

A Method for Predicting Thermal Conductivity for LTCC with various via Densities

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Abstract

Increased power density applications especially for front end modules have created the need for adequate thermal management in microwave design. Although LTCC has a lower thermal resistance than PCB substrates it is still desirable to lower the resistance further by introducing thermal via arrays. A thermal imaging system using an infrared camera was used to measure the top surface temperature over a range of powers with samples that had varying via sizes and densities. The empirical data results from this study were compared to theoretical figures by using the simple rule-of-mixtures as a starting point. The rule-of-mixtures can indicate a trend when the fraction volume of the dissimilar materials is altered, but obviously does not show how via size and density influences the thermal conductivity when the % volume amount stays the same.

The fact that the thermal conductivity and diffusivity of the filled via is so much greater than the LTCC material means that another method of theoretically calculating the resulting thermal conductivity can be used by studying the thermal path. This paper investigates the interface temperature of the filled via and LTCC and explores an alternative method of predicting thermal performance.

Keywords: Thermal via, Thermal Conductivity, LTCC, DuPont 951, DuPont 6141, Thermal diffusivity, rule-of-mixtures

Introduction

A feature of LTCC is that thermal vias can be added to sections of a module to increase thermal conductivity in that region, while leaving the rest of the volume for multi-layer circuitry.

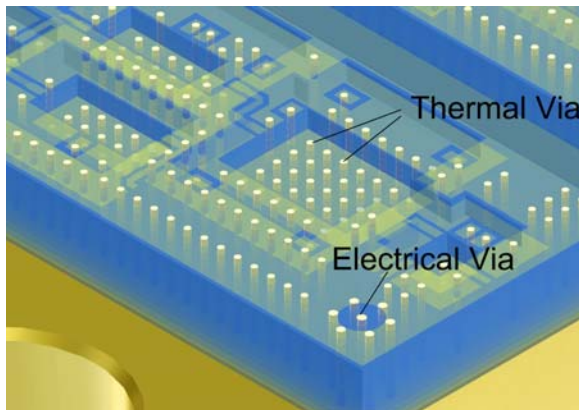


Figure 1: Representation of thermal and electrical vias in a SiP system

Accurate prediction of thermal package performance can only be obtained if the system material thermal conductivity is known and definitive. The main objective of this study is to generate thermal resistance theoretical base for the integration of thermal conductor filled via arrays into LTCC. This study has been developed as an extension to an experimental study that measured the results of various thermal via sizes and densities [1].

There have been several studies of thermal vias; Müller[2], by concentrated heat source; Zampino[3] by flash diffusivity method and Pape[4]; has looked at thermal design within PCBs.

The approach of this investigation was to use a surface area method of calculating the material system thermal resistance and compare it to the rule-of-mixtures method and previously determined measured results. This approach has been coined the “ceramic/metal interface method”. It was realized that since the temperature of the ceramic/metal is

lower than the ceramic due to the via-fill high thermal conductivity and diffusivity. Therefore the interface surface area is critical to the thermal performance and can be used as a design tool.

Method – Empirical Measurement

This section is a summary of the previous experimental study; for complete details see [1]. Power is applied to a conductor serpentine of 6146 Ag/Pd conductor [5], this serpentine allows the power and therefore heat to be evenly distributed across the material. Figure 2 illustrates the serpentine used to test the material and thermal vias samples.

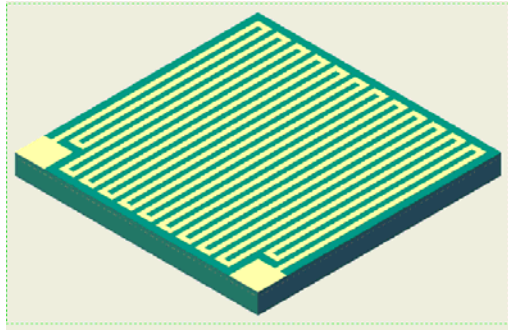


Figure 2: serpentine printed on LTCC 951

The vias were stacked directly on top of one another and filled with Ag 6141 [6], thermal conductivity given by table 2. There was a PX/8.5mil layer of 951 LTCC to separate the top layer serpentine and the printed conductor layer. The vias were inserted in between the conductor planes.

The samples were mounted to a flange and power applied. An infrared thermal camera was used to record the peak temperature. The flange temperature was kept constant at 50°C, while the power was increased in 10 or 25 watt increments.

The thermal resistance of the solder layer and PX separation layer were subtracted from the total thermal conductivity results to obtain the LTCC/via composite thermal conductivity result.

Theoretical Development – Ceramic/Metal Interface Temperature and Area

The rule of mixtures has been used in the past to work out a theoretical composite thermal conductivity – however this method assumes that the resultant composite is homogeneous. In the case of thermal vias in LTCC, the metal has a much higher

thermal conductivity (>70 times) and thermal diffusivity (>100 times), see Tables 1 and 2. The rule-of-mixtures calculations for the via range used in [1] is given in table 3.

Another method of calculating the thermal conductivity is described below and relates to the ceramic-conductor (LTCC-via fill) interface area.

It is assumed that the ceramic LTCC is held at a maximum temperature due to the relative slow thermal diffusivity and low thermal conductivity, see Figure 3. The second assumption is that the metal via is held at the lower temperature, due to the relatively high thermal diffusivity and high thermal conductivity, Figure 3. With these assumptions, equation (1) can be used to work out the LTCC-conductor interface temperature $T(x,t)$ [7].

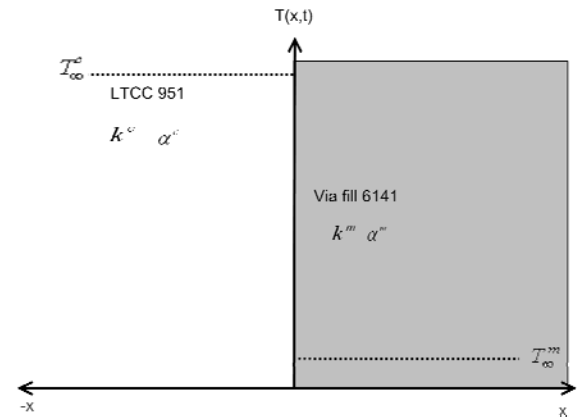


Figure 3: Illustration of the interface between the conductor and ceramic and the relevant temperatures.

$$T(0,t) = \frac{(k^m \sqrt{\alpha^c}) T_{\infty}^m + (k^c \sqrt{\alpha^m}) T_{\infty}^c}{(k^m \sqrt{\alpha^c}) + (k^c \sqrt{\alpha^m})} \quad (1)$$

Equation 1 uses the thermal diffusivity and conductivity, given by tables 1 and 2, of the ceramic and metal materials to calculate the interface temperature.

Table 1: Thermal Diffusivity

Material	cm^2/s
Ag Via fill 6141 (k^m)	1.42 [2]
LTCC 951 – Given by DuPont (k^c)	0.0127 [2]

Table 1 gives the theoretical diffusivity of the materials that make up the substrate material system. The LTCC material has a much lower thermal diffusivity than the thermal via fill material.

Table 2: Comparison of Thermal Conductivities with various materials

Material	$\text{W}/(\text{m}^*\text{K})$
Air	0.025
Thermal Grease	0.7 - 3
FR4	0.27
Glass	1.1
LTCC 951 (α^c)	3.3 [8]
Alumina	18-35
Ag Via fill 6141 (α^m)	247 [6]
Copper	401

Table 2 gives a list of thermal conductivities for some common materials used within the electronics industry. The LTCC material has a much lower thermal conductivity than the thermal via fill material.

$T(0,t)$ gives the interface temperature of the LTCC 951 and silver via fill 6141. If the maximum temperature numbers from the previous study [1] are used in equation 1 (temperature of metal 50 degrees and temperature of ceramic 250 degrees) the calculated interface temperature is 74 degrees centigrade; 24 degrees greater than the base temperature and 176 degrees lower than the radiator temperature – at the highest temperature differential.

The ceramic-metal interface temperature is so low because the heat quickly flows through the via fill material. The majority of the heat flows on the outer cylinder area of the via fill/silver conductor as shown by figure 4. Therefore the ceramic-conductor interface area will have a direct impact on this material system thermal management.

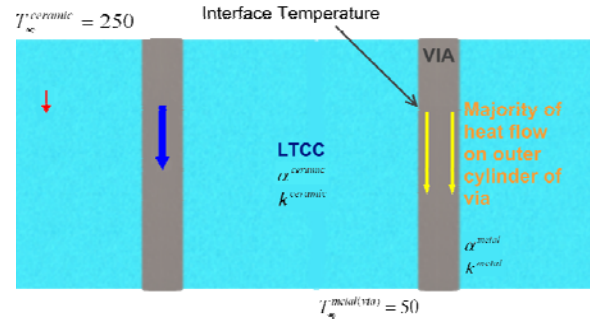


Figure 4: Illustration of the conductor and ceramic materials differences and the flow of heat.

Results

During this study several questions were raised such as the validity of using cylinders to mimic the vias and the possibility of glass diffusion from the LTCC ceramic into the filled via material.

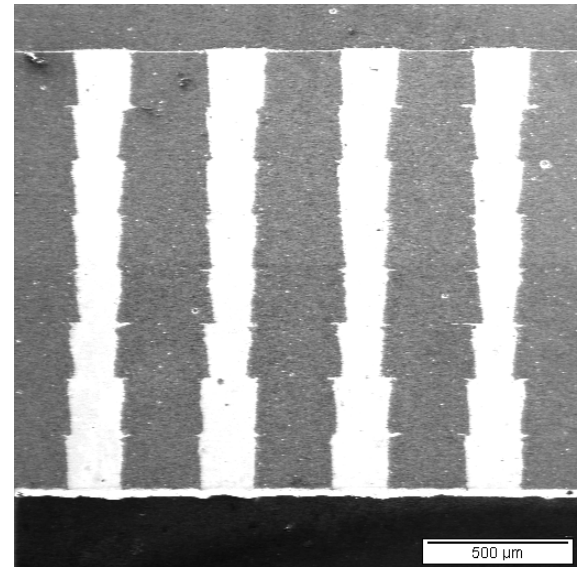
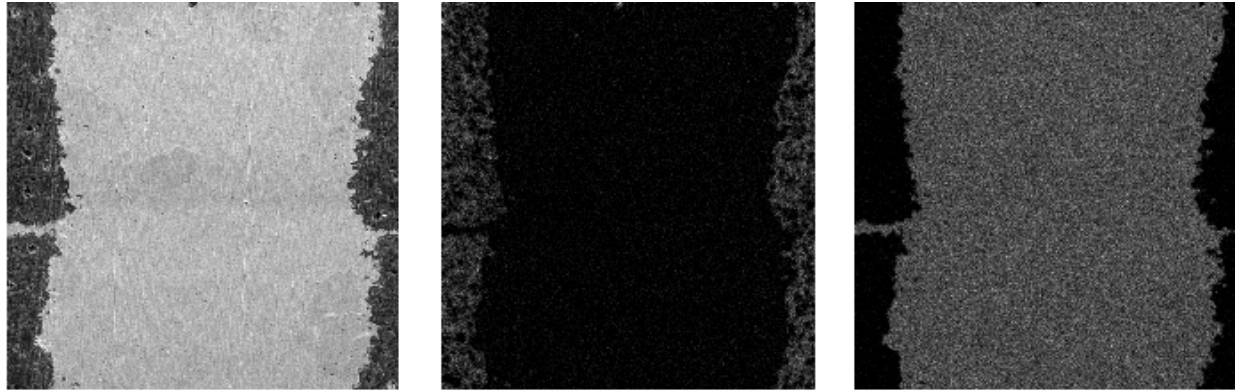


Figure 5: Micrograph of thermal via cross section with eight layers.

A micrograph of thermal vias is shown in Figure 5. Although there is some non-uniformity the thermal vias can be roughly equated to filled cylinders.



Via cross section

Si map

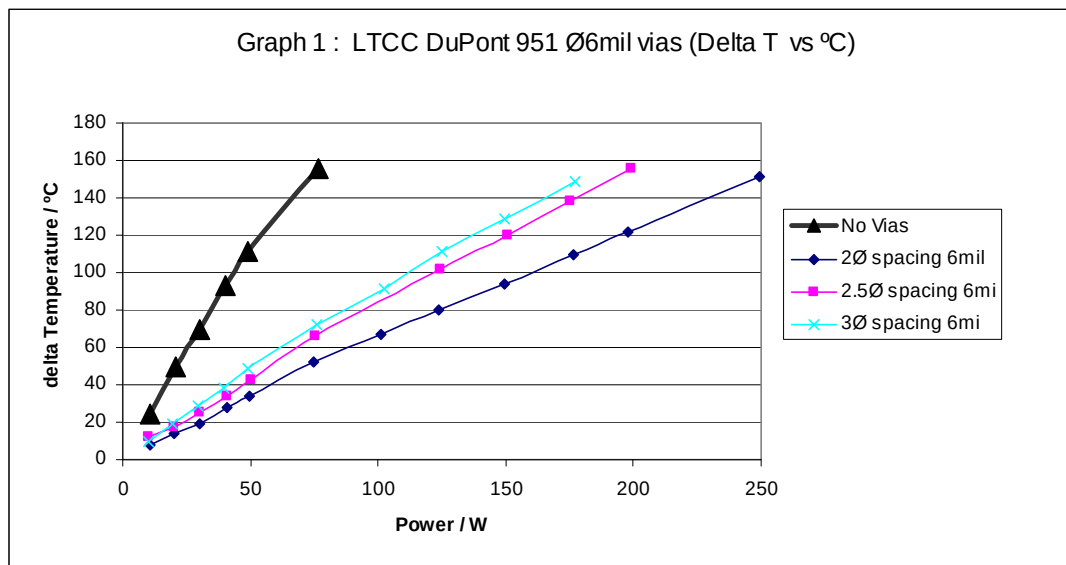
Ag map

Figure 6: EDS Map of thermal via cross section. The image is on the left, map of Si in the middle and map of Ag on the right.

The calculated conductivity is given in Table 3 using the rule-of-mixtures method.

Table 3: Rule-of-mixtures calculation	
Via Spacing	Theoretical Conductivity W/(m°K)
2 Diameters	51.1
2.5 Diameters	33.9
3 Diameters	24.6

The results of the thermal tests on 4 layers of LTCC, using DuPont 951 for 2, 2.5 and 3 diameter center to center spacing were given [1], the 6 mil results are shown in Graph 1.

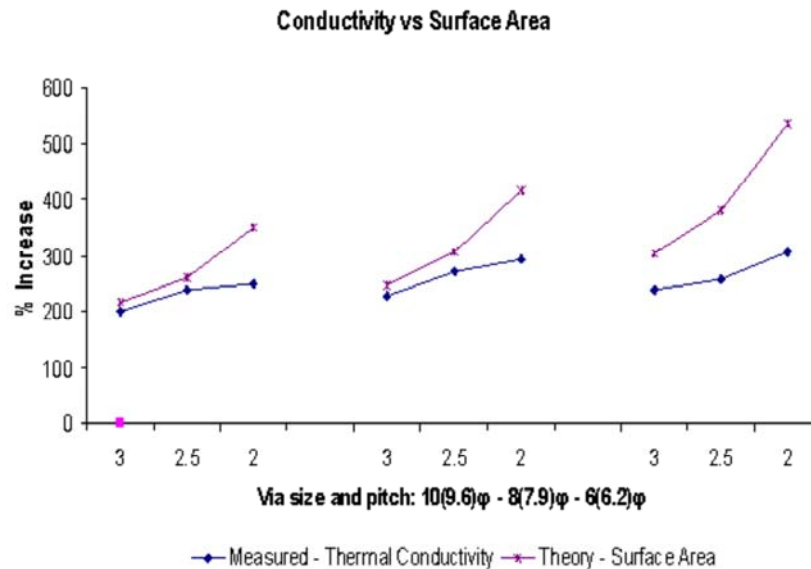


Graph 1: 4 layer DuPont 951 comparing thermal conductivity results of material with no vias, 6mil vias with 2 diameter spacing, 2.5 diameter spacing and 3 diameter spacing

Table 4 gives a summary of the thermal conductivity results from the previous study [1]. The conductivity changes as the via size and density change. The conductivity increases as the via density increases. As the via size decreases the conductivity increases. The 6 mil vias have the highest conductivity results and the 10mil vias have the lowest conductivity.

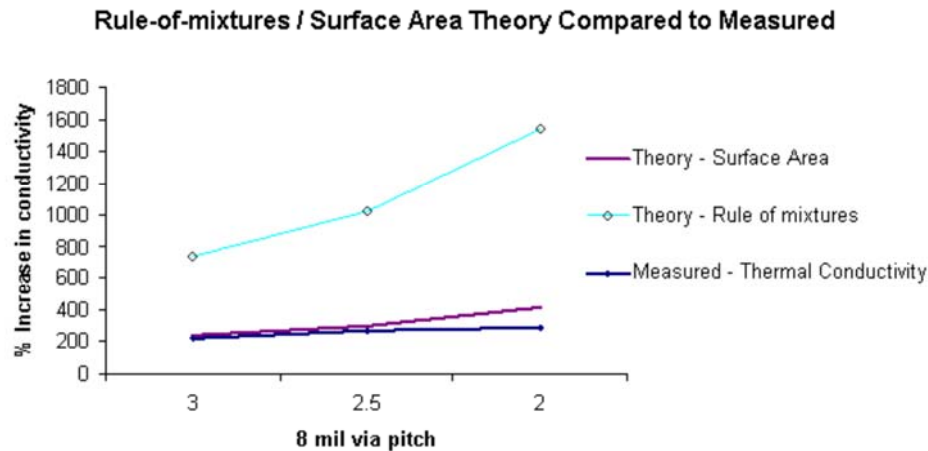
<i>Table 4: Comparison of Thermal Conductivities of measured LTCC (with and without thermal vias)</i>	
<u>Material</u>	<u>W/ (m*K)</u>
LTCC 951 (no vias) measured	3.2
LTCC 6mil via 2Φ spacing	34
LTCC 6mil via 2.5Φ spacing	18
LTCC 6mil via 3 Φ spacing	15
LTCC 8mil via 2Φ spacing	22
LTCC 8mil via 2.5Φ spacing	17
LTCC 8mil via 3 Φ spacing	13
LTCC 10mil via 2Φ spacing	17
LTCC 10mil via 2.5Φ spacing	13
LTCC 10mil via 3 Φ spacing	10

The % increase in thermal conductivity results for the experimental data and the surface area method is given in Graph 2 for 6, 8 and 10 mil diameter vias at 2, 2.5 and 3 diameter densities.



Graph 2: comparing thermal conductivity results of material with the insulator-conductor (ceramic-via fill) surface interface area method

The % increase in thermal conductivity results for the experimental data and the surface area method and rule of mixtures is given in Graph 3 for the 8 mil via at 2, 2.5 and 3 diameter densities. The calculated and measured results are similar for the 8 and 10 mil via sizes at 3 and 2.5 via diameter densities at 2 via diameter densities the measured versus calculated begins to diverge. As the via size decreases both the measured and calculated results improve for all via sizes.



Graph 3: comparing thermal conductivity results of material with the surface/Interface area method and the rule-of mixtures.

Discussion

The results from the experimental study [1] raised questions as to the validity/integrity of the thermal vias; namely the assumption that they can be approximated to full cylinders and therefore the via size used to calculate the rule-of-mixture figures. The other concern was that the conductor and ceramic materials diffuse into each other. Figure 5 shows that, although the vias are not completely uniform, they do take the form of a cylinder close to the expected diameter. A thermal via was mapped with EDS and no diffusion was seen across the boundaries, shown by Figure 6.

Table 4 gives a summary of the thermal conductivity results from the previous study [1]. The conductivity changes as the via size and density change. The conductivity increases as the via density increases, which is expected, and as the via size decreases, which is not expected according to Table 1, the rule-of-mixtures results.

The ceramic-conductor interface temperature is held at the lower temperature due to the high via fill conductivity and thermal diffusivity. The heat flows on the outer cylinder of the thermal via. The ceramic-conductor interface area is calculated and compared to the experimental data, graph 2. The calculated and measured results are similar especially for the 8 and 10 mil via sizes at 3 and 2.5 via diameter densities.

Graph 3 compares the rules-of-mixtures method to the ceramic-conductor interface area method and measured results. The ceramic-

conductor interface method is a better predictor of material system conductivity than rule-of-mixtures which predicts the conductivity to be more than 3 times that of measured conductivity for 8 mil diameter thermal vias.

Conclusion

- An alternative method from rule-of-mixtures has been used to calculate thermal conductivity of LTCC, with thermal vias, material system
- According to experiments, adding thermal vias to DuPont 951 can improve the thermal conductivity of the material system by 10 times but depends on via diameter rather than on volume fill.
- Calculating the conductivity by using the rule of mixture approach does not predict changing the thermal via diameter and usually gives optimistic results.
- Using the ceramic-conductor surface/Interface area method gives a greatly improved prediction of the material system conductivity compared to rule-of-mixtures.

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