Examination of Thermal via Design within LTCC Structures

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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 conductor filled via arrays. Thermal via design within LTCC structures, following public domain guidelines, is investigated in this paper. A thermal imaging system using an infrared camera was used to measure the top surface temperature over a range of powers and design variables. Design variables include via size and spacing. The study includes calculating an equivalent thermal resistance empirically and checking the empirical data against existing theory and ANSYS simulation.

Keywords: Thermal via, Thermal Conductivity, LTCC, DuPont 951, ANSYS

Introduction

Accurate prediction of thermal package performance can only be obtained if the material thermal conductivity is known and definitive. The main objective of this study is to generate thermal resistance guidelines for the integration of thermal conductor filled via arrays into DuPont 951. It is also of use to find the optimal density of vias for performance while considering process limitation. This study illuminates the capacity of thermal vias to reduce thermal resistance within LTCC.

There have been several studies of thermal vias; by . Müller[1]; concentrated heat source; Zampino[2] by flash diffusivity method and Pape[3]; has looked at thermal design within PCB. Chiriac[4] uses FEM analysis for concentrated heat sources.

The approach of this investigation was to directly measure the thermal resistance of a set of samples that had varying size and densities of thermal vias. The measured results are compared against composite thermal conductivity formula and simulation.

Method – Empirical Measurement

Power is applied to a conductor serpentine that has been constructed with 6146 Ag/Pd conductor [5], this serpentine allows the power and therefore heat to be evenly distributed across the material. The serpentine layer has been labeled the radiator.

Figure 1 illustrates the serpentine used to test the material and thermal vias samples.

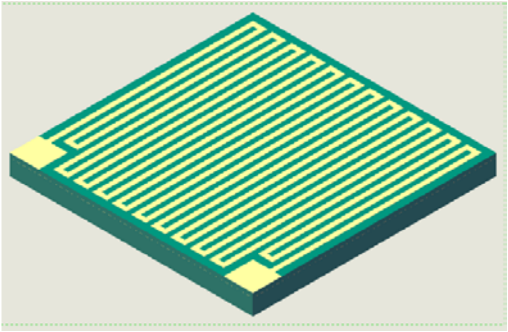


Figure 1: serpentine printed on LTCC 951

There is a limitation to the density of vias that can be easily manufactured. Standard via sizes of 6, 8 and 10 mil diameters were used with a spacing of 2, 2.5 and 3 via diameters; the spacing used is via size center to center. This study does not take hermaticity into consideration; this would add further constraint to the density of vias. A sample without vias is tested as a comparison. The individual sample had an x/y via array area of 0.5"x0.5".

The vias were stacked directly on top of one another and filled with Ag 6141 [6], this paste has reasonable thermal conductivity, see table 1.

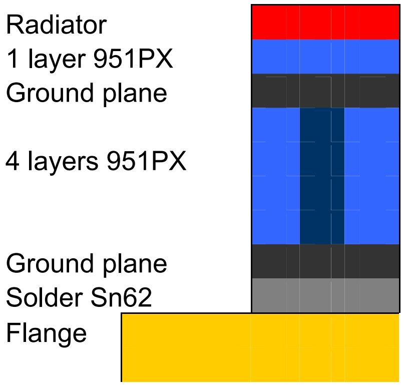


Figure 2: Layer diagram of sample piece.

Figure 2 is a diagram of the various layers. It is important to note that there was a PX/8.5mil layer of 951 LTCC to separate the radiator and the "ground plane" or printed conductor layer. The vias were inserted in between the ground planes.

The samples were mounted to a flange, shown at the base of Figure 2, and power applied across the radiator circuit. An infrared thermal camera was used to record the peak temperature, as shown by Figure 3. The flange temperature was kept to a 50°C constant while the power was increased in 10 or 25 watt increments.

This device has a Biot number under <0.1 therefore convection was not taken into consideration. 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.

Figure 3 is a typical thermal scan of one of the sample pieces under test.

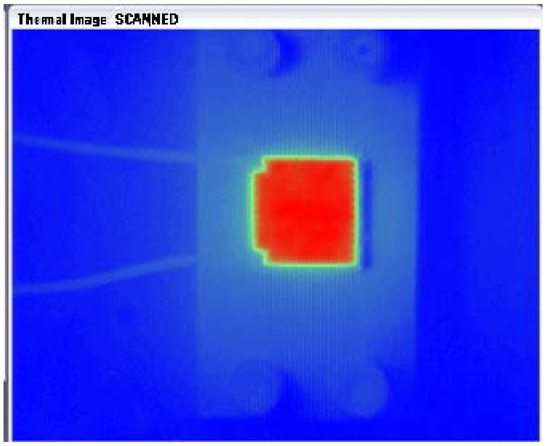


Figure 3: Infra-red thermal image of power applied to serpentine.

Method – Theoretical Composite Thermal Conductivity

The thermal conductivity can be calculated from the rule of mixtures given by equation 1 [7].

$$k_c = k_L\left(\frac{A_{cell} - A_{via}}{A_{cell}}\right) + k_v\left(\frac{A_{via}}{A_{cell}}\right) \qquad (1)$$

A_{cell} is the area of the unit cell, A_{via} is the area of the via. k_c, k_L and k_v are the thermal conductivities of the composite, LTCC and via conductor fill respectively.

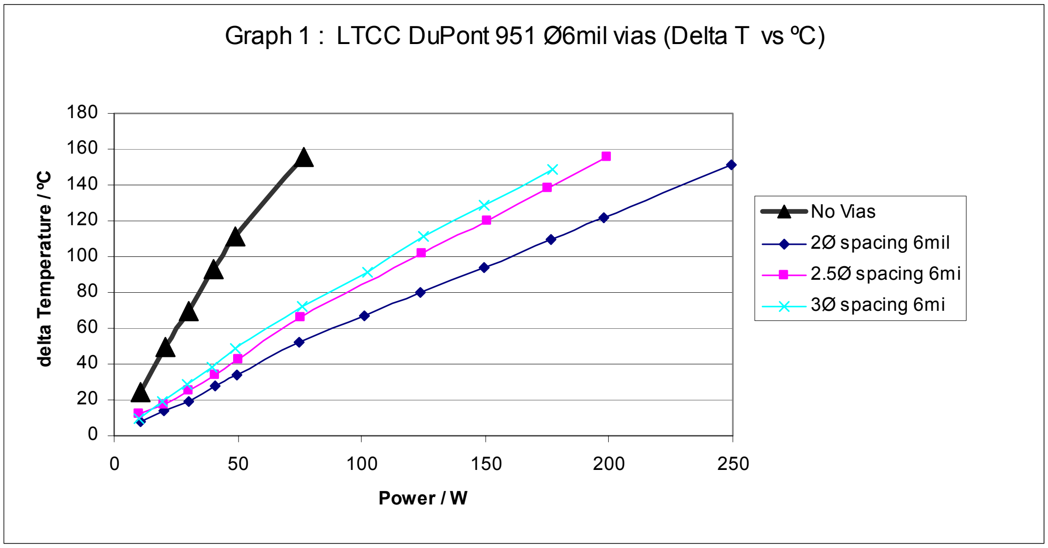
Table 1: Results from rule of mixtures formula

Via Spacing	Axial Theoretical Conductivity **W/ (m*K)**
2 Φ	51.1
2.5 Φ	33.9
3 Φ	24.6

Equation 1 calculates the conductivity of the composite material as if it were homogeneous

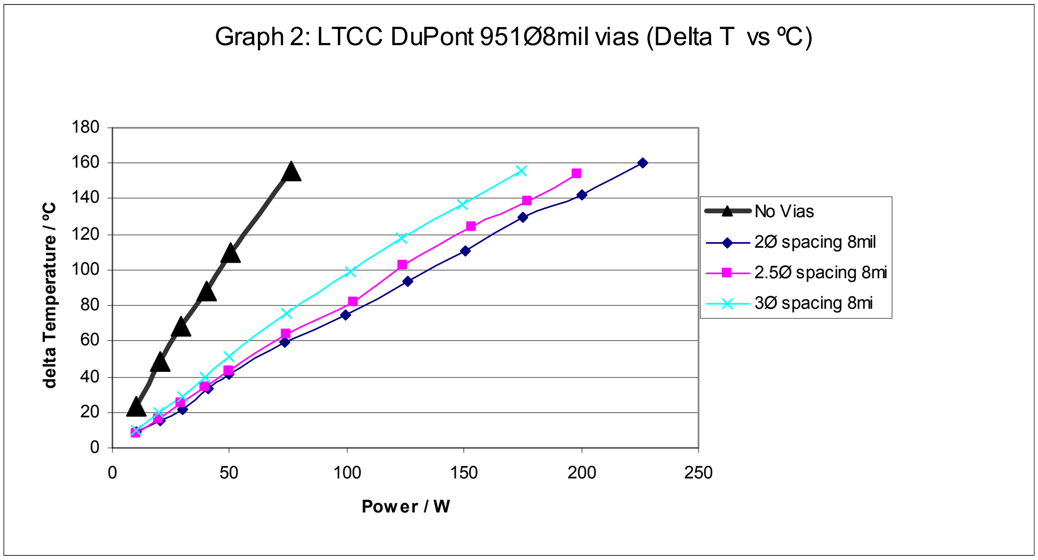
Results

The results of the thermal tests on 4 layers of LTCC, DuPont 951 are given in Graph 1 for the 6 mil via design with 2, 2.5 and 3 diameter center to center spacing.



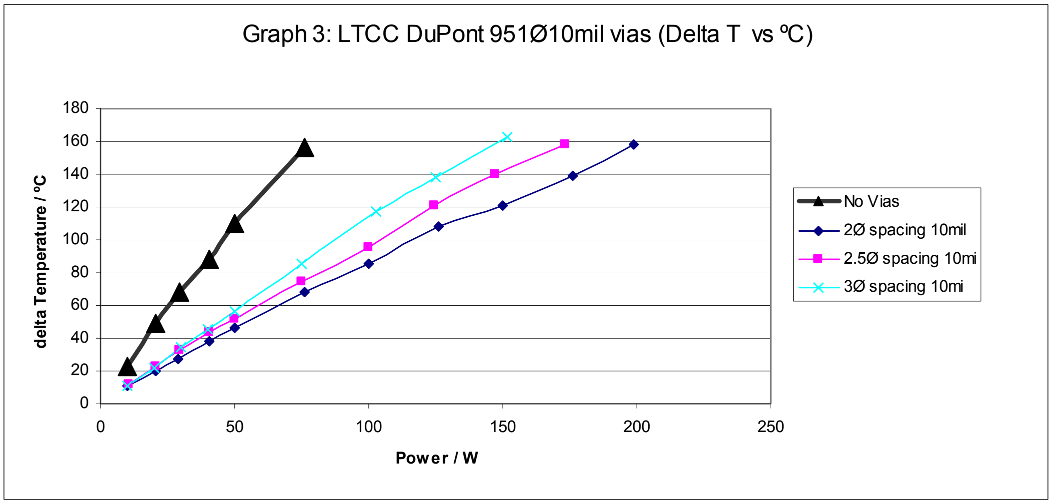
Graph 1: 4 layer DuPont 951 comparing thermal conductivity results of material with no vias, 6mil vias with 2 diameter spacing, 2.5 diameter spacing and 3 diameter spacing.

Graph 2 show the results of the thermal tests on 4 layers of LTCC 951 for 8 mil via size and 2, 2.5 and 3 diameter center to center spacing.



Graph 2: 4 layer DuPont 951 comparing thermal conductivity results of material with no vias, 8mil vias with 2 diameter spacing, 2.5 diameter spacing and 3 diameter spacing.

Graph 3 show the results of the thermal tests on 4 layers of LTCC 951 for 10 mil via size and 2, 2.5 and 3 diameter center to center spacing.



Graph 3: 4 layer DuPont 951 comparing thermal conductivity results of material with no vias, 10mil vias with 2 diameter spacing, 2.5 diameter spacing and 3 diameter spacing.

Table 2 gives a summary of the thermal conductivity results from Graphs 1, 2 and 3.

Table 3 gives a list of thermal conductivities for some common materials used within the electronics industry.

Table 2: Comparison of Thermal Conductivities of measured LTCC (with and without thermal vias)

Material	W/ (m*K)
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

Table 3: Comparison of Thermal Conductivities with various materials	
Material	W/ (m*K)
Air	0.025
Thermal Grease	0.7 - 3
FR4	0.27
Glass	1.1
LTCC 951 – Given by DuPont	3.3
Stainless steel	15
Alumina	18-35
AlN	170
Aluminum	237
Ag Via fill 6141	247
Gold	318
Copper	401
Silver	429

Discussion

Graphs 1, 2 and 3 show that when the density of vias is increased, the heat rise compared to applied power slows down, as expected.

The measured thermal conductivity of DuPont 951 correlates well with the information stated by the DuPont data sheet [8].

For every via spacing, no matter the via size, the equivalent volume percentile or ratio of LTCC ceramic to conductor fill was the same. So the 6mil and 10mil 2 diameter via array have the same via fill percentage volume. Although the % volume of each of the via spacing: 2Φ, 2.5Φ and 3Φ, was the same, the measured thermal conductivity results were different. When compared to the results in Table 1 (given by the rules of mixtures formula), the theoretical results give a higher conductivity than what has been measured. For example the 6mil via array, which gives the best results achieves a thermal conductivity of 34 W/ m*K while the rule of mixtures gives 51.1 W/ m*K.

The calculation of conductivity using equation 1 does not take into consideration the in-homogeneous nature of the material and therefore does not consider mechanical aspects such as via density and shape.

Since the thermal vias are not in view, post fire, it could be that the sizes deviate slightly from the intended sizes of 6, 8 and 10mil. This may add some error to the measured values.

From Table 2 it can be seen that adding thermal vias increase the thermal conductivity of the LTCC structure by 3 to 10 times. The LTCC samples, with vias included, have a thermal conductivity with a magnitude that is similar to Alumina, see Table 3.

Conclusion

Adding thermal vias to DuPont 951 can improve the thermal conductivity of the material by 10 times. Calculating the resultant conductivity by using a volume percentile or rule of mixture approach can prove erroneous and give optimistic results.

The measured results could be checked by testing additional samples with varying layers/thickness. It also may prove useful to test samples with staggered via arrays

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