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New possibilities in the thermal evaluation, offered by transient testing

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ABSTRACT: After giving the theoretical summary of the structure function method for the evaluation the thermal transient measurement results, the broad applicability of the method is demonstrated by practical examples. The first example shows how to control the quality of the die attachment or soldering of packages with fast transient measurements and subsequent evaluation. The second example presents how can transient testing be used to determine thermal material parameters; e.g. the effective thermal conductivity of printed circuit boards.

1 INTRODUCTION

It is well known for decades already [1] that thermal transient measurements that is, measuring the temperature increase inside the system resulting from a step function excitation (see Figure 1) carry a large amount of information about the thermal behavior of the structure and via this about the structure itself. Transforming however the measured data into thermal resistance, thermal capacitance or conductivity values or further into geometrical dimensions is not easy. Many authors deal with the evaluation of the measured heating or cooling curves, since the early paper of [1], like [2-4]. The paper [2] was exceptional in the sense that it has shown for the first time a direct transformation method that is capable to deliver even material structural data from the measured thermal transient curves.

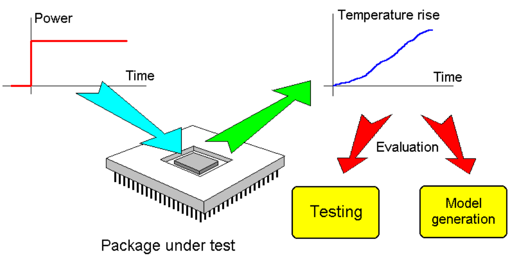


Figure 1. Thermal transient testing of a package

The base of the evaluation method is a relatively recent result in electrical network theory, providing a new treatment of distributed parameter networks [5], the network identification by deconvolution (NID) method. Based on [5] the time constant density, that is the intensity of the time constants in the function of the time of any distributed parameter system can be determined from the response function of the system. Since the heating curve obtained by the thermal transient measurement is the response function of the thermal system, with the NID method the time constants of the thermal system may be determined with arbitrarily fine resolution, in case if the heat flow is mainly into one direction. This enables accurate modeling of the heat flow path with partial thermal resistances and capacitances, and from these values further characteristic features of the system can be calculated.

In the rest of the paper first the theoretical background of the evaluation method is summarized (Section 2), then in Section 3 the applicability is presented with practical examples.

2 THEORETICAL BACKGROUND

The simplest representation of a thermal system is presented in Figure 2 – it is characterized by one thermal resistance and one thermal capacitance.

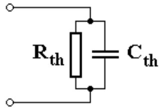


Figure 2. The simplest representation of a thermal system

If we apply a P power step to this model the temperature will rise on its ports according to

$$T(t) = P\,R_{th}\left(1-\exp(-t/\tau)\right) \quad , \tag{1}$$

where $\tau = R_{th}C_{th}$ is the time constant of the system.

Real physical structures have usually more time constants, in this case the temperature response function is the sum of the appropriate exponential functions, as

$$T(t) = P\sum_{i=1}^{N} R_{thi}\left(1-\exp(-t/\tau_i)\right). \tag{2}$$

To such response functions two different model networks may be ordered. These are not independent, one may be calculated from the other: a Foster and a Cauer type network, see Figure 3. Thermal systems are to be represented by Cauer networks, since the thermal capacitances are always connected to the ground, but as every Cauer network has its Foster equivalent, the Foster approximation of thermal networks exists as well.

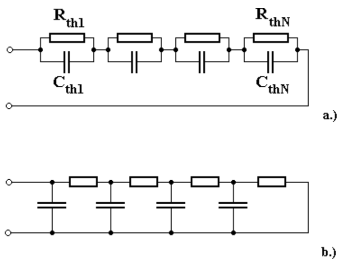


Figure 3. Foster(a) and Cauer (b) type representation of physical structures with finite time constants

Real physical structures however are represented with an infinite number of time constants, since any infinitesimal cube of a matter shows a certain thermal resistance and capacitance value, see Figure 4, resulting in as many number of time constants in the response function as the number of its capacities.

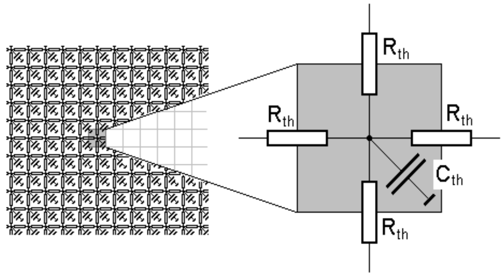


Figure 4. Real physical structures have infinite number of time constants

These amount of time constants may be best represented with their density function.
See Figure 5.

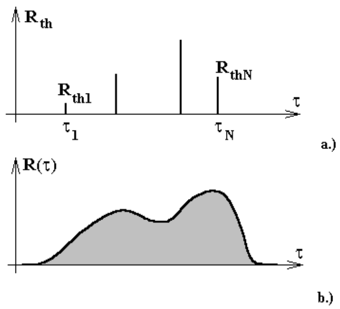


Figure 5. Time constants in a lumped element system (a) and in a distributed parameter system (b). In the latter case the time constants form a continuous curve, the time constant density function

Knowing the time constant density of a system an arbitrarily well approximating Foster equivalent circuit may be constructed by approximating the R(τ) function by infinitesimally narrow boxes, determining each a parallel RC pair in the Foster chain. Finding the Cauer equivalent of this network by textbook transformations we obtain a true physical equivalent of the heat transport in thermal systems. From this circuit we can draw up the so-called *cumulative structure function* [6], that gives the sum of the thermal capacitances C_Σ in the function of the sum of the thermal resistances R_Σ of the thermal system, measured from the point of excitation towards the ambient, see Figure 6.

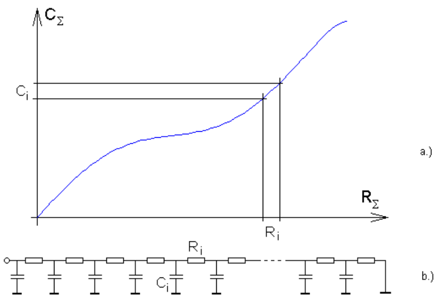


Figure 6. The cumulative structure function and the related Cauer equivalent circuit

The *differential structure function*, referred usually as the *structure function* [2]. is defined as

$$K(R_\Sigma) = \frac{dC_\Sigma}{dR_\Sigma} \ . \tag{3}$$

As the capacitance of a *dx* wide slice of a matter (see Figure 7) is $dC_\Sigma = cAdx$, the resistance is $dR_\Sigma = dx/\lambda A$, where c is the volumetric heat capacitance, λ is the thermal conductivity and A is the cross section area of the heat flow, the value of the structure function is

$$K(R_\Sigma) = \frac{cAdx}{dx/\lambda A} = c\lambda A^2 \ . \tag{4}$$

This value (frequently designated also with *S)* is proportional to the *c* and λ material parameters, and to the square of the cross sectional area of the heat flow, consequently it is related to the structure of the system. In other words: this function provides a map of the square of the heat current-flow cross section area as a function of the cumulative resistance.

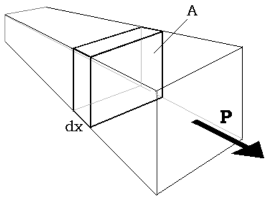


Figure 7. To the interpretation of the Structure function, P is the heat flux

Measured structure functions of power transistors on a cold plate are presented in Figure 8. In this functions the local peaks represent usually reaching new surfaces (materials) in the heat flow path, and their distance on the horizontal axis gives the partial thermal resistances between these surfaces. If we know the λ and *c* parameters for the used materials, even the cross section area vs. distance map can be constructed for the examined structure [7].

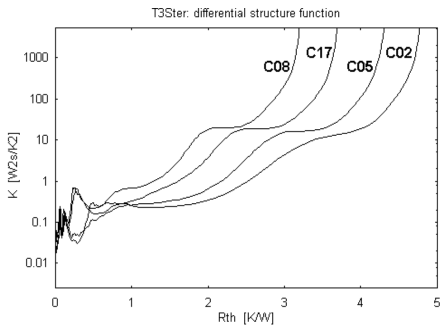


Figure 8. Structure functions of power transistors on a cold plate, measured and evaluated by T3ster® [9]

Obviously this simple interpretation of the structure function is possible only in the case if the heat is streaming along a single main path. In such cases the derived model corresponds directly to the physical structure, enabling the reconstruction of this structure. In case of complex, 3D streaming the derived model may be considered as an *equivalent physical structure* providing the same static or pulse thermal resistance as the original structure. This equivalent structure can not be considered however as a reconstruction of the physical structure to be modeled.

3 PRACTICAL EXAMPLES

The structure functions are extremely useful in the evaluation of the thermal behavior of various structures, especially packages. Now two of these possibilities will be presented.

3.1 *Determining partial thermal resistances, e.g. to control die attach quality*

Die attach failures are very dangerous packaging problems, the increased thermal resistance between the die and the platform may result in locally increased temperatures and eventually in serious reliability problems. In order to detect the samples with die attach failures early enough *in-line testing* of the die attach quality would be rather advantageous. Since a steady state R_{th} measurement for in-line testing is out of question for the reason of the relatively very long time needed to reach the thermal steady state, only transient measurements may be contemplated.

3.1.1 *Theory*

Die attach failures and soldering failures manifest as increased thermal resistances between the die and the platform or between the platform and the board, respectively. The differential structure function offers the possibility of locating the material transitions in the heat flow path, characterized by the cumulative thermal resistance, and finding the partial thermal resistances between the different locations. Comparing the structure function of the measured device with that of a known good device the location and the value of the increased partial thermal resistance may be easily determined.

3.1.2 *Measurement example*

To demonstrate the method we present the results of measuring a series of power transistors, each mounted on a copper base plate and fixed on a larger aluminum mounting plate, see Figure 9, that we measured on a water cooled cold plate in order to assure faster transients. The measurement was done by T3ster®[9], with the resolution of 1µs and 0,012 °C. [10]

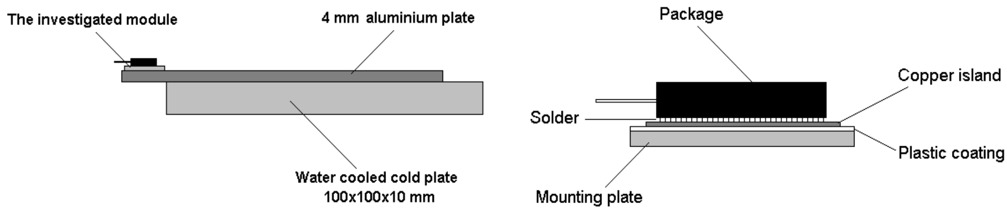


Figure 9. The measurement arrangement, on b. the package mounting area is enlarged

The measured thermal transient curves are presented in Figure 10.

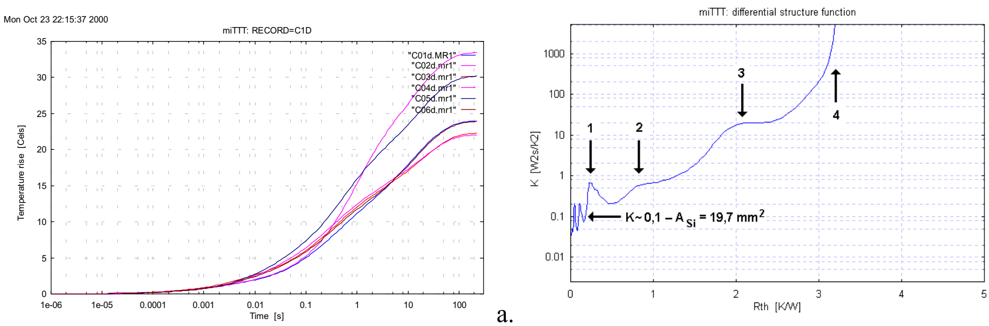
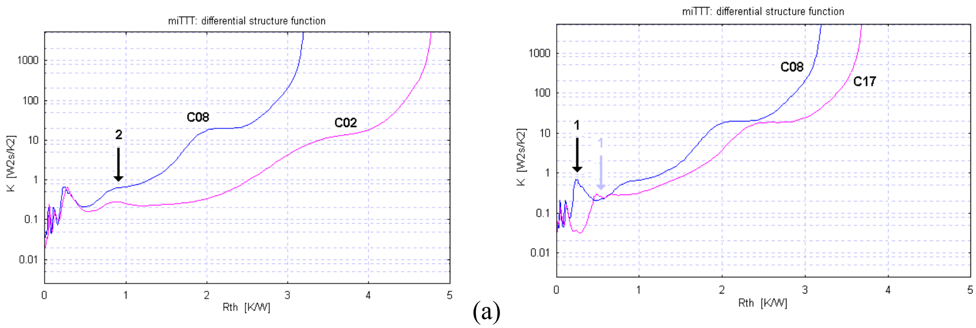


Figure 10 a. Measured thermal transient curves of good and bad devices, b. The differential structure function of the C08 reference device. The arrows point to characteristic locations of the structure.

Examining the measured transient curves we can notice differences, but the evaluation of these curves is rather difficult. The evaluation of the *structure functions* is much easier, see Figure 8. It can be noticed that there are characteristic differences between the presented functions. To understand these differences let us discuss first the differential structure function of C08, the known good reference device, presented in Figure 10b. The left-hand side of this curve refers to the chip, the right hand end to the cold plate, arrow 4 shows this point**.** The value read on the horizontal axis gives the thermal resistance between the chip and the cold plate, it is 3.2 K/W. The zigzagged beginning of the curve shows the presence of some noise, but an average K=0.1 value can be considered. In case of silicon material this is equivalent to a 19.7 mm^2 cross sectional area, which equals in fact the area of the chip. The next peak, 1 refers to the heat capacitance of the transistor case, determined by the dominant heat capacitance of the copper base plate of the case. The next peak 2 refers to of the copper island of the mounting plate, peak 3 is the heat capacitance of the mounting plate itself.

After locating these characteristic points, the partial thermal resistance values can be read from the figure. The thermal resistance between the 1-2 points is about 0.6 K/W, this is the thermal resistance component of the transistor soldering. Between points 2-3 the thermal resistance of the plastic coating can be read, in our case this is about 1.3 K/W. The thermal resistance between the mounting plate and the cold plate determines the distance between the points 3 and 4.

Comparing the structure function of C02 to the reference function of C08 (Figure 11.) we notice that at C02 a characteristic minimum is visible at the right hand side of peak 2, and the thermal resistance to the next plateau is much (2.5 times) higher. This suggests a soldering problem at C02.



(a) (b).

Figure 11 (a).Comparison of the differential structure functions of C02 and C08.The shift in peak 3 suggests soldering error at C02 . (b). The differential structure function of C17 referred to the structure function of C08, the known good device. The shift of peak 1 suggests die attach failure in C17.

The differential structure function of the C17 device is presented in Figure 11b. In case of the C17 device peak 1 is shifted to the right with a value of 0.4 K/W and the rest of the curve shows the same right shift. This means the presence of an extra thermal resistance between the chip and the copper platform of the case, which indicates that the chip is not attached to the platform appropriately.

On the measured transient curves (Figure 10a.) we can notice that the curves of both these devices are running above the nominal one with about 20-25% in the 0.1-0.2 sec range of the transient measurements. This is a very important experience, suggesting that die attach failures can be detected by short transient measurements, offering the possibility of using the method even for in-line testing.

3.2 *Measuring effective board thermal conductivity*

The second example demonstrates how can material parameters be determined by transient testing. Our example is the effective thermal conductivity measurement of patterned printed circuit boards.

Knowing the effective thermal conductivity values of patterned printed circuit boards can be very important both for thermal simulations and design. Thermal transient measurements offer a simple and fast method to determine these values.

3.2.1 *Theory*

In this measurement we exploit that in case of radial heat propagation the structure functions are linear in lin-log scale, and the slope is proportional to the thermal conductivity [10]. Radial heat propagation can be forced in the board by forcing isothermal boundary condition around the area that we wish to measure, and considering the thermal transients in the middle of this region, e.g. by mounting a transistor in the center of the region, see Figure 12., serving both as dissipator and sensor. From the recorded thermal transients the parameters of the board can be extracted as follows.

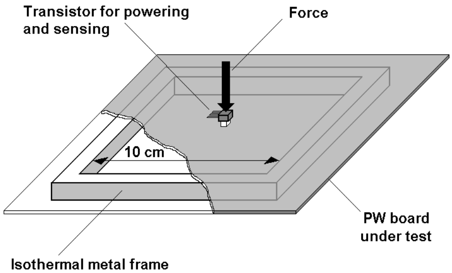


Figure 12 Setup to measure effective board thermal conductivity

For radial heat propagation in a disc of w thickness and λ thermal conductivity the thermal resistance can be written as

$$R_\Sigma = \frac{1}{2\pi w\lambda}\ln(r/r_0) \tag{5}$$

where r_0 is a reference location (e.g. the radius of the contact area under the dissipator/sensor transistor), and R_Σ is the thermal resistance related to the reference location r_0. The thermal capacitance is given by

$$C_\Sigma = wc_v\pi(r^2 - r_0^2) \cong wc_v\pi r_0^2(r/r_0)^2 \tag{6}$$

where c_v is the volumetric heat capacity. This value is related again to the location r_0.
The r location can be expressed in terms of R_Σ as

$$r = r_0\exp(2\pi w\lambda R_\Sigma) \tag{7}$$

Substitution of this equation into (3) results in

$$C_\Sigma = wc_v\pi r_0^2\exp(4\pi w\lambda R_\Sigma) \tag{8}$$

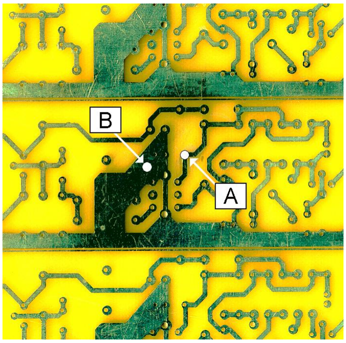
and the derivative of this function is

$$K(R_\Sigma) = (2\pi r_0)^2 wc_v w\lambda\cdot\exp(4\pi w\lambda R_\Sigma) \tag{9}$$

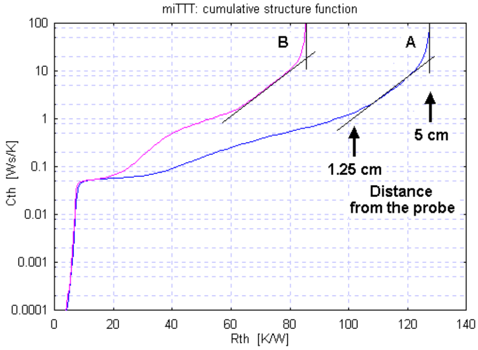
Both $C_\Sigma(R_\Sigma)$ and $K(R_\Sigma)$ appear as a straight line in the lin-log coordinate system, with the slope of $4\pi\lambda w$ where λ is the thermal conductivity. This means that based on this slope, the λw product can be easily determined. A very interesting feature is that this slope is independent of the heat capacity.

3.2.2 *Measurement example*

The use of the method is demonstrated by measuring a board, where the patterning influences the effective thermal conductivity. The sample is shown in Figure 13 a. In two subsequent experiments the probe head was positioned to the points A and B. The results are shown in Figure 13 b.



(a)



9b)

Figure 13 Pattern of the investigated board with the two positions of the probe (a)and the cumulative structure functions for the board at the A and B locations

Although the curves start with the same slope, that refers to the measuring transistor itself, near the probe the actual pattern strongly influences the heat flow, see the 1st and 2nd parts of the curves. The distance data show clearly that most of the board is represented by the rather short section of the curve, above the 1.25 cm mark. Thus, although the near thermal field of the probe produces a confused picture, the "far-field" shows the regular behavior. It is important to observe that the right-hand side of both functions can be approximated with about the same slope and same capacitance values. This shows that it is possible to calculate average or effective material parameters for a patterned board using the structure function, and the actual position of the probe-head is not critical. During the measurements we have to assure however that the shunt thermal resistance of the probe towards the ambient be much larger than that of the panel. Therefore a special probe has to be used that fulfils this requirement [11].

4 CONCLUSIONS

In this paper we intended to demonstrate that the NID method based evaluation of the measured heating curves might reveal a large amount of information about the physical structure, that was measured. Although the evaluation of the time constant spectrum may have similar practical importance in this paper we limited ourselves to the structure function based evaluation of the transient measurements.

Because of the limited length of this paper only two examples could be presented. The first example demonstrates the possibility to determine partial thermal resistances in a heat flow path with the help of transient measurements and the subsequent structure function evaluation. This feature may be used very broadly to measure interfacial thermal resistance values, and among others to detect die attach failures or soldering inaccuracies of packages. The presented other example demonstrated how to measure effective thermal conductivity values of patterned printed circuit boards.

Examples showing how to use the method for structure restoration may be found e.g. in [7].

Because of the length limitation we could not present how to use the *structure function* method e.g. to measure very small steady state thermal resistance values, but the presentation will give some examples also for this and some further applications.

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