Development of a Consistent and Reliable Thermal Conductivity Measurement Method, Adapted to Typical Composite Materials Used in the PCB Industry

François LECHLEITER
Cimulec, Ennery, France

Yves JANNOT
Université de Lorraine, LEMTA, Vandoeuvre-lès-Nancy, France

Abstract

Most of today's printed circuit board base materials are anisotropic and it is not possible to use a simple method to measure thermal conductivity along the different axis, especially when a good accuracy is expected. Few base material suppliers' datasheet show X, Y and Z thermal conductivities. In most cases, a single value is given, moreover determined with a generic methodology, and not necessarily adapted to the reality of glass-reinforced composites with a strong anisotropy.

After reminding of the fundamentals in thermal science, this paper gives an overview of the state-of the art in terms of thermal conductivity measurement on PCB base materials, and some typical values. It finally proposes an innovative method called transient fin method, and associated test sample, to perform reliable and consistent in plane thermal conductivity measurement on anisotropic PCB base materials.

Introduction

Observed on a long enough time scale, electronic systems behave like living species; they obey the evolution laws.
To be successful, they have to adapt to their environment, which means to market requirements, thus to consumer expectations. Any system with a new, more powerful functionality naturally surpasses the previous generation. As consumers, we all know that we normally prefer smaller, lighter, faster, more reliable and cheaper electronic systems. This has driven the electronic industry since its beginning.

The PCB[1] progressively becomes a little bit more than just the backbone of electronic systems. At the beginning, the printed circuit board was providing essentially an electrical function, by interconnecting electrically components together, and a mechanical function, by supporting mechanically the components and holding them into a defined volume. Progressively, evolution towards microwave applications brought electromagnetic functionalities to the PCB. In addition, the constant increase of power density made the PCB more and more capable of providing solutions for efficient thermal management strategy.

Heat transfer is the exchange of thermal energy between physical systems. It always occurs from a region of high temperature to another region of lower temperature. The fundamental modes of heat transfer are conduction, convection and radiation. In a PCB, the predominant mode is conduction, for which thermal conductivity of the material is a good indicator. Therefore, to accompany PCB evolution, base material suppliers improved the thermal conductivity of their laminates and prepregs. Early printed circuit boards were made of bakelite, having around 0.2 $W.m^{-1}.K^{-1}$ thermal conductivity. Nowadays, it is possible to find dielectric materials compliant with printed circuit board manufacturing process and product specifications exhibiting a higher thermal conductivity, typically in the range of 2 $W.m^{-1}.K^{-1}$, where copper is almost 400 $W.m^{-1}.K^{-1}$.

Nowadays, most of the critical parameters of printed circuit boards have reached some limits. Improving the overall performances of the electronic system often means to look for some percentage. This is true for PCB thickness, via size, copper thickness, or etched features. This is also true for thermal behavior. Designers are looking for some Celsius value for the system operating temperature. In this context, it becomes more and more important to have reliable thermal models, and therefore to feed these models with consistent physical properties, including thermal conductivity.

Many methods exist to measure thermal conductivity. Most of them are adapted to isotropic and homogeneous materials, but there is not one single easy method to measure thermal conductivity of composite anisotropic materials, especially dielectrics used in the printed circuit board industry. Therefore, this paper aims at proposing a method for consistent and reliable thermal conductivity measurements, adapted to anisotropic dielectric materials.

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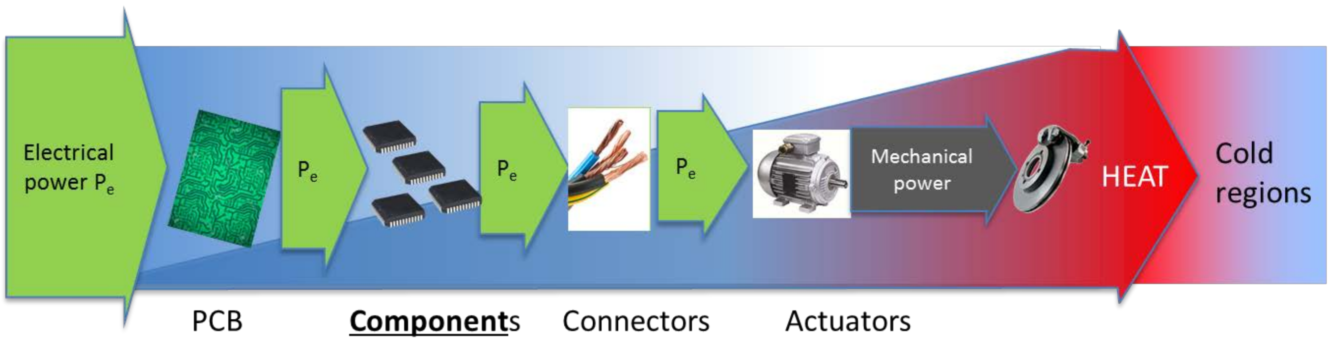
[1] Printed Circuit Board

Fundamentals about thermal science

To understand how to optimize thermal efficiency of a printed circuit board, and why thermal conductivity of dielectric materials is important, this section gives an overview of some aspects of thermal science.

Standard physic models say that heat propagates according to three modes: conduction, convection and radiation. Heat transfer always occurs from hottest region to coolest region.

The first law of thermodynamics says that the total *quantity* of energy in the universe remains constant. This is the principle of the conservation of energy. The second law of thermodynamics states that the *quality* of this energy is degraded irreversibly. This is the principle of the degradation of energy, and systems powered by electricity respect these laws.



Heat is generated all along the chain. At the electronic system level, the main contributors are often components. The printed circuit board, supporting and interconnecting them, is also very helpful to avoid system excessive heating. Indeed, excessive temperatures degrade overall system performance, from speed to long term reliability. Therefore, electronic system designers take great care of operating temperatures. Equations managing thermal exchanges can be easily found in the literature.

Thermal management of a printed circuit board

A multilayer printed circuit board is usually a sandwich mixing copper and glass-reinforced composites. This is an environment where the predominant heat transfer mode is conduction. Inside the material, convection and radiation can be neglected. To optimize thermal efficiency of a PCB, it is therefore important to maximize heat conduction.

In physics, **thermal conductivity** is the property of a material to conduct heat. It is evaluated primarily in terms of Fourier's Law for heat conduction. Heat transfer occurs at a lower rate across materials of low thermal conductivity than across materials of high thermal conductivity. This is why high thermal conductivity materials are preferred for heat sink applications, while materials of low thermal conductivity are used for thermal insulation.

Using dielectric materials having a high thermal conductivity to build a printed circuit board will make the whole structure more thermally conductive, and will help to transfer heat generated by the components to a colder region. This is generally the strategy to maintain both the PCB and the components to an acceptable operating temperature. Thermal conductivity is probably the most interesting characteristic, when it is about to compare different base materials in order to optimize a printed circuit board thermal management, or simply to assess the operating temperature of a system. This is why suppliers usually indicate thermal conductivity properties in their dielectric base materials' datasheets.
There are a number of possible ways to measure thermal conductivity, each of them suitable for a limited range of materials, depending on the thermal properties and the medium temperature. Two classes of methods exist to measure the thermal conductivity of a sample: steady state and non-steady-state (or transient) methods. In general, steady-state techniques perform a measurement when the temperature of the material measured does not change with time. The transient techniques perform a measurement during the process of heating up.

Thermal diffusivity

In heat transfer analysis, **thermal diffusivity** is the thermal conductivity divided by density and specific heat capacity at constant pressure. It measures the ability of a material to conduct thermal energy relative to its ability to store thermal energy. In a material with high thermal diffusivity, heat moves rapidly through it, because the material conducts heat quickly relative to its volumetric heat capacity or 'thermal bulk'. It characterizes the heat propagation velocity in a material, without information on its intensity.

Thermal diffusivity is often measured with the flash method (this is the case for ASTM E1461 and IPC-TM-650-2-4-50). It involves heating a **strip** or cylindrical sample with a short energy pulse at one end and analyzing the temperature change (reduction in amplitude and phase shift of the pulse) a short distance away. Thermal diffusivity is usually denoted α. The following formula explains the relationship between thermal conductivity λ, the density ρ, and the specific heat C_p.

$$\alpha = \frac{\lambda}{\rho c_p}$$

Where

α: thermal diffusivity ($m^2.s^{-1}$)

λ: thermal conductivity ($W.m^{-1}.K^{-1}$)

ρ: density ($kg.m^{-3}$)

Cp: specific heat capacity ($J.kg^{-1}.K^{-1}$)

Note: ρCp is called volumetric heat capacity ($J.m^{-3}.K^{-1}$). When ρCp is known, measuring thermal diffusivity is very interesting to assess thermal conductivity.

Current PCB base material thermal conductivity measurement situation

There are a number of possible ways to measure thermal conductivity, each of them suitable for a limited range of materials, depending on the thermal properties and the medium temperature. Every field of application, from building to semiconductor industry has its own nature of materials, performance expectations, and range of temperatures. Most of printed circuit board materials are made of woven glass-fiber impregnated with resin. Glass and resin do not have the same properties. Therefore, thermal conductivity in the XY plan (along the glass fibers) cannot be the same as thermal conductivity along the Z-axis (thickness of the PCB).

Table 1 : Thermal conductivities of normal PCB base materials main components, (orders of magnitude, $W.m^{-1}.K^{-1}$)

Glass E	1
Standard epoxy	0.2 to 0.3
Copper	390

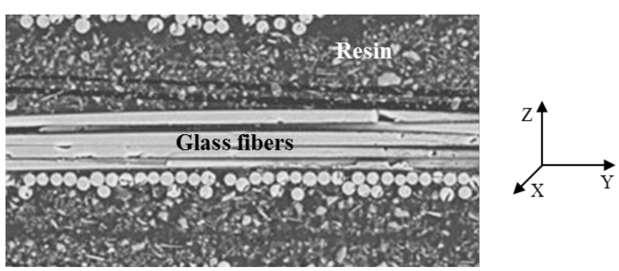


Figure 1: Thermal transfer representation in a glass-reinforced material

As represented in the figure above, the XY plane is the plane of the woven glass fibers, while Z is the axis of the thickness of the base material. When examining various datasheets of major dielectric base materials (typically High Tg glass-epoxy materials), it appears that base material suppliers use a wide range of methods to measure the thermal conductivity of their products. In most cases, it is also evident that anisotropy of materials is not considered.

Table 2 : Some supplier's datasheet extracted information

Supplier	Type	Name of the parameter in the datasheet	Unit	Value	Method claimed
A	Glass-polyimide	Thermal conductivity	$W.m^{-1}.K^{-1}$	0,20	ASTM E1461
I	Glass-PTFE	Thermal conductivity	$W.m^{-1}.K^{-1}$	0,23	not specified
E	Glass-epoxy	Thermal conductivity	$W.m^{-1}.K^{-1}$	0,30	not specified
B	Glass-epoxy	Thermal conductivity (-100-250°C)	$W.m^{-1}.K^{-1}$	0,32	ASTM F433
J	Glass-PTFE ceramic	Thermal conductivity	$W.m^{-1}.K^{-1}$	0,49	ASTM C518
H	Glass-epoxy	Thermal conductivity	$W.m^{-1}.K^{-1}$	0,53	Laser flash
J	Glass-hydrocarbon ceramic	Thermal conductivity	$W.m^{-1}.K^{-1}$	0,60	ASTM F433
E	Glass-epoxy	Thermal conductivity	$W.m^{-1}.K^{-1}$	0,79	not specified
D	Thermally improved glass-epoxy	Thermal conductivity-Z-Axis	$W.m^{-1}.K^{-1}$	2,00	ASTM E1461
		Thermal conductivity-X-Y-Axis	$W.m^{-1}.K^{-1}$	3,50	ASTM E1461

This table gives an overview of the range of thermal conductivities of typical existing dielectric base materials, and thermally improved glass-epoxy. Because of this specificity, only supplier **D** considers anisotropy, and specifies thermal conductivity according to the direction of measurement. All others provide a single value.

Thermally improved dielectrics are more expensive than standard products, and more difficult to process. Therefore, a good knowledge of thermal conductivities in all directions may be important for the designer to optimize their products, from a pure technical prospective, but also from a cost efficiency prospective. Indeed, heat can be transferred to colder regions laterally, on the component side, on the opposite side, or a combination of these three options.

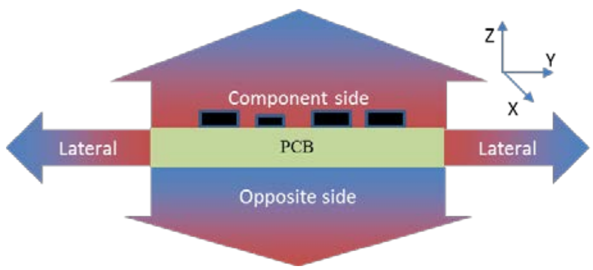


Figure 2: Printed circuit board thermal management possibilities

Thermal conductivity measurement methods used by material suppliers

ASTM E1461: "Standard Test Method for Thermal Diffusivity by the Flash Method"
"[…]this test method covers the determination of the thermal diffusivity of **primarily <u>homogeneous isotropic</u> solid materials**. Thermal diffusivity values ranging from 0.1 to 1000 (mm)2 s-1 are measurable by this test method from about 75 to 2800 K.[…]This test method is applicable to the measurements performed on essentially fully dense (preferably, but low porosity would be acceptable), **homogeneous**, and **isotropic** solid materials that are **opaque** to the applied energy pulse.[…]"

ASTM F433: "Standard Practice for Evaluating Thermal Conductivity of **<u>Gasket</u>** Materials"
[…]This practice covers a means of measuring the amount of heat transfer quantitatively through a material or system.
This practice is similar to the Heat Flow Meter System of Method C 518, but modified to accommodate small test samples of higher thermal conductance.

ASTM D5930: "Standard Test Method for Thermal Conductivity of **<u>Plastics</u>** by Means of a Transient Line-Source Technique"
[…] This test method covers the determination of the thermal conductivity of plastics over a temperature range from – 40 to 400°C. The thermal conductivity of materials in the range from 0.08 to 2.0 W/m.K can be measured covering thermoplastics, thermosets, and rubbers, filled and reinforced. […] There is no known ISO equivalent to this test method."

ASTM C518: “Standard Test Method for Steady-State **Thermal Transmission Properties** by Means of the Heat Flow Meter Apparatus”
“[…] This test method covers the measurement of steady state thermal transmission through flat slab specimens using a heat flow meter apparatus […] Applicable to the measurement of thermal transmission through a wide range of specimen properties and environmental conditions. The method has been used at ambient conditions of 10 to 40°C with thicknesses up to approximately 250 mm, and with plate temperatures from -195°C to 540°C at 25 mm thickness […]. To meet the requirements of this test method the thermal resistance of the sample must be greater than 0.10 $K.m.W^{-1}$ in all directions […]”

Laser Flash: “Method to measure thermal diffusivity”
The laser flash method is used to measure thermal diffusivity of a thin disc in the thickness direction. This method is based upon the measurement of the temperature rise at the rear face of the thin-disc specimen produced by a short energy pulse on the front face. With a reference sample, specific heat can be achieved, and with known density the thermal conductivity is calculated.

IPC-TM-650 2.4.50: Thermal Conductivity, Polymer Films”

“[…] This test method defines the procedure for determining the Thermal Conductivity of polymer coatings on inorganic substrates, such as polyimide on silicon wafer […]”.

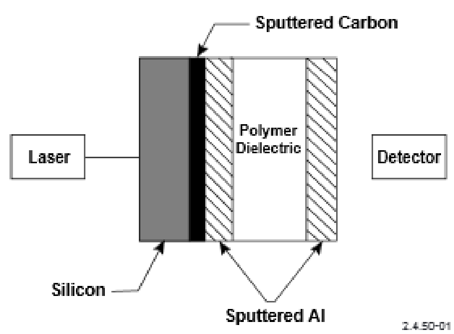


Figure 3: IPC-TM-650-2-4-50: Laser is flashed and the heat rise is measured on the back Al by the detector

First conclusion

Base material suppliers use many different methods, making it difficult to compare the relative performances of their products or to check the actual properties. Some methods are clearly not adapted to anisotropic materials. The flash method, described in both IPC-TM-650 2.4.50 and in ASTM E1461, is claimed to be adapted to measuring thermal diffusivity of only isotropic material. It does not allow for determination of the XY plane thermal diffusivity of a thin anisotropic sample.

Proposed method to measure XYZ thermal conductivity: “Transient fin method”
The proposed method is called **transient fin method**. It aims at measuring the thermal diffusivity in the XY plane, with a simple setup and a sample which is easy to produce. Associated with differential scanning calorimetry and the flash method, it allows to have thermal conductivity values along the Z-axis and in the XY plane.

The method is based on heat generation by a copper conductor patterned on the dielectric material to analyze, and temperature measurement by an optical sensor (infrared camera). The copper pattern is easily produced by a printed circuit board manufacturer. It does not require particular capabilities. Typically, starting from a laminate with copper on both sides, the pattern is produced by direct photolithography.

When it is preferred to analyze the temperature variation on the opposite side, in order to ease the centering of the optical sensor on this opposite side, some fiducials can be added also by photolithography of a copper pattern. However, this copper pattern should be far enough from the analyzed zone, not to disturb the measurement.

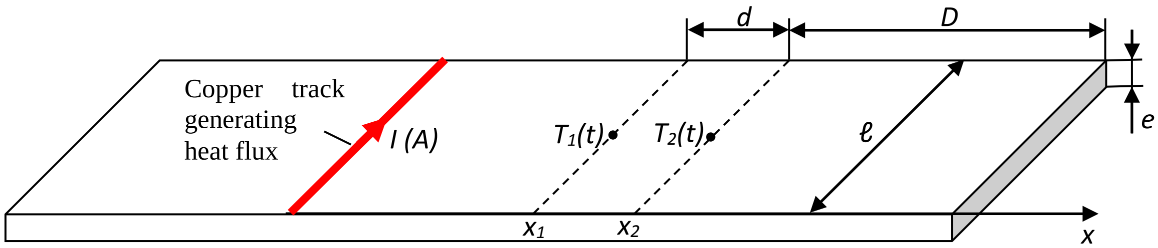


Figure 4: Transient fin method principle

The principle is to inject a step of current between the two extremities of a copper track to generate heat, and to measure the temperature variation in two distinct points at a defined distance from the heating track, by placing an optical sensor (infrared camera) either on the same or on the opposite side of the test sample.

Review of physics for the model

At first, the mathematical model of $T_2(t)$ has to be determined. Once this is done, the transient fin method consists of recording thermograms (output of the IR sensor), and finding the best parameter values to make the model stick to the experimental curves (thermograms).

This model developed is based on the following assumptions;

- The sample is considered as initially at a uniform temperature, equal to ambient air temperature T_a. A step of current is supplied to the copper track, and generates heat flux $\Phi(t)$. Very interesting for the transient fin method is that it is not necessary to know intensity or time variations of the heat flux.

  The thermal gradient in the thickness *e* is negligible with regards to the other dimensions. This is verified if the thickness is less than one tenth of the other dimensions, which is clearly the case for our test sample. In other words, when distance x_1 between the heating track and the first line, and the distance $d = (x_1 - x_2)$ are large enough with regards to the sample thickness, the heat transfer is considered as mono-dimensional (no heat gradient along Z). As an order of magnitude, the typical PCB sample to analyze is ~100 to 200µm thick, while x_1 and d can easily be around 10mm.

- The test sample is large enough to be considered as semi-infinite during the measurement time.

The evolution of temperatures $T_1(t)$ and $T_2(t)$ at respective distances x_1 and $x_2$from the copper track edge, is recorded by the IR sensor (could be also thermocouples or any other temperature measurement system, with appropriate time constant and accuracy).The output of this process is the experimental curves (in time domain).

With Laplace transform formalism, $\theta_2(p)$ and $\theta_1(p)$ are the Laplace transforms of $T_1(t)$ and $T_2(t)$.

H(P) is the transfer function between $\theta 2(p)$ and $\theta 1(p)$.

$$H(p) = \frac{\theta_2}{\theta_1}$$

To determine H(P), we use the quadrupole formalism;

$$\begin{bmatrix} \theta_1 \\ \Phi_1 \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} \theta_2 \\ E\sqrt{p}\theta_2 \end{bmatrix}$$

With

$$A = D = cosh(qd)$$
$$B = \frac{1}{\lambda q} sinh(qd)$$
$$C = \lambda q sinh(qd)$$

And:

$$q = \sqrt{\frac{p}{a} + \frac{hP_e}{\lambda S}}$$

Where:
$P_e = 2(e + \ell)$ is the perimeter
$S = e\ell$ is the heat flux flow section
λ is the thermal conductivity and $E = \sqrt{\lambda\rho c}$ is the thermal effusivity

We can write;

$$\theta_2 = \frac{\theta_1}{A + BE\sqrt{p}} = \frac{\theta_1}{cosh(qd) + \frac{E}{\lambda q} sinh(qd)\sqrt{p}}$$

With $\frac{E}{\lambda} = \frac{\sqrt{\lambda\rho c}}{\lambda} = \sqrt{\frac{\rho c}{\lambda}} = \frac{1}{\sqrt{a}}$

It shows that θ_2 is only a function of θ_1, p, a and $\frac{hP_e}{\lambda S}$, and thus;

$$H(p) = \frac{1}{cosh(qd) + \frac{E}{\lambda q} sinh(qd)\sqrt{p}} = \frac{1}{cosh(qd) + sinh(qd)} = exp(-qd)$$

With $q = \sqrt{\frac{p}{a} + \frac{hP_e}{\lambda S}}$

To come back in the real space (time domain) and find T_2(t) function, we have to make the convolution product of T_1(t) by the inverse Laplace transform of *H(P)*:

$$T_2(t) = T_1(t) \otimes L^{-1}[H(p)]$$

Note : L^{-1}[*H(p)*] is the inverse Laplace transform of *H(p).*

From the above, the model (shape of the curve) of $T_2(t)$is known. With appropriate parameters, it can be adjusted to the experimental curve. An optimization algorithm is then used to determine the best *a* and *h* values minimizing the difference between the experimental and theoretical curves. The next graphs represent this optimization.

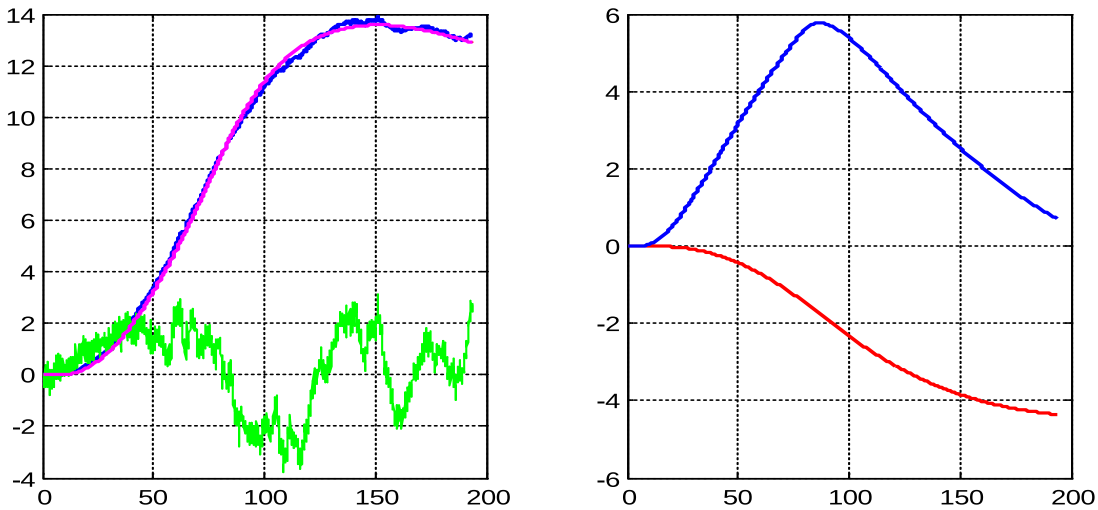


Figure 5:Example of experimental and optimized theoretical curves. Reduced $T_1(t)$ sensitivity to *a* (blue) and *h* (red)

Note: everything was done using mathematical software

Measurement system setup

The transient fin samples have to be prepared first. A square shape, approximately 100mm x100mm, is sufficient, with the heating copper track in the middle, and power supply bars on one side. There is no other specific treatment required. Temperature variation can be recorded on the front side or rear side. In order to ease the centering of the optical sensor on this opposite side, fiducials can be added by etching (photolithography). In that case, the resulting copper fiducials should be far enough from the analyzed zone not to disturb the measurements.

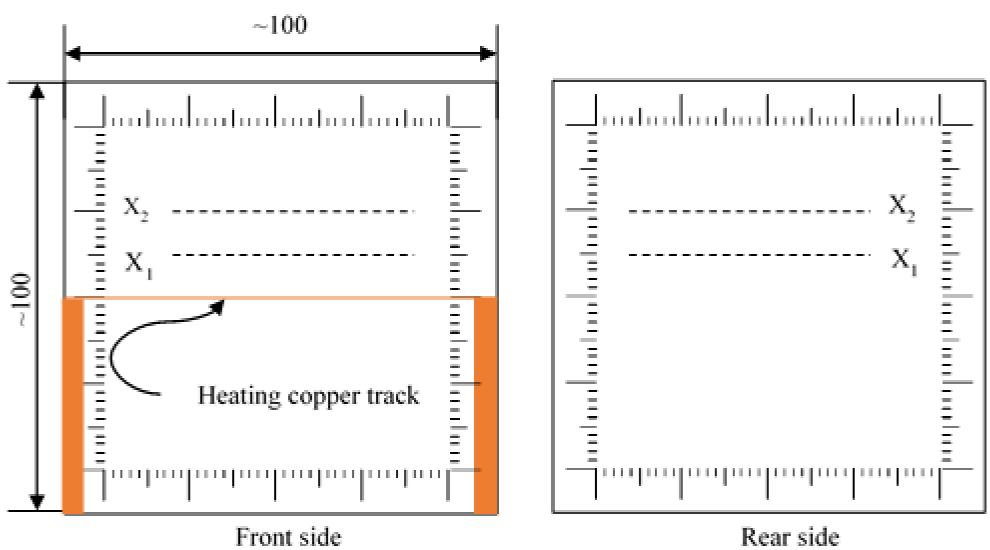


Figure 6: Transient fin sample design

The transient fin sample has to be connected to a current source, and placed in front of an IR sensor, which will record temperature over time variations, at defined distances from the copper track. To make the measurement easy and repetitive, an apparatus is suggested in Figure 7.

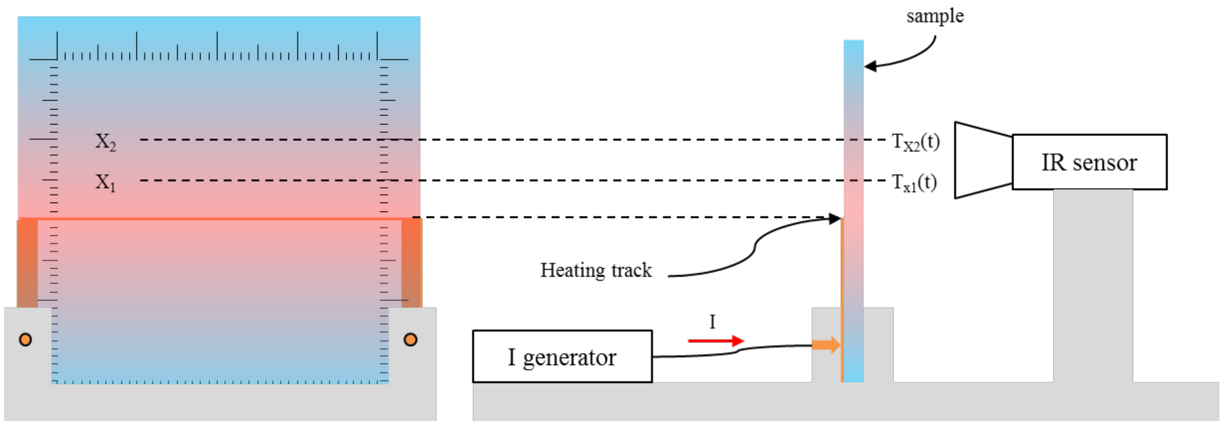


Figure 7: Transient fin sample method apparatus example

Method to get XY and Z Thermal Conductivities

Step 1

Density and specific heat have to be measured first. Specific heat is measured by Differential Scanning Calorimetry (DSC). Together, density and specific heat give volumetric heat capacity ρCp, considered as isotropic. As this is quite standard, and many measuring equipment are commercially available, this will not be discussed further here. For DSC and density measurement, depending on the equipment and specified method for DSC and density measurement, no specific samples are required, with usually only a small piece of material.

Step 2

The Flash method is then used to measureα_z, thermal diffusivity along Z axis (thickness of the base material). Combining α_z and volumetric heat capacity ρCp gives thermal conductivity along the Z-axis. Here again, the flash method is well documented and standards exist (see ASTM E1461, IPC-TM-650 2.4.50).Samples have to be prepared according to the standard method, for example ASTM1461. It will not be discussed further here.

Step 3

In a third step, the proposed transient fin method is used. The specific transient fin samples have to be made. With an electrical step stimulus, the copper track is heated-up while an optical thermal sensor (IR detector) records top surface temperature. The mathematical process described above is used to find the best a and h values to make the model stick to the experimental curve. It allows to get the thermal diffusivity in the XY plane, and later on, combined with the volumetric heat capacity (isotropic), it gives the XY thermal conductivity value.

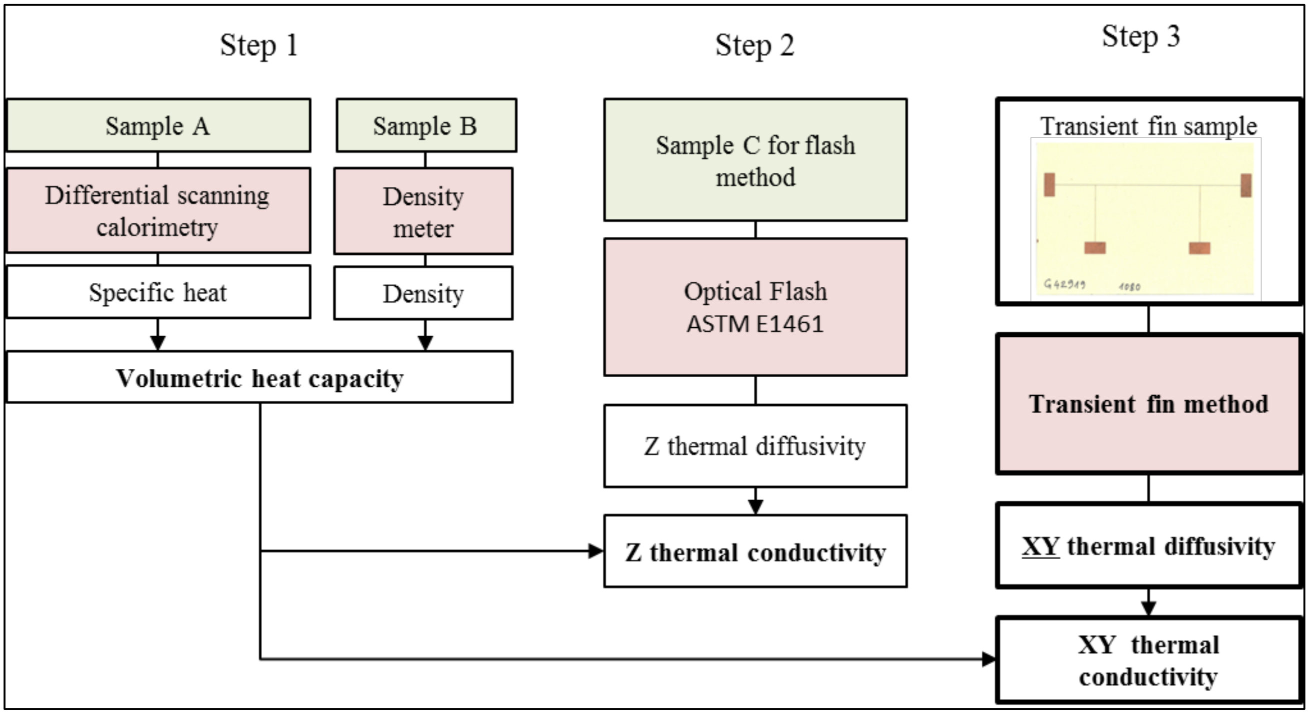


Figure 8: Measurement methodology flow-chart

Results
In this case, glass-reinforced dielectrics have been measured as an example. Measurements were performed on two different prepregs of thermally improved base materials. Test samples were manufactured with these prepregs. For the transient fin method, test samples were manufactured by hydraulic vacuum lamination, photolithography, and routing, with standard printed circuit board industry process conditions.

- Sample 1080 = made of thermally optimized glass-reinforced epoxy 1080 type prepreg
- Sample 106 = made of thermally optimized glass-reinforced epoxy 106 type prepreg

Step 1 – Volumetric heat capacity
Measured by production Differential Scanning Calorimetry equipment.

Table 1: Specific heat capacity Cp of 1080 and 106 prepregs measured by DSC

	T (°C)					Density
	20	30	40	50	60	ρ ($kg.m^{-3}$)
Cp of **1080** ($J.kg^{-1}.K^{-1}$)	887	915	945	977	1006	2249
Cp of **106** ($J.kg^{-1}.K^{-1}$)	884	911	939	970	998	2201

From the above,
- Specific heat capacity for 1080 is given by : $C_p = 825.6 + 3.001T$ ($\mathrm{J\ kg^{-1}K^{-1}}$) with T in Celsius.
- Specific heat capacity for 106 is given by : $C_p = 825.6 + 2.8683T$ ($\mathrm{J\ kg^{-1}K^{-1}}$) with T in Celsius.

With density ρ,
- Volumetric heat capacity for 1080 (at 30°C) is $\rho C_p = 2.058 \times 10^6$ ($J\ m^{-3}\ K^{-1}$)
- Volumetric heat capacity for 106 (at 30°C) is $\rho C_p = 2.005 \times 10^6$ ($J\ m^{-3}\ K^{-1}$)

Step 2 - Z Thermal conductivity by flash method
Note: To perform such an optical flash method measurement, one side of the sample has to be black. To do that, one side is covered with an appropriate black paint instead of carbon sputtering. It was verified by a separate complex method (simulation using production finite element analysis/simulation software) that this black paint does not affect the results.

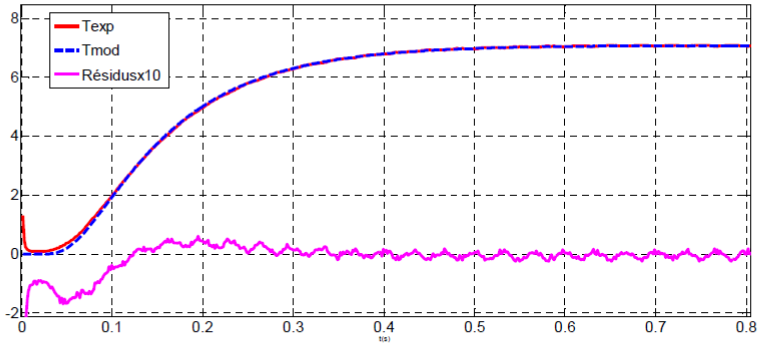


Figure 9 : Example of the theoretical and experimental thermogram by the flash method

The measured Z thermal diffusivities have been extracted in Table 2

Table 2 : Z thermal diffusivity measurements by the flash method

Material	$\alpha_z(m^2.s^{-1})$
1080	8.20×10^{-7}
106	7.80×10^{-7}

Step 3 - XY Thermal diffusivity by the transient fin method

As described previously, the copper track designed on the sample is connected to a generator to produce a linear heat flux. An infrared camera is placed to measure the temperature of the two distant points $x_1$and $x_2$of the sample. Identifying the transfer function of the heat coefficient transfer H(t) allows to compute the thermal diffusivity.

Sample preparation

Using a standard PCB fabrication process, the samples were manufactured with the relevant 1080 or 106 prepregs. A stack-up of approximately 200µm thick was built. Hereafter is a picture of the realized sample.

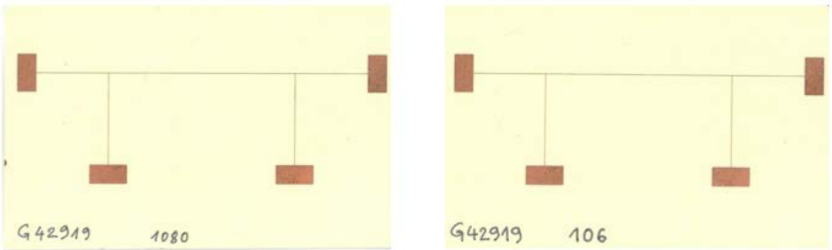


Figure 10: 106 and 1080 test samples for the transient fin method

Thermal conductivities determination

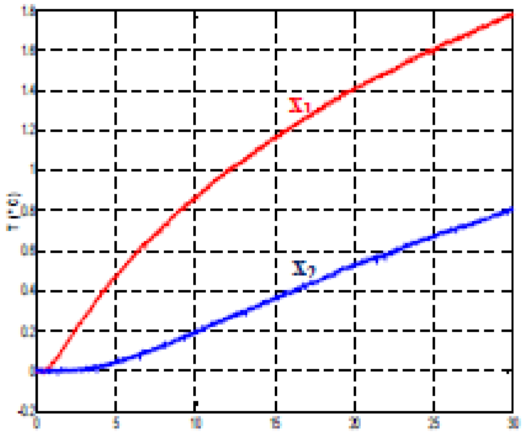


Figure 11 : Example of the thermograms at x_1 and x_2 distances

The transient fin method is used to determine XY thermal diffusivity. The thermograms (recorded by the IR sensor) give the temperature variation at x_1 and x_2 distances from the heating line, as a function of time. Using the appropriate mathematical equations described above, it allows to determine the thermal diffusivity. Results are in Table 3:

Table 3 : XY thermal diffusivity measurements

Material	$\alpha_{xy}(m^2.s^{-1})$
1080	1.23×10^{-6}
106	1.32×10^{-6}

Using the previously measured specific heat capacities and densities, it is now possible to compute the thermal conductivities in the XY plane and along the Z-axis;

Table 4 : XYZ thermal conductivities calculated

Material	Datasheets		Measurements	
	λ_z $(W.m^{-1}.K^{-1})$	λ_{xy} $(W.m^{-1}.K^{-1})$	$\lambda_z(W.m^{-1}.K^{-1})$	$\lambda_{xy}(W.m^{-1}.K^{-1})$
A	2	3.5	1,7	2,5
B	2	3.5	1,6	2,6

Discussion of Results

In this particular case, the base material manufacturer's datasheet differentiates the thermal conductivity along Z or in the plane. But it does not indicate specific values for 106 or 1080 prepregs, nor onto which laminate (thickness and composition in terms of glass-content) measurements were made. As indicated in the datasheet: "*Results listed above are typical properties, provided without warranty, expressed or implied, and without liability. Properties may vary, depending on design and application*".

Transient fin measurements gave lower values than the typical values indicated in this datasheet. A quick look at the resin content of the 1080 and 106 indicates respectively 85% and 90% resin content. As seen before, glass is a better heat conductor than "normal" epoxy resin, but this improved material does not contain "normal" epoxy resin. It has been filled with ceramic particles, precisely to improve its thermal conductivity, bringing it significantly above the ~1 $W.m^{-1}.K^{-1}$ of the glass fibers. Therefore, it is normal to obtain a lower XY thermal conductivity for 1080, containing more glass than 106.

Conclusions

In the printed circuit board ecosystem there is currently no unique and common standard method to measure thermal conductivity. However, modern applications require an accurate knowledge of base material properties for thermal optimization of electronic systems. Thermally improved dielectrics become more and more popular in various printed circuit board applications. These copper-clad laminates products and corresponding prepregs are usually glass-reinforced, and therefore quite strongly anisotropic. Significantly expensive to buy and to process, the benefit brought by their use should be accurately known or at least easy to assess when designing a new product. 3D Thermal models are nowadays common tools for system designers, but to provide consistent simulation results, these tools need accurate thermal properties to provide good simulations.

The transient fin method presented in this paper is at its beginning. At this stage, it seems suitable and efficient enough to help suppliers and manufacturers to complete thermal conductivity information on most of the dielectric base materials used in the printed circuit board industry. It requires to manufacture a dedicated but simple test sample, to use a measurement chain with a current step generator, an IR sensor, and appropriate engineering skills. It can be improved by building a dedicated device, comprising the current source, the sample holder, the IR sensor, and the appropriate digital signal analysis to output automatically the XY thermal diffusivity. Sample shape and size can be easily standardized.

This method, combined with the existing ones to measure specific heat, density and thermal diffusivity in the Z-axis, allows to get often missing data about thermal conductivity in the XY plane, along the glass fibers. It also gives the possibility of discriminate more precisely X and Y thermal conductivities by rotating the sample, in case base materials have also an anisotropy between yarn and chain of the woven glass mesh. It will be continued, improved, and deployed on a large range of printed circuit board dielectric base materials to help manufacturers and designers to optimize thermal management of printed circuit boards and more generally electronic system performances and efficiency.

General References

1. Hadisaroyo D., Batsale J. C.,Degiovanni A., « Un appareillage simple pour la mesure de la diffusivité thermique de plaques minces », Journal de Physique III, vol. 2 No. 1, 1992.
2. Guiles C., “Beating the Heat – A nonmathematical introduction to thermal properties (Part I)”, Arlon, 2009.
3. Mayoh I., “Thermally conductive substrates and thermal management”, Ventec Europe Limited, 2014.
4. IPC-TM-650-2-4-50.
5. Various ASTM standards.

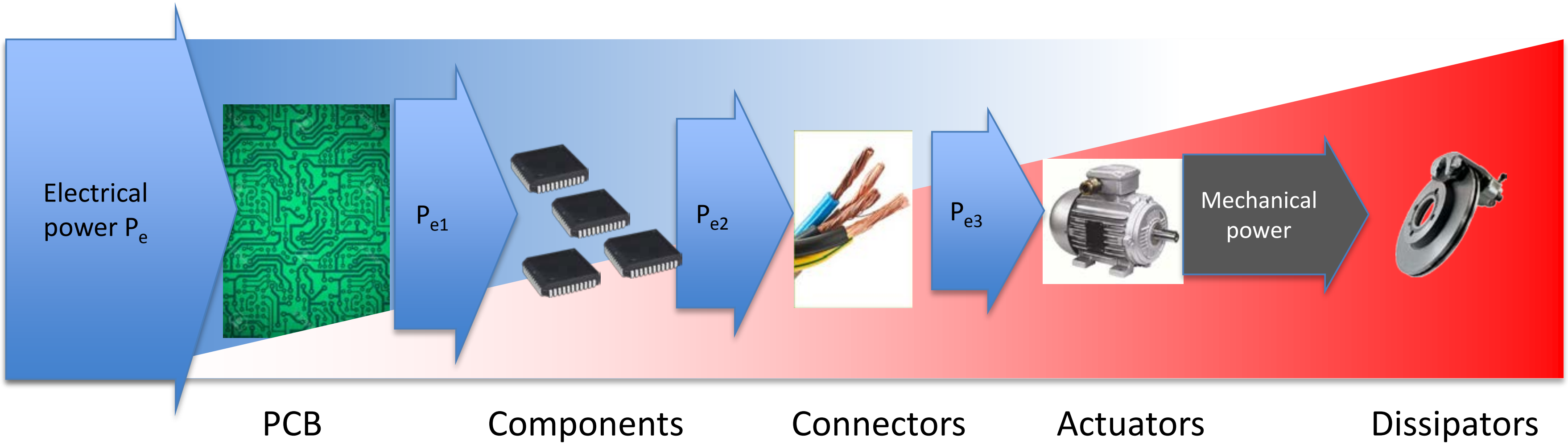
Development of a Consistent and Reliable Thermal Conductivity Measurement Method, Adapted to Typical Composite Materials Used in the PCB Industry

François LECHLEITER
Cimulec
Ennery, France

Yves JANNOT
Université de Lorraine, LEMTA,
Vandoeuvre-lès-Nancy, France

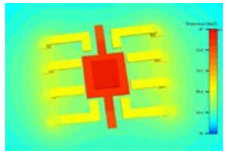
Heat...

(Almost) all energy is converted to heat...



Electrical energy brought to a system is almost integrally turned into heat, *but not necessarily locally*, and that is a reason of problems for PCB designers...

Electronic System Thermal Management



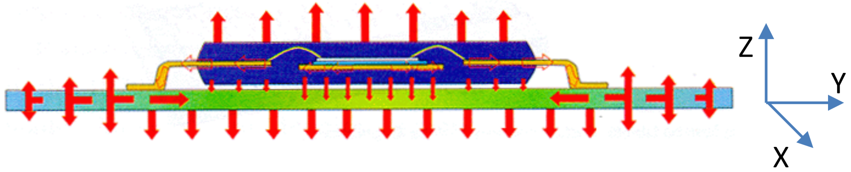
If correctly concentrated, even 1W can be a source of ignition

- Laptop is 10-30W
- LCD TV 100W
- Desktop computer 200-500W

Components can be considered as the source of heat

Electronic system designers options;

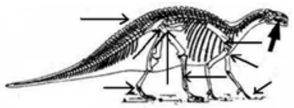
- Dissipate on component side
- Dissipate on opposite side
- Dissipate Laterally
- \+ Different combinations…



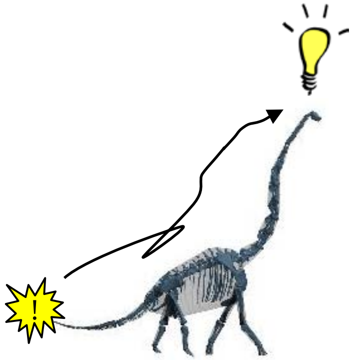
=> PCB is the key in heat management of electronic systems

PCB Evolution : like backbones…

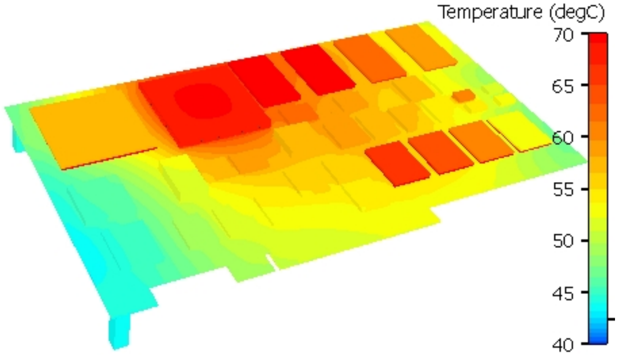
- Mechanical support

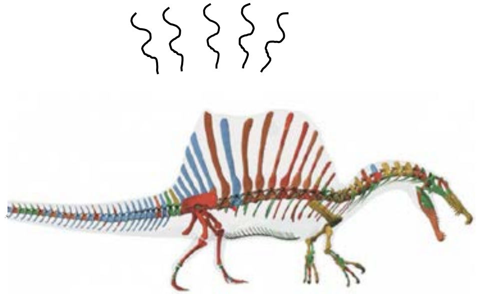


- Mechanical support
- Electrical interconnection



- Mechanical support
- Electrical interconnection
- Thermal management





How to Optimize PCB for Heat Transfer

Heat transfer always occurs from a region of high temperature to another region of lower temperature

Systems are more and more dense and compact

PCBs are not efficient to *dissipate* heat. The best strategy is to use the PCB to transfer heat to a colder region (heatsink)

The fundamental modes of heat transfer are conduction, convection and radiation. In a PCB, heat propagates according to these three modes

In a PCB, **conduction** is the most significant heat transfer mode

=> PCB structure must be optimized for heat conduction

PCB Material Composition

Available materials on earth

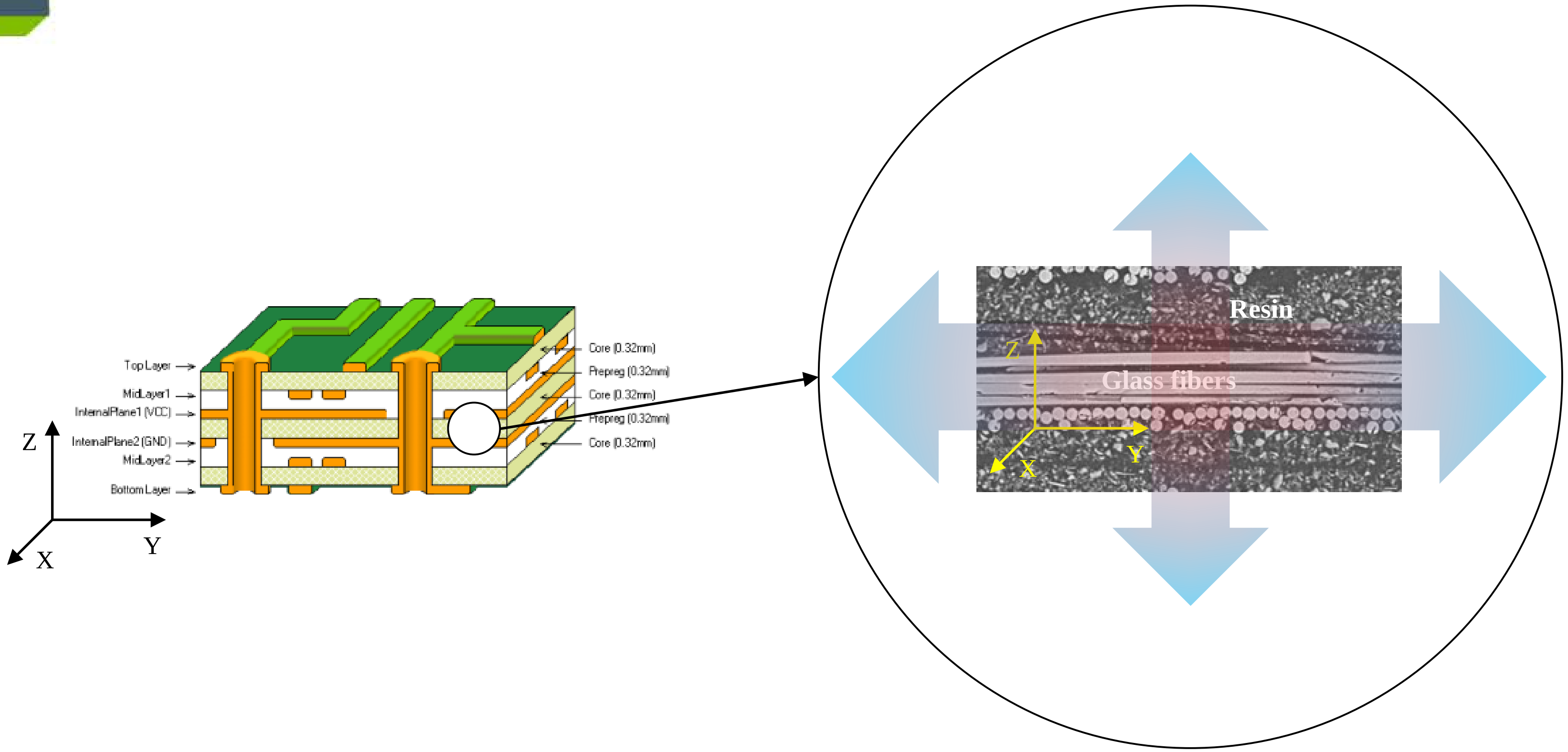
Material	W/m.K
Graphite, natural	470
Silver, pure	406
Copper, pure	385
Gold, pure	314
Aluminium, pure	204
Aluminium nitride	170
Zinc, Pure	116
Brass Cu70%	109
Nickel	90,9
Lead free solder, Sn/95.6% Ag/3.5% Cu/0.9%, Sn/95.5% Ag/3.8% Cu/0.7% (SAC)	60
Iron, cast	55
Solder, Sn/63% Pb/37%	50
Steel, carbon	36
Lead, pure	35
Aluminium oxide, pure	26
Zinc oxide	21
Quartz (single crystal)	12
Quartz-Fused or Vitreous Silica or Fused Silica	1
Glass	1
Epoxy	1
…	1

Typical PCB base material components

Material	Usage in PCB materials	~ Thermal conductivity (W/m.K)
Standard epoxy	Resin	0,2
Glass E	Reinforcement	1
Thermally conductive epoxy	Resin	2,2 to 4
Aluminum oxide	Filler	30
Boron nitride	Filler	360
…	…	…
Copper	Conductor	385

Base material choice (Laminates, prepregs)

Printed Circuit Board Model



Note: From a mechanical and thermal prospective, laminates and prepregs are **anisotropic** materials

Laminates thermal conductivity Typical Values (*)

Supplier	Type	Name of the parameter in the datasheet	Unit	Value	Method claimed
D	Thermally improved glass-epoxy	Thermal conductivity-X-Y-Axis	$W.m^{-1}.K^{-1}$	3,5	**ASTM E1461**
		Thermal conductivity-Z-Axis	$W.m^{-1}.K^{-1}$	2	ASTM E1461
E	Glass-epoxy	Thermal conductivity	$W.m^{-1}.K^{-1}$	0,79	not specified
J	Glass-hydrocarbon ceramic	Thermal conductivity	$W.m^{-1}.K^{-1}$	0,6	**ASTM F433**
H	Glass-epoxy	Thermal conductivity	$W.m^{-1}.K^{-1}$	0,53	**Laser flash**
J	Glass-PTFE ceramic	Thermal conductivity	$W.m^{-1}.K^{-1}$	0,49	**ASTM C518**
B	Glass-epoxy	Thermal conductivity (-100-250°C)	$W.m^{-1}.K^{-1}$	0,32	ASTM F433
E	Glass-epoxy	Thermal conductivity	$W.m^{-1}.K^{-1}$	0,3	not specified
I	Glass-PTFE	Thermal conductivity	$W.m^{-1}.K^{-1}$	0,23	not specified
A	Glass-polyimide	Thermal conductivity	$W.m^{-1}.K^{-1}$	0,2	ASTM E1461

Base materials manufacturers use **different standards** for thermal conductivity

(*) All data extracted from datasheets

Example of Standards Used…

ASTM E1461: "Standard Test Method for Thermal Diffusivity by the Flash Method"

[…] this test method covers the determination of the thermal diffusivity of *primarily homogeneous isotropic solid materials*. Thermal diffusivity values ranging from 0.1 to 1000 (mm)2 s-1 are measurable by this test method from about 75 to 2800 K.

[…]This test method is applicable to the measurements performed on essentially *fully dense* (preferably, but low porosity would be acceptable), *homogeneous, and isotropic solid* materials that are opaque to the applied energy pulse. […]

ASTM F433: "Standard Practice for Evaluating Thermal Conductivity of *Gasket Materials*"

[…] This practice covers a means of measuring the amount of heat transfer quantitatively through a material or system […]

ASTM D5930: "Standard Test Method for Thermal Conductivity of Plastics by Means of a Transient Line-Source Technique"

[…] This test method covers the determination of the thermal conductivity of *plastics* over a temperature range from – 40 to 400° C. The thermal conductivity of materials in the range from *0.08 to 2.0 W/m.K* can be measured covering thermoplastics, thermosets, and rubbers, filled and reinforced. […] There is no known ISO equivalent to this test method."

Example of Standards Used…

ASTM C518: "Standard Test Method for Steady-State Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus"

"[…] This test method covers the measurement of steady state thermal transmission through flat slab specimens using a heat flow meter apparatus […] Applicable to the measurement of thermal transmission through a wide range of specimen properties and environmental conditions. […] with thicknesses up to approximately 250 mm, and with plate temperatures from -195° C to 540° C at 25 mm thickness […]".

IPC-TM-650 2.4.50: "Thermal Conductivity, Polymer Films "

"[…] This test method defines the procedure for determining the Thermal Conductivity of *polymer coatings* on inorganic substrates, such as polyimide on silicon wafer […]".

For designers or PCB manufacturers : ☹

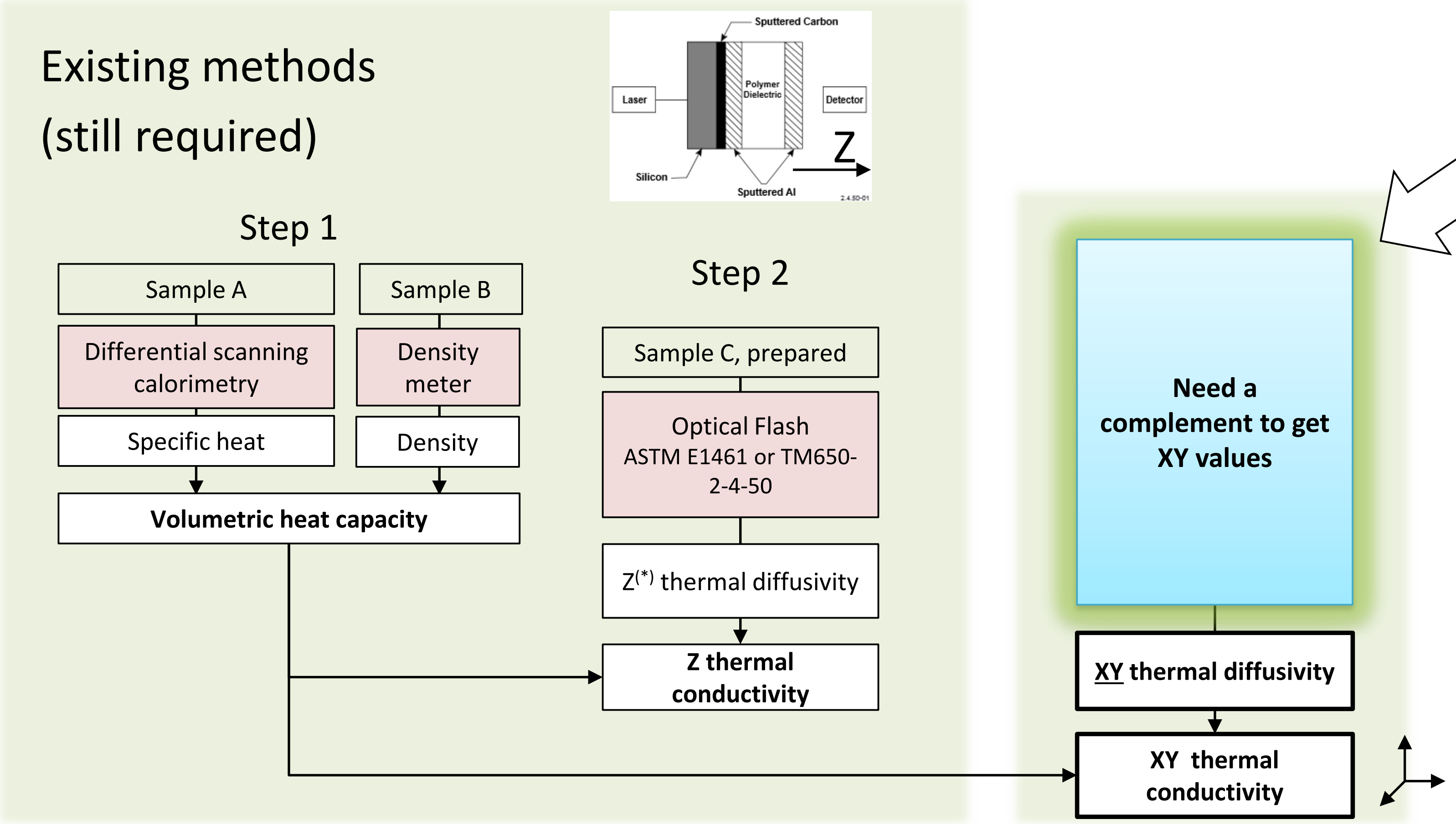
Difficult to compare base material properties

Anisotropy not always assessed

Different measurement methods / standards

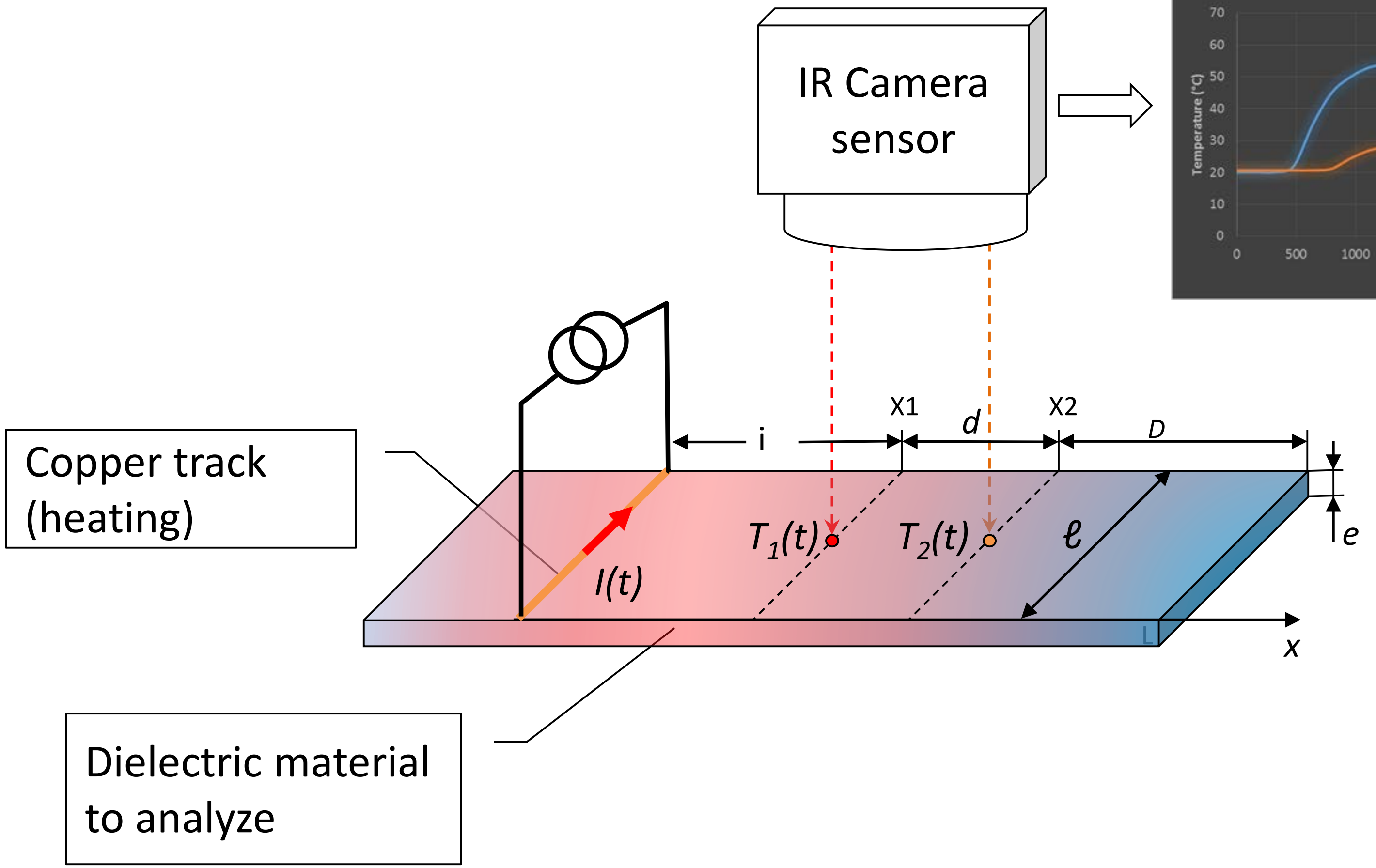
A **common** and **easy** to setup standard test method would be useful for thermal conductivity measurement on PCB materials

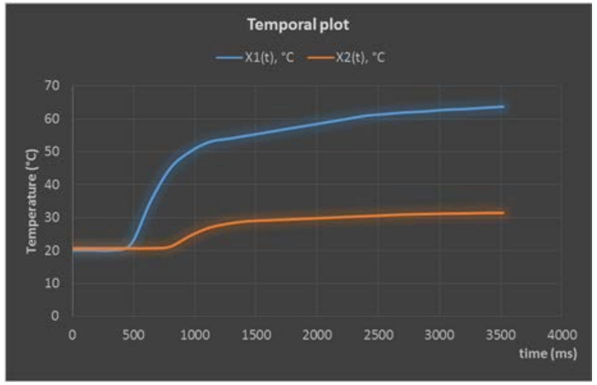
How to Complete Existing Methods ?

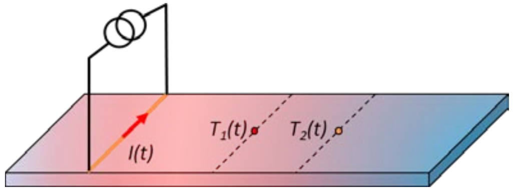


Optical Flash gives 1 axis measurement.
Because laminates are thin, this axis is commonly Z

Transient Fin Method, Principle (1)

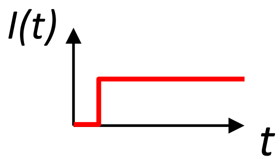






Transient fin, Principle (2)

1. The sample is considered as initially at a uniform temperature, equal to ambient air temperature Ta
2. The test sample has to be large enough (XY) to be considered as semi-infinite during the measurement time
3. Thickness (Z) has to be less than one tenth of the other dimensions (XY) so that the thermal gradient in the thickness e is negligible with regards to the other dimensions. *Easy with a 100mm x 100mm square sample, 100µm thick…*



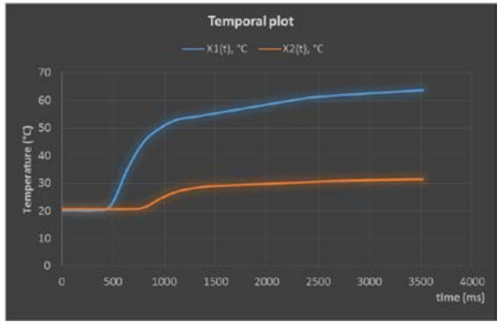
A step of current is supplied to the copper track, and generates heat flux Φ(t).

☺ *it is not necessary to know intensity or time variations of the heat flux* ☺

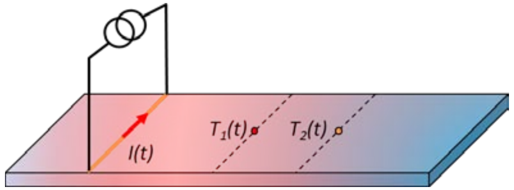
The evolution of temperatures T1(t) and T2(t) at respective distances x1 and x2 from the copper track edge, is recorded by the temperature sensor (eg. IR camera).

The output is the experimental T1(t) and T2(t) curves in time domain.

An appropriate mathematical model gives thermal diffusivity only from $T_1(t)$ and $T_2(t)$…



Transient fin, Theory (1)



$\vartheta_2(p)$ and $\vartheta_1(p)$ are the Laplace transforms of $T_1(t)$ and $T_2(t)$.

$H(P)$ is the transfer function between $\vartheta 2(p)$ and $\vartheta 1(p)$: $H(p) = \frac{\theta_2}{\theta_1}$

With the thermal quadrupole formalism: $\begin{bmatrix} \theta_1 \\ \Phi_1 \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} \theta_2 \\ E\sqrt{p}\theta_2 \end{bmatrix}$

$$A = D = cosh(qd)$$
$$B = \frac{1}{\lambda q} sinh(qd)$$
$$C = \lambda q\ sinh(qd)$$

$$q = \sqrt{\frac{p}{a} + \frac{hP_e}{\lambda S}}$$

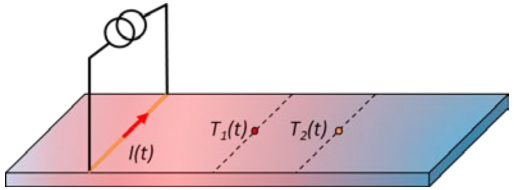
Where:

$P_e = 2(e + \ell)$ is the perimeter

d = distance between X1 and X2

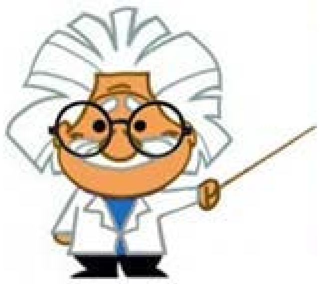
$S = e\ell$ is the heat flux flow section

λ is the thermal conductivity and $E = \sqrt{\lambda \rho c}$ is the thermal effusivity



Transient fin, Theory (3)

From before : $$\theta_2 = \frac{\theta_1}{A + BE\sqrt{p}} = \frac{\theta_1}{cosh(qd) + \frac{E}{\lambda q} sinh(qd)\sqrt{p}}$$

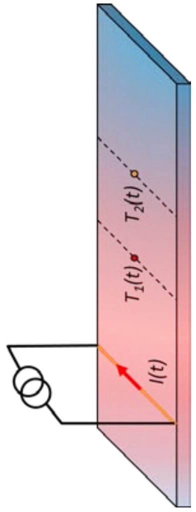


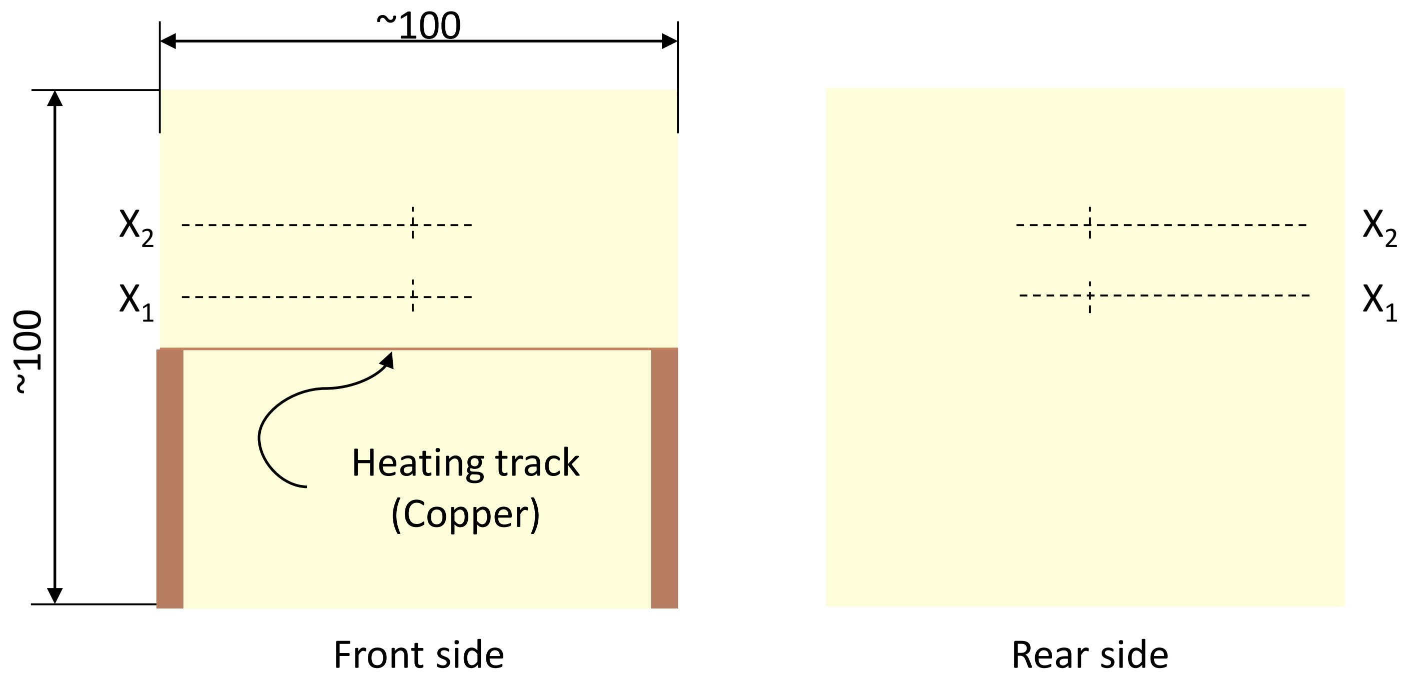
$$H(p) = \frac{1}{cosh(qd) + \frac{E}{\lambda q} sinh(qd)\sqrt{p}} = \frac{1}{cosh(qd) + sinh(qd)} = exp(-qd)$$

With a last effort … $$T_2(t) = T_1(t) \otimes L^{-1}[H(p)]$$

All this is easily done with an appropriate technical computing software

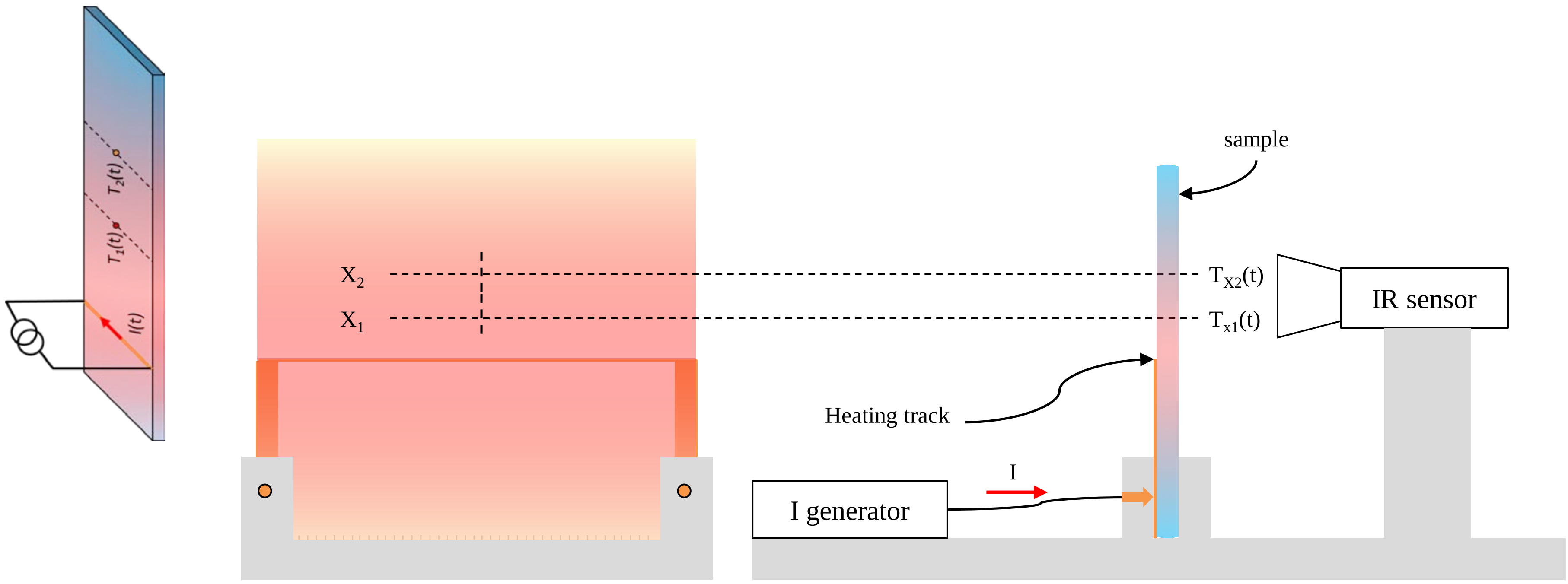
Transient fin Test Samples Design





Any laminate thickness up to 1mm can be analyzed

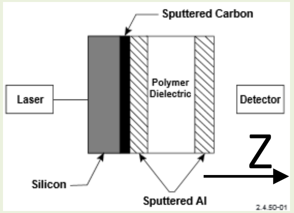
Transient fin Measurement Chain



Transient fin : Complement to Existing Methods

Existing methods

(still required)



Step 1

Sample A

Differential scanning calorimetry

Specific heat

Sample B

Density meter

Density

Volumetric heat capacity

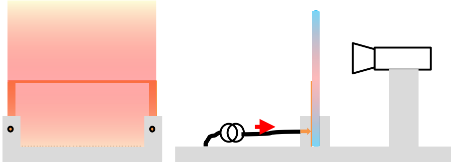
Step 2

Sample C, prepared

Optical Flash
ASTM E1461 or TM650-2-4-50

Z(*) thermal diffusivity

Z thermal conductivity



☺

Transient fin

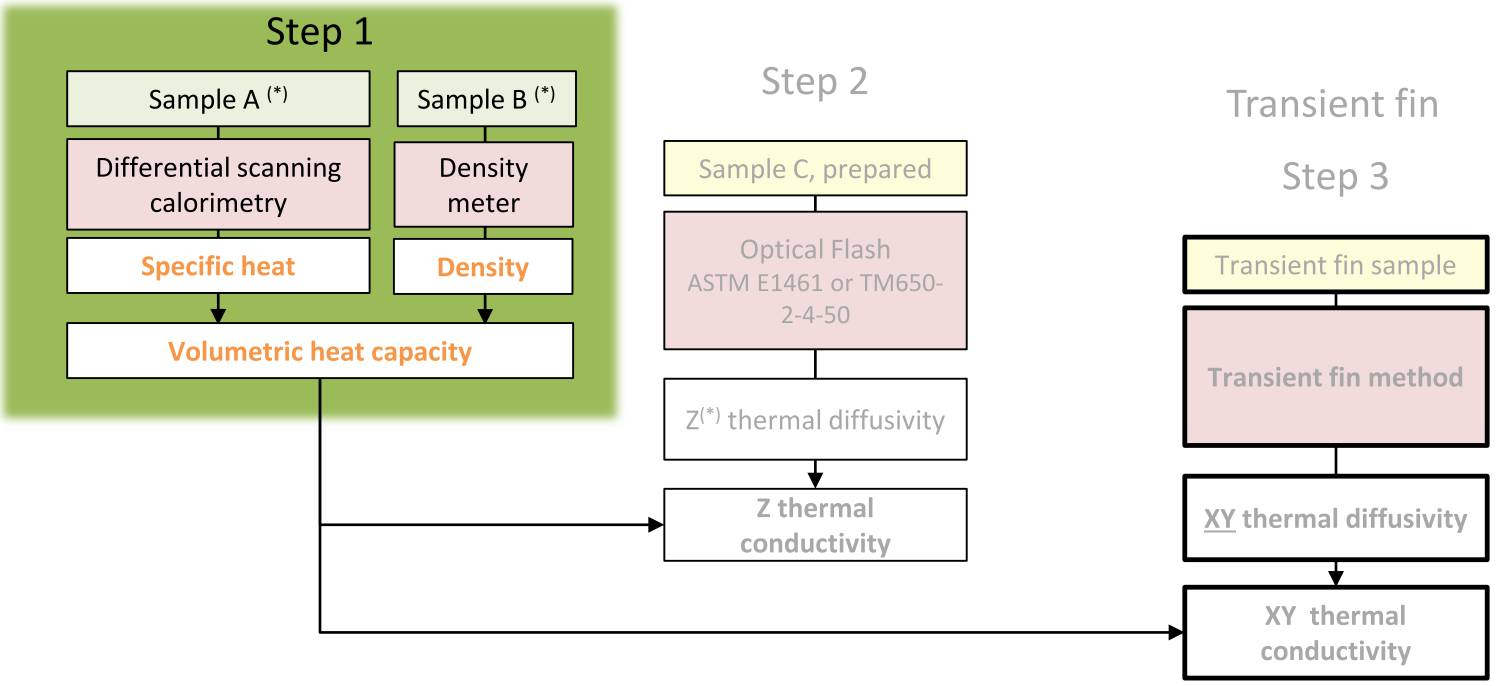
XY thermal diffusivity

XY thermal conductivity

Optical Flash gives 1 axis measurement.
Because laminates are thin, this axis is commonly Z

Complete Measurement Procedure

Step 1 : determine volumetric heat capacity



(*): Samples A and B = small pieces of material

Example of Results – Step 1

Samples:
small pieces of
material

Step 1 – Volumetric heat capacity
Measured by production Differential Scanning Calorimetry equipment.

Table 1: Specific heat capacity Cp of 1080 and 106 prepregs measured by DSC

	T (°C)					Density
	20	30	40	50	60	ρ ($kg.m^{-3}$)
Cp of **1080** ($J.kg^{-1}.K^{-1}$)	887	915	945	977	1006	2249
Cp of **106** ($J.kg^{-1}.K^{-1}$)	884	911	939	970	998	2201

From the above,

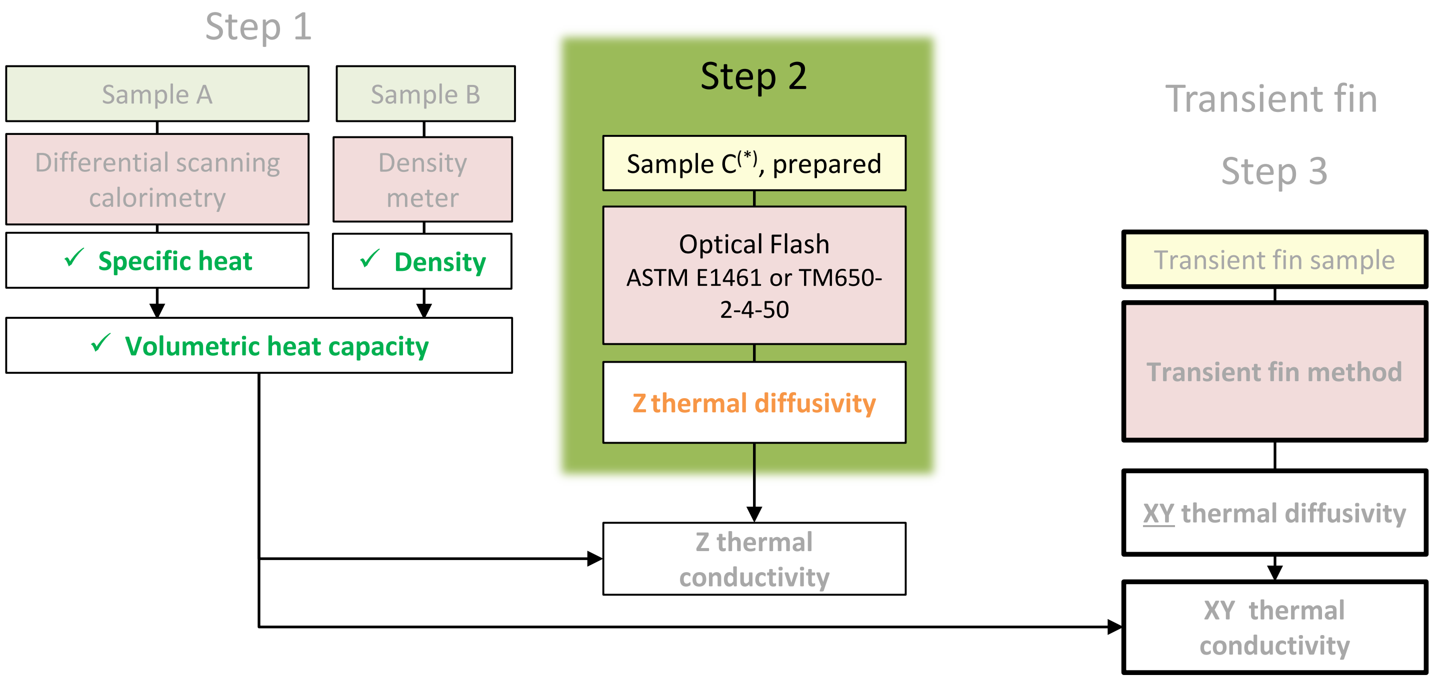
- Specific heat capacity for 1080 is given by : $C_p = 825.6 + 3.001T$ ($\mathrm{J\ kg^{-1}K^{-1}}$) with T in Celsius.
- Specific heat capacity for 106 is given by : $C_p = 825.6 + 2.8683T$ ($\mathrm{J\ kg^{-1}K^{-1}}$) with T in Celsius.

With density ρ,

- Volumetric heat capacity for 1080 (at 30°C) is $\rho C_p = 2.058 \times 10^6$ ($J\ m^{-3}\ K^{-1}$)
- Volumetric heat capacity for 106 (at 30°C) is $\rho C_p = 2.005 \times 10^6$ ($J\ m^{-3}\ K^{-1}$)

Example of Measurement

Step 2 : determine Z thermal diffusivity



(*) Sample C to be prepared according to ASTM E1461 or TM650-2-4-50

Example of Results – Step 2

Samples According to IPC TM-650-2-4-50

Step 2 - Z Thermal conductivity by flash method

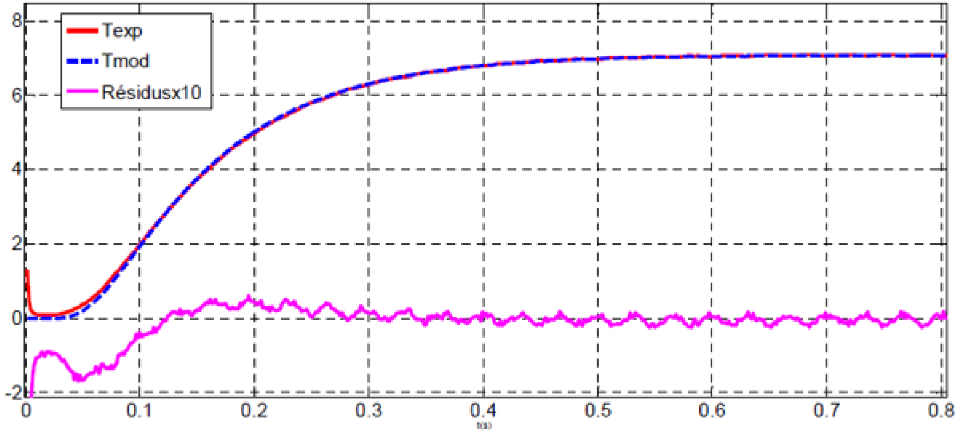


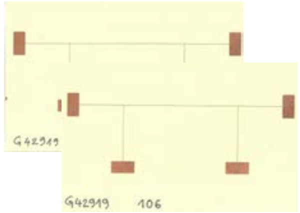
Figure 9 : example of theoretical and experimental thermogram by flash method

The measured Z thermal diffusivities have been extracted in the following table

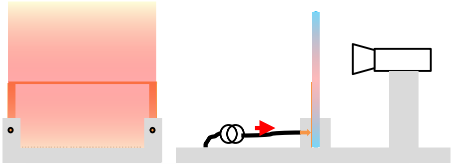
Material	$\alpha_z\ (m^2.s^{-1})$
A	8.20×10^{-7}
B	7.80×10^{-7}

Example of Measurement

Step 3 : determine XY thermal diffusivity



Specific samples



Step 1

- Sample A → Differential scanning calorimetry → ✓ Specific heat
- Sample B → Density meter → ✓ Density
- → ✓ Volumetric heat capacity

Step 2

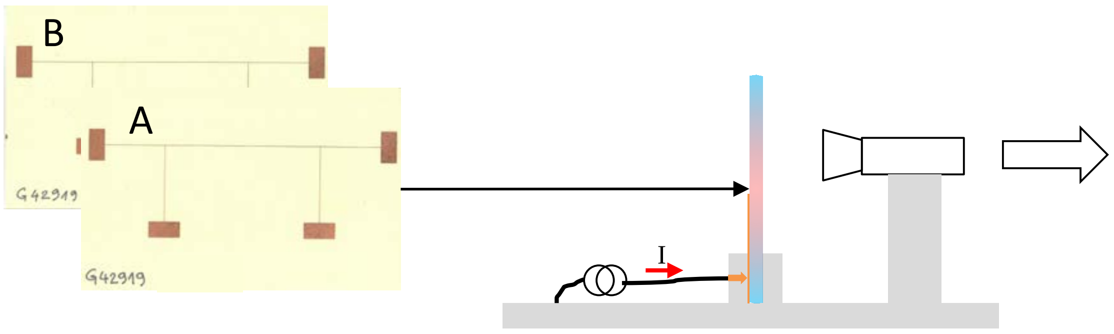
- Sample C, prepared → Optical Flash ASTM E1461 or TM650-2-4-50 → ✓ Z thermal diffusivity → Z thermal conductivity

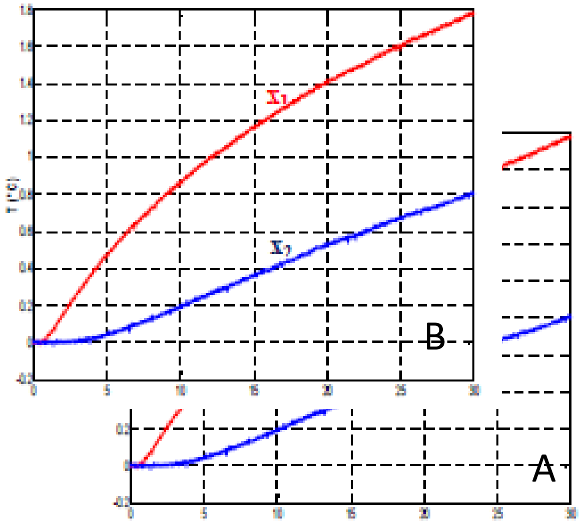
Transient fin

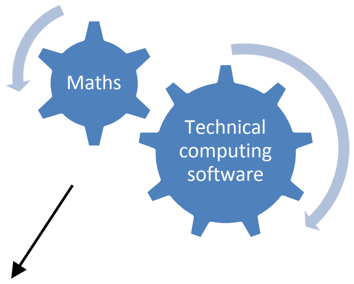
Step 3

- Transient fin samples → Transient fin method → XY thermal diffusivity → XY thermal conductivity

Example of Results – Step 3

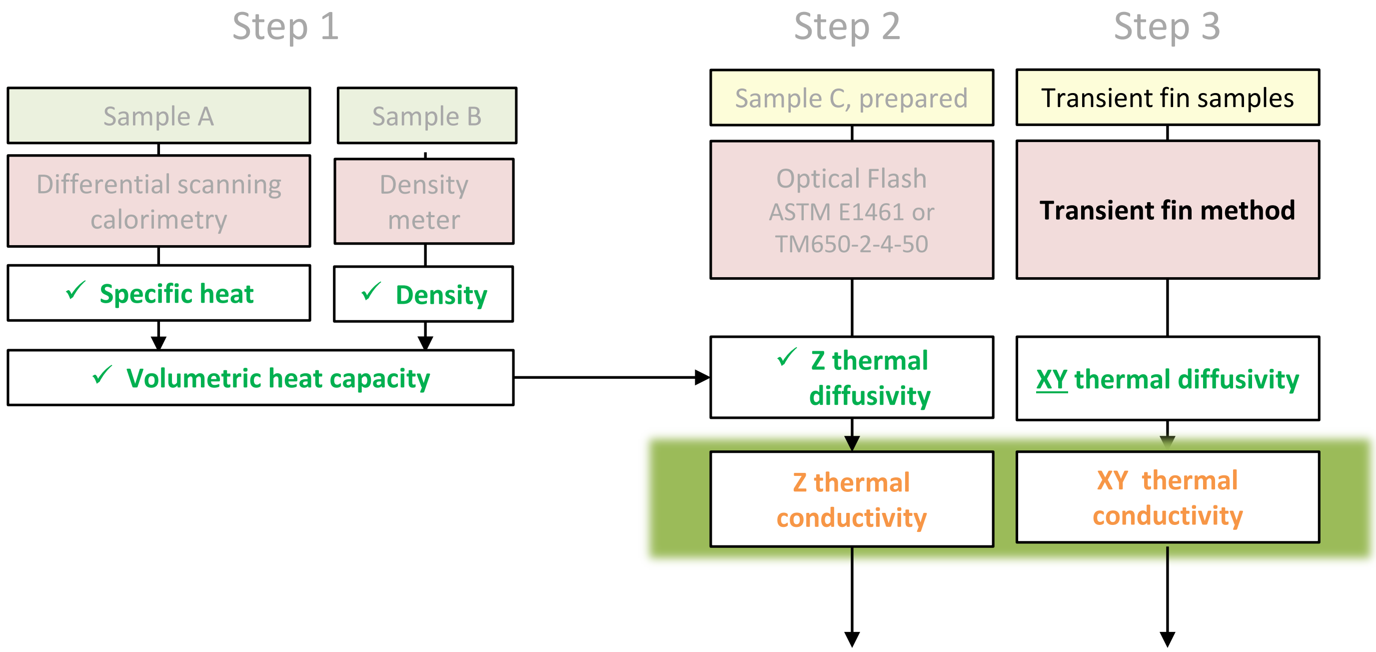






Material	α_{xy} ($m^2.s^{-1}$)
A	1.23×10^{-6}
B	1.32×10^{-6}

Combine Data to get XYZ Thermal Conductivities



Material	Datasheets		Measurements	
	λ_z ($W.m^{-1}.K^{-1}$)	λ_{xy} ($W.m^{-1}.K^{-1}$)	λ_z ($W.m^{-1}.K^{-1}$)	λ_{xy} ($W.m^{-1}.K^{-1}$)
A	2	3.5	1,7	2,5
B	2	3.5	1,6	2,6

Conclusions

Dielectric thermal properties should be accurately known when designing a new product, especially for thermally optimized systems or applications

The proposed **Transient fin** method seems suitable and efficient enough to check or complete thermal conductivity information on most of dielectric base materials used in the printed circuit board industry

- ✓ Samples are easy to prepare with PCB capabilities
- ✓ No need for accurate input control (current, time, heating track size…)
- ✓ Measurement chain easy to setup
- ✓ Short measurement time
- ✓ Cheap method

This method, combined with the existing ones, allows to get XYZ thermal conductivities of anisotropic PCB materials

THANK YOU!

François LECHLEITER
Cimulec
Ennery, France

Yves JANNOT
Université de Lorraine, LEMTA,
Vandoeuvre-lès-Nancy, France