease. For the cases with epoxy bead, case temperature was monitored at the tip of the silver epoxy. Figure 7 shows a comparison of thermal resistance values predicted by the 3 models viz. no bead, cold plate hole of air and cold plate hole of grease, for both 60W and 80W each. The epoxy bead is in the path of the thermal gradient, so its temperature is expected to be lower than the lid temperature. Also when the bead in the cold plate hole is surrounded with thermal grease instead of air, an even lower temperature is predicted because grease conducts the heat to the cold plate better than air. Hence, due to the lower bead temperature, the thermal resistance prediction by including epoxy bead on the package is higher than when no bead is included in the calculations. For the baseline case, the prediction is greater than 25%.

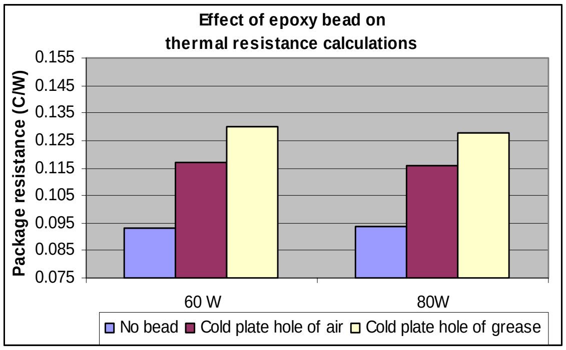


Figure 7: Effect of thermocouple bead for numerical prediction of package thermal resistance.

## Effect of TIM bond line thickness on package thermal resistance:

As discussed previously, thickness of the thermal interface material between the chip and lid varies between 2 and 4 mils. Thickness of the TIM eventually affects the resistance to heat flow. A previous study of the thermal properties of the TIM shows that the thermal impedance at the interface varies linearly with the thickness of the TIM bond line. Figure 8 is a plot for variation of thermal impedance at the interface with TIM bond line.

In this section numerical study is presented to investigate the impact of TIM bond line thickness on thermal resistance of the package. Based on the data shown in Figure 8, the thermal conductivity of the TIM was varied in the numerical model such that the thermal impedance offered at the chip lid interface corresponds to TIM bond line thickness of 2, 3 and 4 mils. It should be noted that, for constant TIM thickness higher value of thermal impedance will translate to a lower value of thermal conductivity.

Hence a thicker TIM layer with a higher value of thermal impedance will have a higher package thermal resistance. Figure 9 shows package thermal resistance for different TIM bond line thickness. As seen clearly, package resistance increases as the TIM thickness increases from 2 mils to 4 mils.

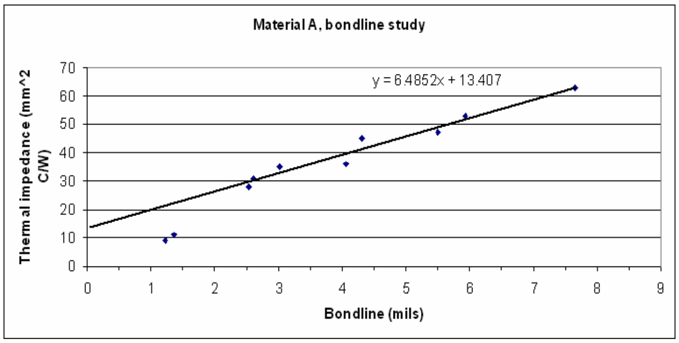


Figure 8: Variation of thermal impedance at the interface with TIM bond line.

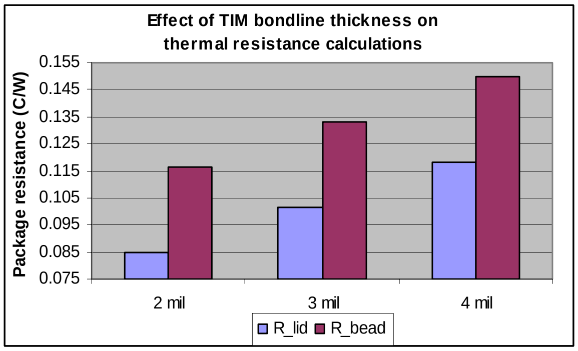


Figure 9: Effect on TIM bond line thickness on package thermal resistance

Results shown in figure 9 are for a package with power dissipation of 60W. Results for 80W power dissipation have not been included because the values and trends were exactly similar to that of 60W package power (also refer to figure 7). To predicted the range, thermal resistance for all the numerical models are calculated based on case temperatures monitored at the center of package lid (R_lid) and at the tip of silver epoxy bead (R_bead). For all the experimental values, minimum and maximum calculated package thermal resistance was 0.08 ºC/W and 0.13 ºC/W respectively. For all the numerical models analyzed above minimum and maximum calculated package thermal resistance was 0.085 ºC/W (R_lid for 2 mils bond line) and 0.15 ºC/W (R_bead for 4 mils bond line) respectively. Hence minimum and maximum values predicted by the numerical models are within 15% of the minimum and maximum experimental values. Also if only R_lid is considered the minimum and maximum thermal resistance values are 0.085ºC/W and 0.12 ºC/W. These values agree within 8% of the minimum and maximum experimental values.

## Effect of the epoxy bead size on thermal resistance calculations:

To measure the case temperature, thermocouple bead is attached to the package lid by epoxy adhesive. This epoxy bead holds the thermocouple bead in place. Size of epoxy bead varies for every attachment. Hence in this section numerical study is presented to investigate the effect of epoxy bead size on thermal resistance calculations. For all the attachments epoxy bead sizes were measured. For parametric study, 3 epoxy bead sizes are chosen to represent the entire range of measurements. Hence the epoxy bead sizes chosen are 2.08 mm (minimum), 2.58 mm (mid-range) and 2.84 mm (maximum).

However in numerical models spherical beads are approximated by equivalent cubes of dimensions 2.08 mm, 2.58 mm and 2.84 mm respectively. These cubes were given thermal conductivity of 0.15W/m-K (non conductive epoxy). The clear epoxy cubes sit over silver epoxy cube (1W/m-K) of half the dimension. The case temperature is monitored at the tip of silver epoxy cube (smaller cube). These beads attached to the package lid sit inside the cold plate hole of dimension 3 mm. The clearance between the cold plate hole and epoxy bead is assumed to be filled with thermal grease. All the models are run with these bead sizes for 60W & 80W power dissipations. However results for 80W power dissipation have not been included because the values and trends were exactly similar to that of 60W package power. Figure 10 shows a comparison between calculated package thermal resistances (R_lid & R_bead) for the three bead sizes.

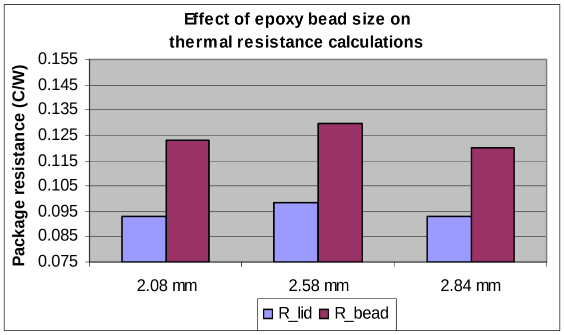


Figure 10: Effect of epoxy bead size on package thermal resistance calculations.

No fixed pattern in variation of thermal resistance due to increasing epoxy bead size is seen. This variation in thermal resistance values is due to the variation in case temperatures (lid and bead). There was about a 5% variation in the package resistance values due to variation in epoxy bead size for the range of sizes considered.

### Effect of thermal grease thickness on thermal resistance calculations:

As discussed previously, case temperatures monitored at the package lid and epoxy bead may be affected by the thickness of thermal grease between the lid and the cold plate. Case temperature eventually affects the thermal resistance values. For most of the experimental measurements thermal resistance values dropped when the weight was placed over the balsa wood insulator. Weight was placed above the balsa wood to squeeze the layer of thermal grease and make a more intimate contact.

In this section, numerical study is presented to investigate the effect of grease layer thickness on thermal resistance calculations. Thermal grease was applied to the cold plate using a 10 mils thick stencil. Hence maximum grease thickness is 10 mils. Utilizing the weight further squeezes the grease layer, so numerical models are also analyzed for a grease thickness of 7.5 mils and 5 mils.

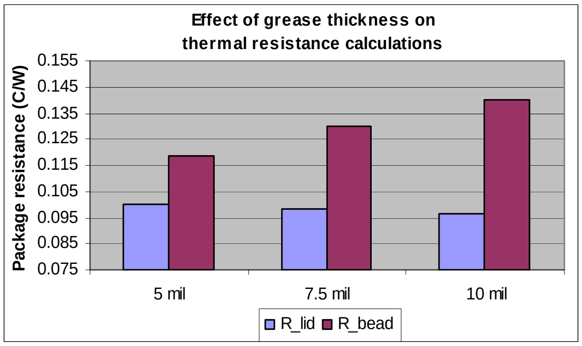


Figure 11: Effect of grease thickness on thermal resistance calculations.

Figure 11 shows a comparison between thermal resistance values (R_lid and R_bead) for the three thicknesses of grease, for 60W power dissipation. Results for 80W power dissipation have not been included because the values and trends were exactly similar to that of 60W package power.

Thermal grease is an interface material between the package lid and cold plate, so it should not affect the package thermal resistance. Numerical model showed less than 2% variability in the thermal resistance values (R_lid) for the case temperature monitored at the lid. However, when the case temperature was monitored at the tip of the epoxy bead, package thermal resistance predicted a steady increase with the increase in grease layer thickness. Hence package thermal resistance for case temperature monitored at the tip of silver epoxy bead (R_bead) shows about a 20% increase as the grease layer increase from 5 mils to 10 mils thickness. This is consistent with the experiment observation of decrease in thermal resistance when a weight was placed over the balsa wood insulator. Utilizing the weight decreased the grease layer thickness and increased the package thermal resistance.

## CONCLUSIONS

In this paper cold plate steady state test method for thermal characterization of electronic packages is discussed. Experimental results are presented for three high performance flip chip packages. Variability in data is seen for similar packages. Variability in data is also seen for same packages with different thermocouple attachments, grease layer thickness (no weight and with weight) and repeatability. Results are discussed in detail.

Numerical modeling of the high-performance flip chip package is demonstrated. Based on the thermal analysis heat flow paths through different layers of the package are presented for 60W and 80W power dissipations. Typically chip dissipates 95% of the heat from its top surface. Out of the remaining 5%, stiffener picks 95% of the heat and conducts it to the copper lid. Hence less than 1% of the heat dissipated by the chip goes into the board through the BGA layer.

Parametric study is presented to investigate the effect of various experimental parameters on thermal resistance calculations. To investigate the effect of thermocouple attachment, an epoxy bead is modeled at the center of the package lid. Monitoring the case temperature at the tip of the silver epoxy bead is shown to predict a higher value to thermal resistance when compared to the case when the case temperature is monitored at the center of the package lid.

Layer of thermal interface material between the chip and lid varies between 2 and 4 mils from package to package. This is responsible for variation in thermal resistance values for all the three packages considered to present the study. Thicker layer of TIM offers higher thermal impedance to heat flow and hence the corresponding package has higher thermal resistance. Variation in epoxy bead sizes predicted about 5% variation in thermal resistance values.

Thermal grease is applied at the lid-cold plate interface for efficient heat transfer rates. Most of the experimental measurements showed a decrease in thermal resistance values when weight was placed over the balsa wood insulator. Putting weight squeezes the grease layer and decreases its thickness. Hence numerical models were evaluated for three grease thicknesses. When the case temperature was monitored at the center of the package lid, there is negligible variation seen in the results (less than 2% variation in R_lid). However when the case temperature was monitored at the tip of the epoxy bead, thermal resistance of the package increased by ~20% when the grease layer increased from 5 mils to 10 mils.

For all the experimental values, minimum and maximum calculated package thermal resistance was 0.08 ºC/W and 0.13 ºC/W respectively. For all the numerical models analyzed above minimum and maximum calculated package thermal resistance was 0.085 ºC/W (R_lid for 2 mils bond line) and 0.15 ºC/W (R_bead for 4 mils bond line) respectively. Hence minimum and maximum values predicted by the numerical models are within 15% of the minimum and maximum experimental values. Also if only R_lid is considered the minimum and maximum thermal resistance values are 0.085ºC/W and 0.12 ºC/W. These values agree within 8% of the minimum and maximum experimental values.

From this study, it appears that the greatest effect on the thermal resistance measurement variability is due to the TIM1 thickness variation and grease layer thickness (for R_bead). The variability is as much as 25% of the actual value. This test method might be better suited for packages with thermal resistance greater than 0.2 C/W. Ongoing research efforts focus on the development of more accurate measurement techniques for thermal characterization of such packages.

## References

[1] V.V. Calmidi and S.B. Sathe, "Thermal Performance of a High End Flip Chip Organic Package", IMAPS 2003, Proceedings of the 36th International Symposium on Microelectronics, November 16-20, Boston, MA, USA

[2] S.B. Sathe and B. Sammakia, 1996, "A Numerical Study of the Thermal Performance of a Tape Ball Grid Array (TBGA) package", 31st ASME National Heat Transfer Conference, HTD Volume 309, pp 83-94

[3] "Thermal Characterization of IC Packages", Application Note 4083, http://www.maxim-ic.com/

[4] K.K Sikka, "Advanced Thermal Tester for Accurate Measurement of Internal Thermal Resistance of High Power Electronic Modules" ITHERM 2000, The 7th Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems, Vol. 2, pp 208-212

[5] Claassen, A., Shaukatullah, H., 2003, "Effect of Thermocouple Wire Size and Attachment Method on Measurement of Thermal Characteristics of Electronic Packages", Proceedings of the 19th IEEE SEMITHERM .

[6] V.V. Calmidi, "Thermal Performance of a Thin High Interconnect Density Organic Substrate for Flip-Chip Applications" ECTC 2005, Electronic Components and Technology Conference, 31May-3 June 2005, pp. 1728 - 1734 Vol. 2

[7] V.V. Calmidi and I. Memis, "Thermal Enhancement of Systems using Organic Flip Chip Packages (FC-PBGA) with an Alternate Cooling Path through the Printed Wiring Board", ECTC 2006, Electronic Components and Technology Conference, 30 May-2 June 2006

[8] IcePak 6.2 User Manual