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Predicting the Thermal Conductivity of Low Temperature Co-fired Ceramic with Embedded Thermal via Arrays using the Rule-of-Mixtures and Interface Area Analytical Methods

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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 low-temperature co-fired ceramics (LTCCs) have 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 IR 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 with conventional and an interface area method. The conventional method used to compare the experimental results to predicated results is the simple rule-of-mixtures. The fact that the thermal conductivity and diffusivity of the filled via are so much greater than those of the LTCC material means that another method of theoretically calculating the resulting thermal conductivity can be used by studying the thermal path. The ceramic–conductor interface area is also calculated to predict material system conductivity and compared with the conventional method and experiments.**

Keywords—**DuPont 951, DuPont 6141, LTCC, rule-of-mixtures, thermal conductivity, thermal diffusivity, thermal via**

Introduction

A feature of low-temperature co-fired ceramics (LTCC) is the addition of thermal vias to subsections in order to increase thermal conductivity in that region while leaving the rest of the volume available for multilayer circuitry (Fig. 1). Accurate prediction of the thermal package performance, with these embedded thermal vias, can be attained if a mathematical model is used that follows the underlying physical nature of the thermal system.

There have been several measurement studies of LTCC with thermal vias: Pierce et al. [1] and Müller et al. [2] by concentrated heat source method; Zampino et al. [3] by flash diffusivity methods; and Pape et al. [4] who examined the thermal via system design within organic PCBs. In addition to the measured data, most of these studies used the rule-of-mixtures analytical method to calculate the thermal conductivity of LTCC with thermal vias. The rule-of-mixtures is a standard and established method for calculating various parameters for composite materials.

The main objective of this study is to test two analytical methods used to calculate the conductivity of composite material: surface/interface-area and rule-of-mixtures methods; the validity of the analytical method is found by comparing the theoretical calculations against measured data.

The "ceramic–metal interface method" approach has not been tested for an LTCC with thermal vias materials system. This method is realized because the temperature of the ceramic–metal interface is low, close to that of the heatsink. The vias operate as paths of low thermal resistance to the heat sink. Therefore, the interface area of the ceramic–conductor, where the heat exchange takes place, can be used as a design tool to calculate the expected thermal conductivity.

Experimental Procedures

The heat source is generated by applying power to a conductor serpentine constructed with a 6146 Ag/Pd conductor [5] this conductor provides an electrical resistance of 60mΩ/sq. The serpentine resistor, printed to span the area of vias, allows the applied power to be converted to heat which is evenly distributed across the material. The serpentine layer is labeled as the radiator (see Fig. 2 and Fig. 3).

A reasonable manufacturing limit of the via spacing is 2-via diameters and is therefore the smallest spacing used in this study. Standard via sizes of 6-, 8-, and 10-mil diameter were used with a 2-, 2.5-, and 3-via diameter spacing. The spacing is measured from the via centers. Additionally, this study does not take hermaticity into consideration, which would add a further constraint to the minimum via spacing limit. Each sample had an *x*/*y* via array area of 0.5 in. × 0.5 in. The number of vias, within this area, could be increased by 15.7% if the vias were staggered in a rhombus configuration; a square grid has been used for this study.

The vias were stacked directly on top of one another and filled with 6141 Ag [6]. The layer design is illustrated by Fig. 3. It is important to note that there was a PX/8.5-mil layer of 951 LTCC to separate the radiator and the "ground plane" or printed conductor layer. The fired via fill 6141 paste has a reasonable thermal conductivity, approximately half that of pure silver (see Table I). The vias were inserted between the ground planes.

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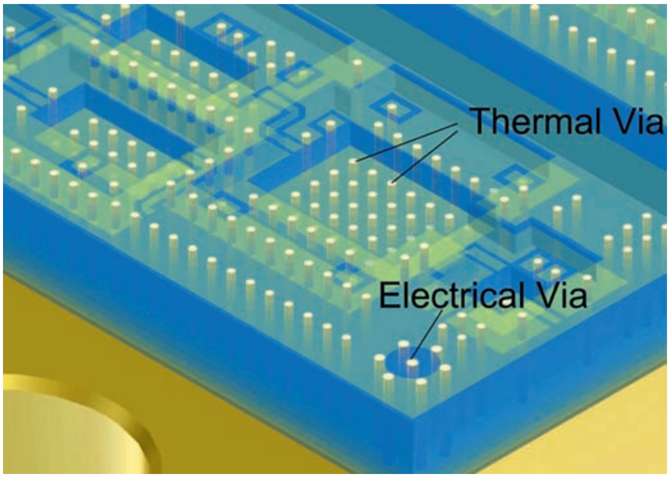

Fig. 1. Representation of thermal and electrical vias in a SiP system.

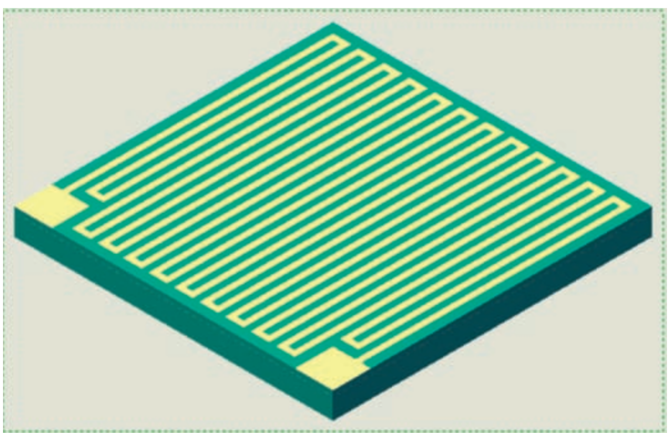

Fig. 2. Serpentine printed on LTCC 951.

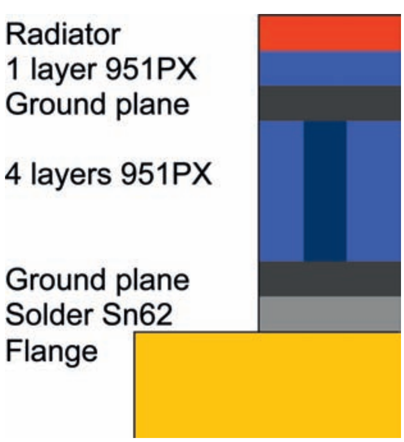

Fig. 3. Layer diagram of sample piece.

The LTCC samples were mounted to a flange/heatsink (see Fig. 3). Power was applied across the radiator circuit; an IR thermal camera was used to record the peak temperature (Fig. 4) of the radiator circuit and the temperature at the top of the flange. A typical thermal scan of one of the sample

Table I
Comparison of Thermal Conductivities with Various Materials

Material	Conductivity (W/m·K)
Air	0.025
Thermal grease	0.7–3
FR4	0.27
Glass	1.1
LTCC 951 (k^c)	3.3 [8]
Alumina	18–35
Ag via fill 6141 (k^m)	247 [6]
Copper	401

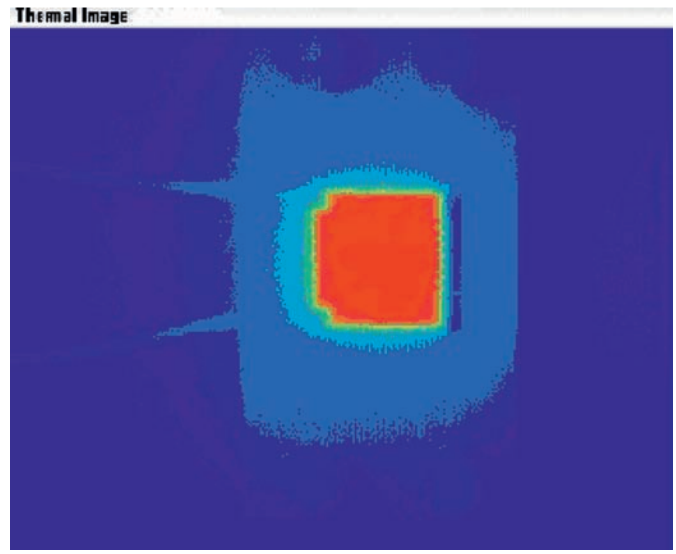

Fig. 4. Infra-red thermal image of power applied to serpentine.

pieces under test is shown in Fig. 4. The top of the flange was kept at a constant 50°C while the power was increased in 10- or 25-W increments. The flange temperature was also checked using a thermocouple. Two samples of each via array type were made and tested.

The thermal resistance of the solder layer and PX separation layer were calculated and subtracted from the total thermal conductivity to isolate the LTCC/via composite thermal conductivity result. To validate this measurement method a blank sample of LTCC, without vias, was tested. The thermal conductivity of the blank LTCC was found to be 3.2 W/mK; the datasheet states that the thermal conductivity of LTCC 951 is 3.3 W/mK [9].

For the samples used in the study, the Biot number was calculated to be under 0.1; therefore, convection was not taken into consideration. The Stefan Boltzmann law was used to calculate the Watts lost by radiation heat transfer. The emissivity of the spray material was, previously, tested to be 0.8. At 200°C an emissivity of 0.6 gives 0.3 Watts lost, an emissivity of 1 gives 0.4 Watts lost, therefore, radiative loss was also disregarded.

Theory 1 for Composite Thermal Conductivity: Rule of Mixtures

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

Table II
Table of Symbols

Symbol	Description
k^c	LTCC (ceramic) thermal conductivity
k^m	Via fill (metal) thermal conductivity
A_{cell}	Area of the until cell/area of repeating via structure
A_{via}	Area of via fill
$k_{composite}$	Thermal conductivity of LTCC and Via fill compostite material
α^c	LTCC (ceramic) thermal diffusivity
α^m	Via fill (metal) thermal diffusivity
T^c_∞	Steady state maximum ceramic/LTCC temperature measured with thermal camera
T^c_∞	Steady state maximum ceramic/LTCC temperature measured with thermal camera

Table III
Results from Rule-of-Mixtures Formula

Via spacing	Axial theoretical conductivity (W/m·K)
2&	51.1
2.5&	33.9
3&	24.6

Table IV
Thermal Diffusivity

Material	(cm^2/s)
Ag via fill 6141 (α^m)	1.42 [2]
LTCC 951, from DuPont (α^c)	0.0127 [2]

$$k_{composite} = k^c\left(\frac{A_{cell} - A_{via}}{A_{cell}}\right) + k^m\left(\frac{A_{via}}{A_{cell}}\right), \quad (1)$$

Please refer to Table II below for a list of symbols and their meanings.

The conductivity of the composite material is calculated by eq. (1), as if the material system were homogeneous. Using the rule of mixtures, the 2, 2.5 and 3 via diameter pitch give a different area fill of material and therefore a different rule-of-mixtures calculation/prediction. However the 6, 8 and 10 mil vias have the same rule-of-mixture prediction for each via spacing. The rule-of-mixture results are given in Table III.

Theory 2 for Composite Thermal Conductivity: Ceramic-Conductor Interface Area

The rule-of-mixtures, outlined above, has been used in the past to work out a theoretical composite thermal conductivity. However, this method assumes that the composite material is homogeneous. In the case of thermal vias in LTCC, the material system functions at a scale where the materials can be considered as segmented into ceramic and conductor sections.

The conductor has a much higher thermal conductivity (>70 times) and thermal diffusivity (>100 times) (Tables IV and I) than the ceramic, and this dictates how the heat flows through the material. Due to this, another method of calculating the thermal conductivity is used for this study and relates to the ceramic–conductor (ceramic = LTCC and metal = via fill) interface area.

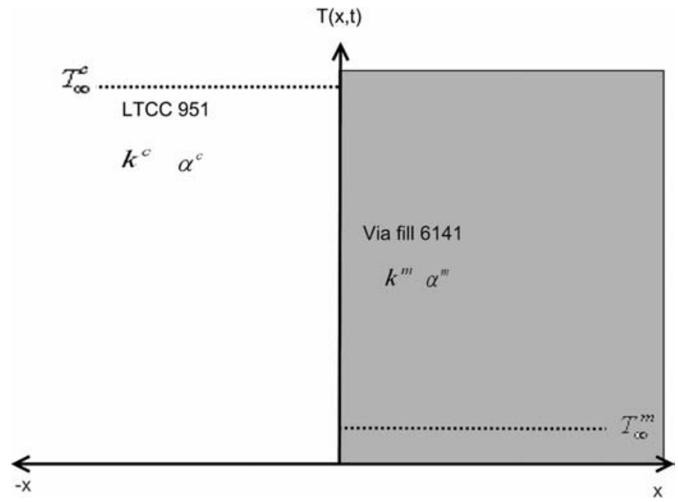

Fig. 5. Illustration of the conductor–ceramic interface and relevant temperatures.

It is assumed that the ceramic LTCC is held at a maximum temperature due to the relative slow thermal diffusivity and low thermal conductivity (Fig. 5). 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 (Fig. 5). With these assumptions, eq. (1) can be used to work out the LTCC–conductor interface temperature $T_{interface}$ [8].

$$T_{interface} = \frac{(k^m\sqrt{\alpha^c})T^m_\infty + (k^c\sqrt{\alpha^m})T^c_\infty}{(k^m\sqrt{\alpha^c}) + (k^c\sqrt{\alpha^m})} \quad (2)$$

Eq. (2) uses the thermal diffusivity and conductivity (see Tables IV and I) of the ceramic and metal materials to calculate the interface temperature.

Table IV shows 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 I lists 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.

$T_{interface}$ T, in eq. (2), gives the interface temperature of the LTCC 951 and silver via fill 6141. The temperature values from a previous study [1] are inserted into eq. (2) (temperature of metal, 50°C; temperature of ceramic at its maximum, 250°C). This gives the interface temperature of 74°C, which is only 24°C greater than the flange/base temperature, for the worst case maximum temperature scenario, and 176°C lower than the radiator temperature.

The ceramic–metal interface temperature is kept low because the heat flows quickly 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 Fig. 6. Therefore the ceramic–conductor interface area has direct impact on this material system's thermal management. The increase of conductor interface area by the addition of thermal vias is given by eq. (3), the via length is given by L.

$$\text{Conductor Interface}_{\%\text{increase}} = \frac{A_{\text{cell}} + \pi \text{via}_{\theta} \text{L}}{A_{\text{cell}}} \times 100 \times 100 \quad (3)$$

The area of the cell is the unit area of the original heatsink, this has been increased by the thermal via cylinder surface area. The calculations of the conductor-ceramic interface area increase are compared against the measured increase of thermal conductivity in Fig. 11.

An ANSYS simulation was carried out to view the vector results for thermal flux. The 6-mil via with 2 diameter spacing configuration is shown in Fig. 7. Again, the via-fill material is clearly seen to be the path of heat flow through the composite material.

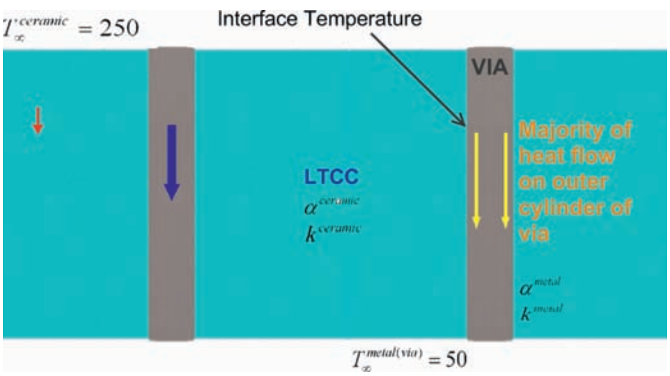

Fig. 6. Illustration of the conductor–ceramic materials differences and heat flow.

Results

Results of the thermal tests on four layers of LTCC, DuPont 951, are given in Fig. 8 for the 6-mil via design with 2-, 2.5-, and 3-diameter center-to-center spacing.

Results of the thermal tests on four layers of LTCC 951 for 8-mil via size and 2-, 2.5-, and 3-diameter center-to-center spacing are shown in Fig. 9.

Results of the thermal tests on four layers of LTCC 951 for 10-mil via size and 2-, 2.5-, and 3-diameter center-to-center spacing are shown in Fig. 10.

Conductivity measurements in Figs. 8, 9, and 10 are summarized in Table V.

Comparison of Measured Conductivity and Theoretical Conductivity

The percentage increase in thermal conductivity results for the experimental data and the surface-area method and rule-of-mixtures is given in Fig. 11 for the 6-, 8-, and 10-mil via at 2-, 2.5-, and 3-diameter densities.

The 8- and 10-mil vias at 3- and 2.5-via diameter pitch spacing have similar calculated and measured results. The measured versus calculated begin to diverge the 2-via diameter pitch spacing.

Discussion

As the spacing of vias is increased, the heat rise compared with applied power slows down, as expected (see Figs. 8, 9, and 10). As via size decreases, the thermal conductivity increases; this is not expected. The equivalent volume percentile or ratio of LTCC ceramic to conductor fill depends on the via spacing not the via diameter for the via configuration used in this study. Therefore, the via fill percentage volume

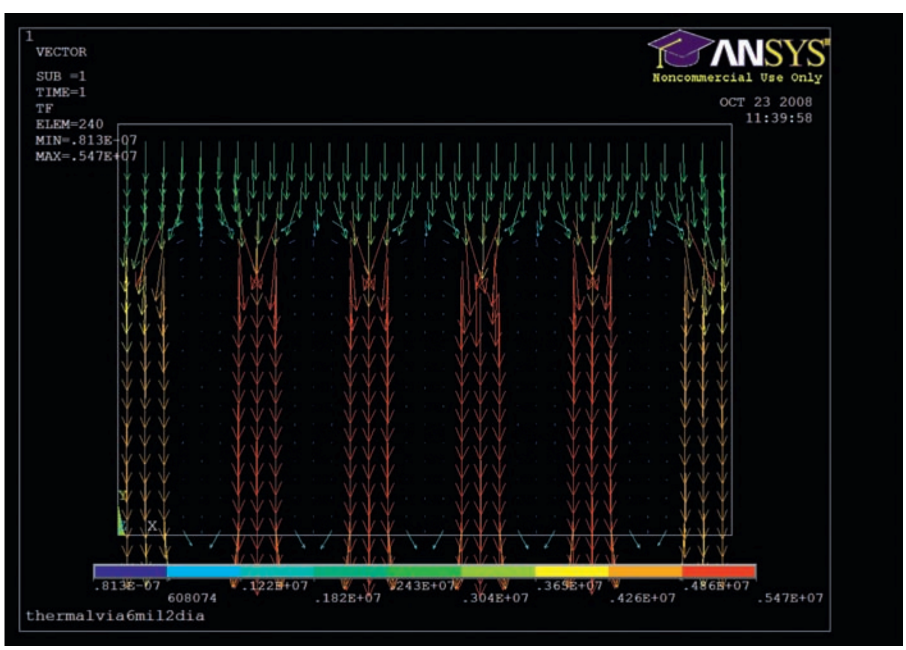

Fig. 7. ANSYS simulation of 6-mil diameter via with 2 diameter spacing showing heat flux.

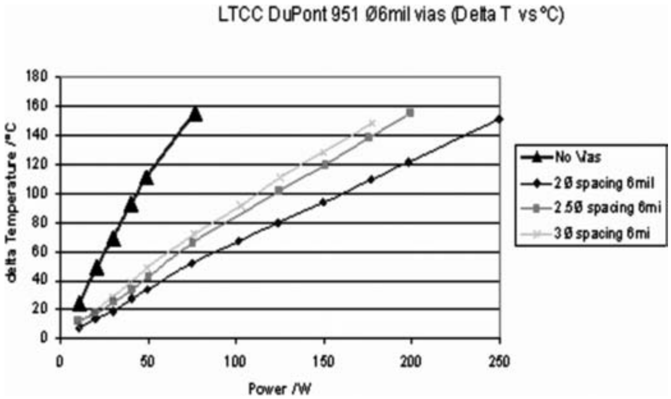

Fig. 8. Four-layer DuPont 951 comparing thermal conductivity results of material with no vias and 6-mil vias with 2-, 2.5-, and 3-diameter spacing.

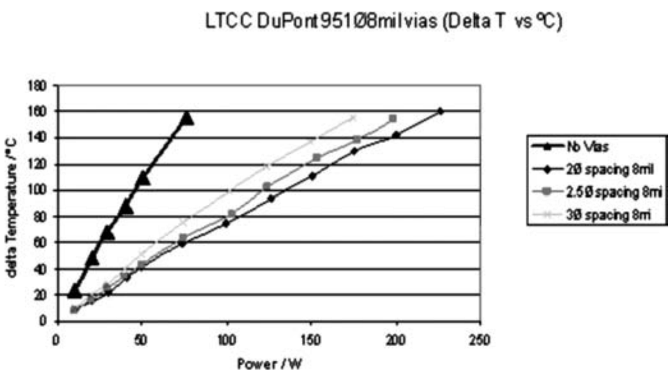

Fig. 9. Four-layer DuPont 951 comparing thermal conductivity results of material with no vias and 8-mil vias with 2-, 2.5-, and 3-diameter spacing.

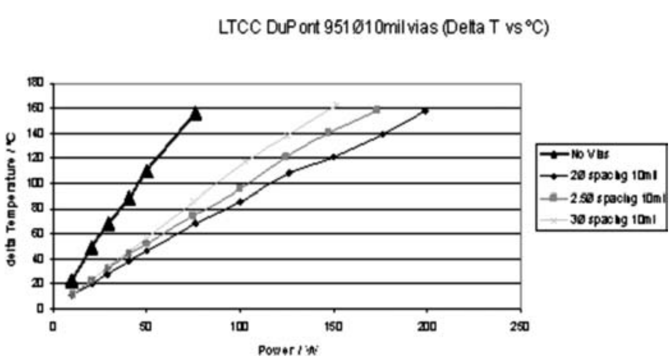

Fig. 10. Four-layer DuPont 951 comparing thermal conductivity results of material with no vias and 10-mil vias with 2-, 2.5-, and 3-diameter spacing.

of 6-mil and 10-mil vias with 2 diameter via spacing are the same and according to the rule-of-mixtures should give the same result. Although the percentage volume of each of the via spacings—2&, 2.5&, and 3&—is the same, the measured thermal conductivity results are different. The rule-of-mixtures calculation gives a higher conductivity calculation than what has been measured, as seen by Table III. The 6-mil via array, which gives the best results, achieves a thermal conductivity of 34 W/m·K while the rule-of-mixtures analysis gives 51.1 W/m·K.

Table V
Measured Thermal Conductivities of LTCC (with and without thermal vias)

Material	Conductivity (W/m·K)
LTCC 951 (no vias)	3.2
LTCC 6-mil via	
2& spacing	34
2.5& spacing	18
3& spacing	15
LTCC 8-mil via	
2& spacing	22
2.5& spacing	17
3& spacing	13
LTCC 10-mil via	
2& spacing	17
2.5& spacing	13
3& spacing	10

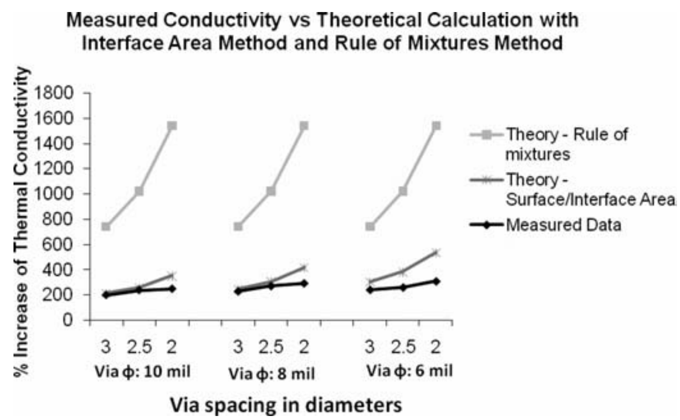

Fig. 11. Comparing measured thermal conductivity results with the surface/interface area method and the rule-of-mixtures method.

The calculation of thermal conductivity using eq. (1) does not take into consideration the inhomogeneous nature of the material and therefore does not consider mechanical aspects such as via spacing and shape.

The ceramic–conductor interface temperature is held close to the flange temperature due to the high via fill conductivity and thermal diffusivity. The majority of the heat flows in the via fill material as seen by Fig. 7. Therefore the increase in thermal conductivity is related to the increase of the ceramic–conductor interface area.

The measured results are seen to be similar to the ceramic–conductor interface area method, especially for the 8- and 10-mil via sizes at 3- and 2.5-via diameter spacing, by Fig. 11. The ceramic–conductor interface method gives a more accurate prediction of material system conductivity than the rule-of-mixtures which estimates the conductivity to be more than 3 times that of measured conductivity for 8-mil diameter thermal vias.

At a spacing of 2 diameters the 8 and 10-mil vias deviate slightly to the surface area calculation. The 6-mil vias results deviate from the surface area calculation at all spacings and especially at 2 diameters. The interface method does not directly calculate the average distance the heat has to travel through the ceramic to reach a heatsink/thermal via. It could be when the vias are at a close range the increase in interface area has a lower impact; this would depend on the spreading resistance of the ceramic. When the vias are packed closer together the heat has a shorter path to travel through the ceramic but may only utilize the top portion of the thermal via conductor–ceramic interface. This could be determined quantitively by further simulation work.

Adding thermal vias increases the thermal conductivity of the LTCC structure 3–10 times (Table V). The LTCC samples, with vias included, have thermal conductivities with magnitudes similar to that of alumina (Table I).

The measured thermal conductivity of DuPont 951 correlates well with the information stated in the DuPont data sheet [9].

Conclusion

- LTCCs with a range of thermal via sizes and densities were measured for material system thermal conductivity. These results were compared against calculated results from two analytical methodologies: the rule-of-mixtures and the ceramic–conductor area interface.
- Adding thermal vias to DuPont 951 can improve the thermal conductivity of the material system by up to 10 times, but the degree of improvement depends on via diameter size rather than on volume fill.
- Calculating the conductivity by using the rule-of-mixtures approach does not predict changing the thermal via diameter and usually gives optimistic results.
- The ceramic–conductor surface/interface area method gives a greatly improved prediction of the material system conductivity compared with rule-of-mixtures analysis for the design parameters sed in this study.

Acknowledgment

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Biography

Tracey S. Vincent became a Member (M) of IMAPS in 2003 and has a Masters degree in Electrical and Electronic Engineering from Heriot-Watt University, Scotland, United Kingdom, and a Masters degree in Numerical Methods for Ferrite Junction Circulators from Napier University, Scotland, part-time 2001-2005.

She was employed as a senior RF design engineer at Barry Industries from 2002 to 2007. Previous to this she worked as a circulator designer for Filtronic Comtek in the United Kingdom. Currently she is a Ph.D. candidate and Stoddard Fellow at WPI in Worcester, Massachusetts, USA. Ms. Vincent has also been a member of IEEE since 2001 and of ACers since 2006.