Measuring Partial Thermal Resistances in a Heat-Flow Path

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***Abstract*—The paper presents how to measure partial steady state thermal resistance values in a heat flow path with the help of thermal transient measurements and the subsequent numerical evaluation. The method is based on the further evaluation of the *structure functions* of the heat flow path. After presenting the theoretical background of the evaluation two different practical examples are presented to demonstrate the use of the method. The first example presents with a series of experiments how to use the method to detect die attach and/or soldering failures in packaged devices. The second example demonstrates that the method can be applied to measure the very small R_{th} values of thin conducting layers. Various practical solutions are discussed and demonstrated by simulations. The chances and the limits of the methodology are discussed in details in the conclusion section.**

***Index Terms*—Die attach qualification, die attach quality, interface thermal resistance, partial thermal resistance, soldering failure, structure function, thermal transient evaluation, thermal transient measurement, transient thermal testing.**

I. Introduction

THERMAL transient measurements have been used to qualify the thermal behavior of packages for more than 20 years [1]. In these measurements we investigate how the temperature of the chip is increasing in the function of the time after switching a constant power on the chip. This temperature–time function is characteristic to the geometrical and material structure of the surroundings of the chip, that is, to the heat flow path of the structure, and evaluation of this curve may lead to various models of this heat flow path [2]–[5]. In this paper we present how can we determine small steady state thermal resistance values, that are otherwise very difficult to measure by using thermal transient measurements and a subsequent evaluation.

Die attach failures are very dangerous packaging problems. They frequently can not be detected by standard R_{th} measurements, but 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 imperfections early enough, *in-line testing* of the die attach quality during the fabrication 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. In spite of the fact that most of the transient evaluations need the whole transient curve reaching the steady state, there are some evaluations, e.g., finding the dominant time constants of the structure, that can work on much shorter time data than the entire transient. In our examinations we on one hand try to find methods that can be used to determine partial thermal resistances, on the other hand we try to sunder the ones that can be really fast.

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 *structure functions* [2] of the heat flow path offer the possibility of locating either the material transitions in this path or/and the changes in the cross sectional area of the heat flow. In the *structure functions* the locations (x axis) are characterized by their thermal resistance values measured from the chip, the vertical axis shows a value that is characteristic to another heat flow property of the heat structure, either to the cross sectional area or to the C_{th} at the location. Any of these values may be used to identify physical locations in the heat flow path. If we identified the locations from the values measured on the vertical axis finding the partial thermal resistances between the identified different locations is very easy: it is their distance on the horizontal R_{th} axis.

The methodology can be used also for testing purposes. If we compare the structure function of a measured device with that of a known good device the location and the value of the increased partial thermal resistance may be easily determined. The known good device does not even have to exist it can be produced also by simulation.

The method is applicable also to measure interface thermal resistances or very small R_{th} values. There are various methods experimented today to measure interface thermal resistances. A very good critical summary of these is given in the paper of Bosch and Lasance [6]. None of these methods were designed however to distinguish the partial thermal resistances along a heat flow path. Our suggestion is that, to measure very small thermal resistance values the sample has to be placed in a sandwich like mount for which the *structure function* is known, we call this mounting the fixture. Comparing the structure function of the sandwich structure, containing the unknown thermal resistance, with the structure function of the fixture itself the unknown R_{th} value may be determined. The R_{th} increase in the

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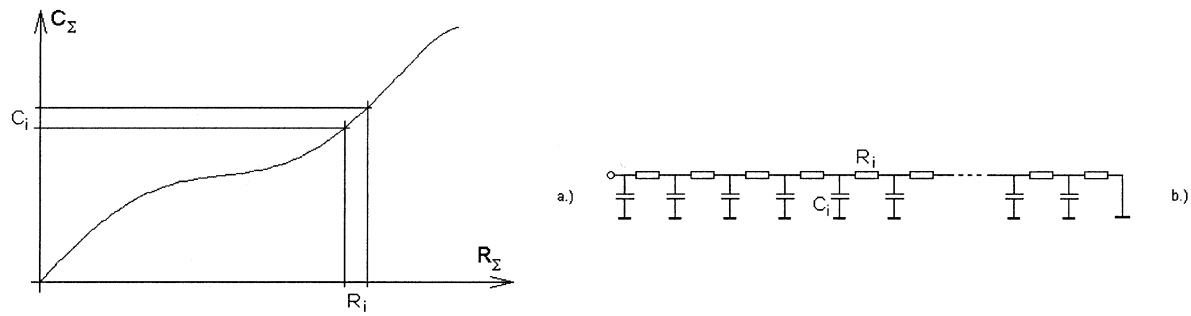

Fig. 1. Cumulative structure function and the related Cauer equivalent circuit.

structure function at the location of the unknown thermal resistance in the structure gives the thermal resistance to be measured.

In the rest of the paper first we present the theoretical background of the *structure function* evaluation of the transient results. In Section III. we demonstrate with experiments some practical applications of the method: using it for testing purposes, for the detection of die attach inaccuracies and soldering failures, and using it for the measurement of small thermal resistance values.

II. Theoretical Background

The evaluation of the measured thermal transient curves delivers the *time constant density* of the system [2]. Knowing the $R(\tau)$ time constant density of an electrical or thermal system an arbitrarily well approximating *Foster equivalent circuit* may be constructed, by approximating the $R(\tau)$ function by infinitesimally narrow boxes of the height of $R(\tau)$. These determine each a parallel RC pair, connected serially in the Foster chain [7]. 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* introduced by E. N. Protonotarios and O. Wing in [8]. This function gives the sum of the thermal capacitances C_Σ with respect to the sum of the thermal resistances R_Σ in the thermal system, measured from the point of excitation toward the ambient, see Fig. 1.

On this monotonously increasing function each new slope represent either a new material or an increase in the cross sectional area of the heat flow or both. If we know that the cross sectional area is supposed to be constant, like e.g., in a sandwich structure, where the layers have the same area, the plateaux represent materials with large R_{th} and small C_{th}, that means, insulator materials. The widths of these plateaux give the related thermal resistances. The steeply increasing intervals in such structures represent better conductor material components. A material transition appears in the function usually as a change in the slope of the curve.

A descendant of the Protonotarios–Wing function is the *differential structure function* introduced in [2] as *the structure function*. The differential structure function is defined as the derivative of the cumulative thermal capacitance with respect to the cumulative thermal resistance, by

$$K(R_\Sigma) = \frac{dC_\Sigma}{dR_\Sigma}. \quad (1)$$

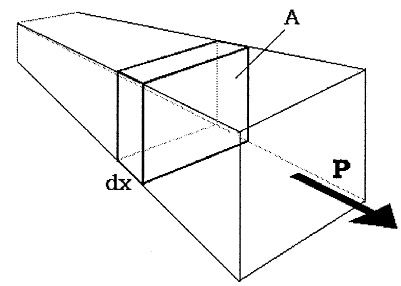

Fig. 2. Interpretation of the structure function, P is the heat current.

After [2] this function is referred usually shortly as the *structure function*. Since the capacitance of a dx wide slice of a matter (see Fig. 2) is $dC_\Sigma = cAdx$, and the resistance of this slice is $dR_\Sigma = dx/\lambda A$, where c is the volumetric heat capacitance, λ is the thermal conductivity and A is the cross sectional area of the heat flow, the value of the structure function is

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

This value 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 these functions the local peaks indicate reaching new surfaces/materials in the heat flow path, and their distance on the horizontal axis gives the partial thermal resistance between these surfaces. More precisely the peaks point usually to the middle of any new region where both the areas, perpendicular to the heat flow and the material are uniform. If we know the λ and c parameters for the used materials, the cross section area versus distance map can be constructed for the examined structure [9].

A measured heating curve, the calculated cumulative and differential structure functions of an Intel 386 microprocessor are presented in Figs. 3–5, respectively.

As it is visible from Fig. 3, the heating curve is not offering easy evaluation. The cumulative structure function of Fig. 4, calculated by direct transformations from the curve of Fig. 3 provides however much more information about the heat flow path of the processor structure. The C_{th} values representing the "ingredients" of the structure may be well identified as steps in the cumulative structure function.

The inserts in Fig. 4 show the C_{th} values calculated from the geometrical data of the package elements.

The partial thermal resistances are easier to be read from the differential structure function, see Fig. 5. On these curves peaks

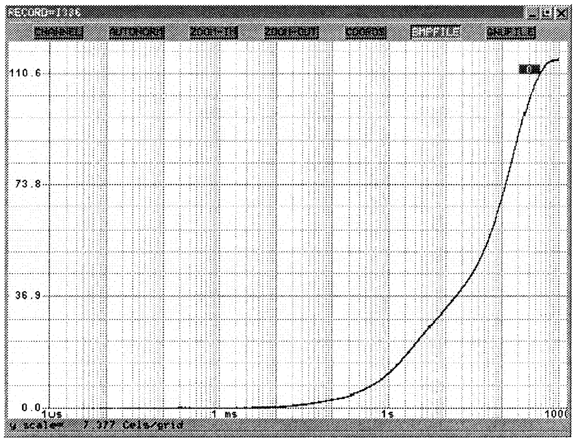

Fig. 3. Heating curve of an Intel386 microprocessor on a cold plate, measured and evaluated by T3ster [10].

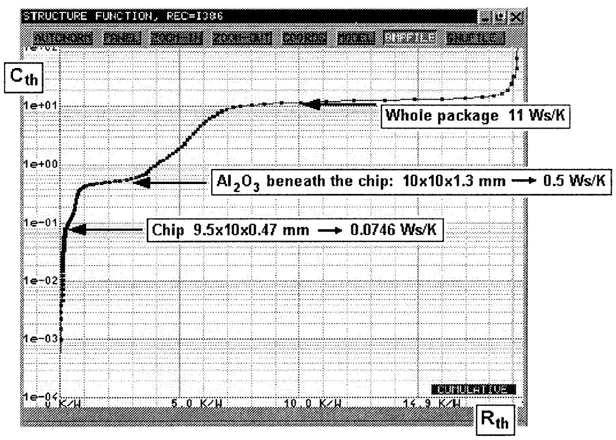

Fig. 4. Cumulative structure function calculated from the curve of Fig. 3.

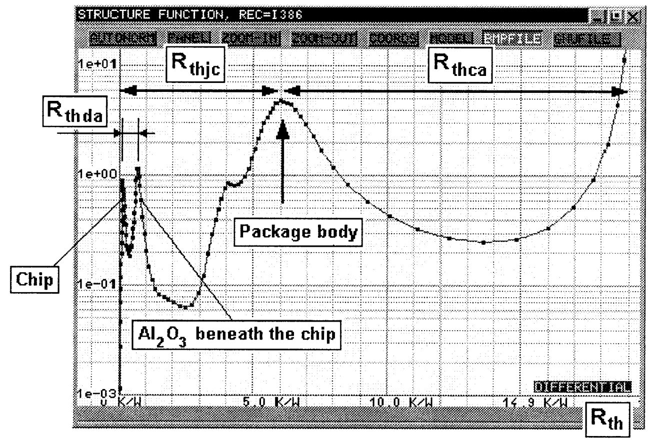

Fig. 5. Differential structure function calculated from the curve of Fig. 3.

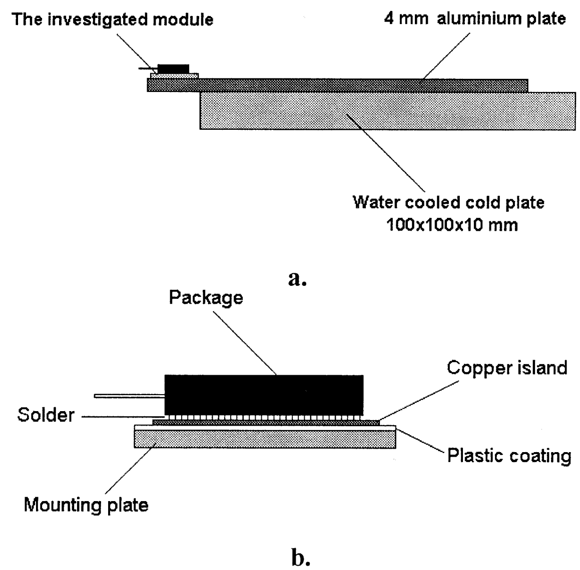

Fig. 6. (a) Measurement arrangement. (b) Shows the enlarged area of interest.

represent the new materials, and the R_{th} distances of these give the partial thermal resistances along the heat flow path between them, e.g., R_{thda} is the thermal resistance of the die attach. Further measured examples will be presented with more details in the next section.

Obviously this simple interpretation of the structure functions is possible only in the case if the heat is streaming along a single main path. If the heat-flow follows (dominantly) a single path, the derived model corresponds directly to the physical structure, enabling the reconstruction of this structure. This model may be used in a large part of the practical cases. If however there are more comparably important paths of the heat flux e.g., toward the top surface, toward the sides and toward the pins of the package etc. the physical interpretation of the resistance/capacitance fractions becomes difficult. In case of complex, 3-D streaming the derived model has to 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.

III. Experiments

We have experimented with various applications of the method. In this paper two such applications are presented that may have particularly high importance in the qualification of the heat transfer properties of structures and materials. The first application may be very useful in the qualification of packages, the second one in the qualification of various materials used in thermal management.

A. Detecting Die Attach and Soldering Failures

To demonstrate the potential importance of the method in our first example we present the results of an experiment, in which we measured a series of power transistors for a European semiconductor manufacturer, in order to detect the ones with die attach or soldering failures. The sample modules were mounted on a copper base plate and fixed on a larger aluminum mounting plate, see Fig. 6, that we measured on a water cooled cold plate in order to assure faster transients. In case of measuring on cold plate 300 s was needed to reach the steady state. The measurement was done by T3ster [10], with the resolution of 1 μs and 0.012 °C.

The measured thermal transient curves for a set of samples are presented in Fig. 7. Examining the measured transient curves we

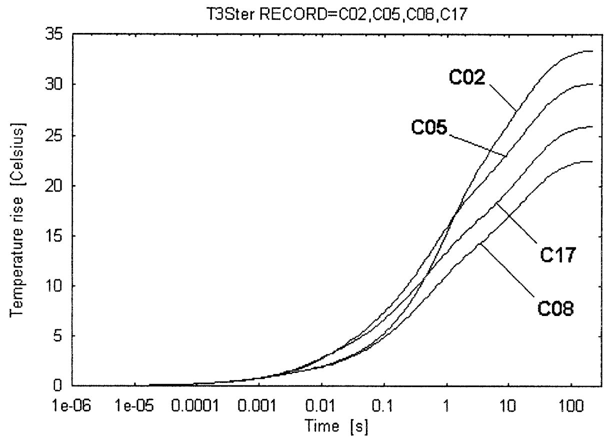

Fig. 7. Measured thermal transient curves of good and bad devices.

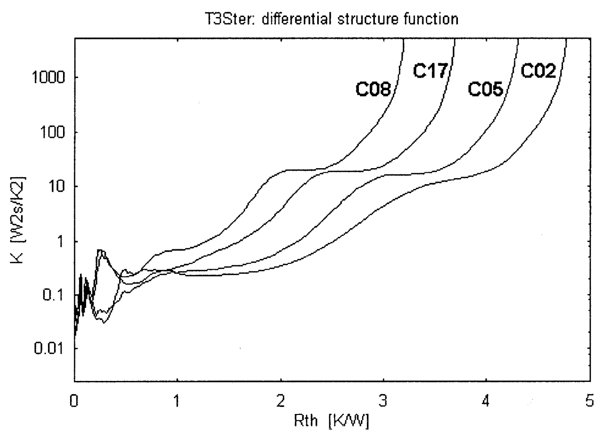

Fig. 8. Differential structure functions of good and bad devices.

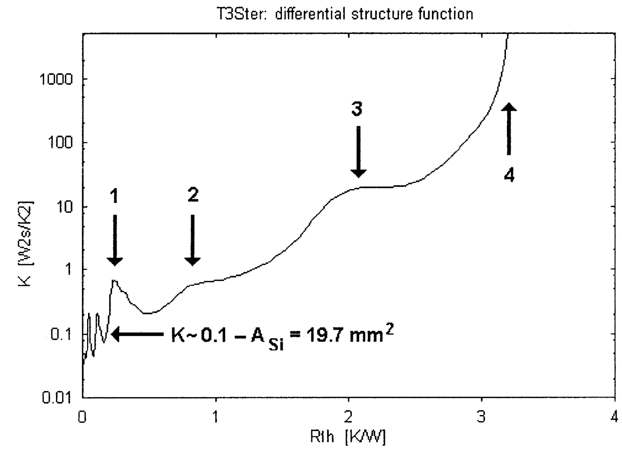

Fig. 9. Differential structure function of the reference device. The arrows point to characteristic locations of the structure.

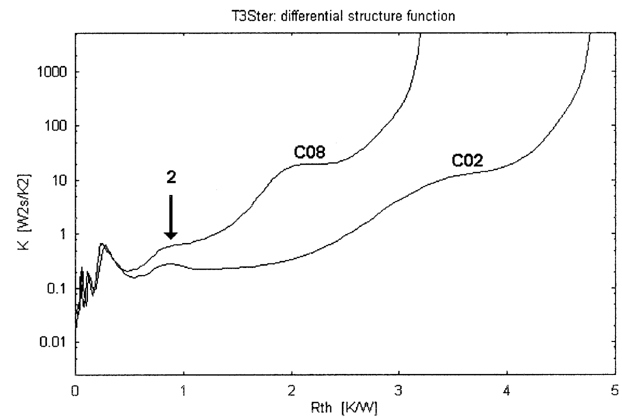

Fig. 10. Comparison of the differential structure functions of C02 and C08. The shift in peak 3 suggests soldering error.

can notice differences, but the evaluation of these curves without any prior knowledge about the structure is rather difficult.

The evaluation of the *structure functions*, see Fig. 8, that can be calculated from the heating curves by direct mathematical transformations is much easier.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 the device C08, the known good reference device (Fig. 9). To understand the curve see also Fig. 6.

The left-hand side of the curve of Fig. 9 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 steady state 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 is in fact the area of the chip. The next peak, designated as **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** is the heat capacitance 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 (Fig. 10) 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 the presence of a soldering problem.

The differential structure function of the C17 device is presented in Fig. 11.

In case of the C17 device the peak **1** is shifted to the right with a value of 0.4 K/W and the entire rest of the curve shows the same right shift. This means the presence of an extra thermal resistance between the chip and the copper base plate of the case, which indicates that the chip is not attached to the platform appropriately.

It is important to note that these problems can be observed already on the measured transient curves. Examining the measured transient curves we can notice that the measured curves of both faulty devices are running above the nominal curves with about 20–25% in the 0.1–0.2 s range of the transient measurements. This is a very important experience, suggesting that die

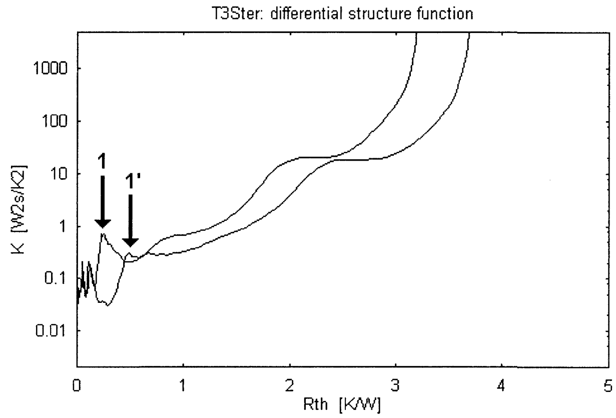

Fig. 11. Differential structure function of C17 referred to the structure function of C08. The shift of peak 1 suggests die attach failure.

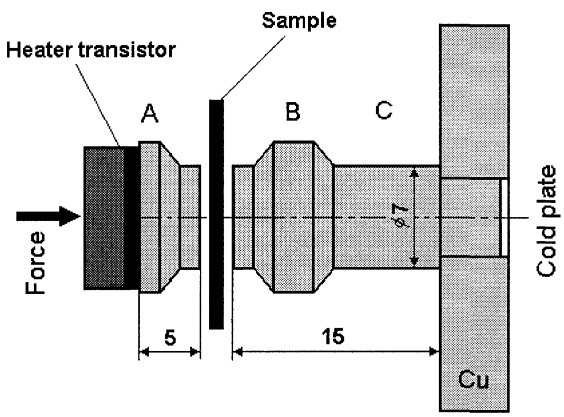

Fig. 12. Fixture used to measure the thermal resistance of thin conducting layers.

attach failures can be detected by short transient measurements, offering the possibility of using the method even for in-line testing.

Soldering errors of the module can be recognized from steady state thermal resistance measurements as well, but such measurements are much more time consuming. We found however that steady state thermal resistance measurements can be approximated by short transient measurements. In the present example the steady state was reached in about 300 s but all the problematic devices could be detected already with a 1–5 s transient measurement. The closer is the failure to the chip itself the shorter is the time needed to detect it.

B. Measuring Small R_{th} Values

Another example for the application of the same idea is the use of the method for measuring small thermal resistance values. This can be very useful e.g., if we wish to compare the thermal properties of different interface materials.

In this measurement we exploit the fact that if we know the geometrical structure of the heat flow path and the material parameters of the subsequent regions in it, we can identify the different material regions on the differential structure function from the location of the peaks. From the distances of these peaks on the horizontal axis we may read the thermal resistance between the material regions represented by these peaks [11].

On Fig. 12 we present the fixture, that was developed with the goal of producing a differential structure function with two well defined peaks, referring to the middle of the two broadening of the cylindrical copper structure, designated by ***A*** and ***B***. It is not visible on the figure, but we have devoted extra efforts to assure good alignment for the best possible contact of the surfaces and to assure that the pressure is evenly distributed on the contact surfaces. This was also needed to obtain good repeatability of the measurements. On the left-hand side of this figure a heater transistor is fixed to the structure, serving as heat source and temperature sensor at the same time. This transistor in connected to a thermal transient tester that measures the heating curve, from which the structure function is calculated.

We have verified by thermal simulation that most of the heat propagates in fact in this structure, and the error coming from the heat lost outside the structure is in fact negligible.

The structure consists of two parts: the sample to be measured has to be placed between the narrower faces of ***A*** and ***B***.

Our first idea was that during the measurements first we measure and calculate the differential structure function of the fixture itself, without any sample. This occurs with closed ***A*** and *B* faces, assuring the best possible thermal contact with thermal grease and the application of a prescribed and controlled force. Then we place the unknown thermal resistance between the faces, and the increased thermal resistance between the ***A*** and ***B*** peaks in the structure function gives the value of the unknown thermal resistance. In this case however together with the unknown thermal resistance we measure also the two additional interface thermal resistances, which are though small, not zero.

To eliminate the appearance of these interface thermal resistance values in the measured results we first place a piece of copper between the faces of the fixture with its known thermal conductivity value. What we measure in this case is the known R_{th0} value of the copper, plus the thermal resistances of the two interfacial layers, kept as low value as possible. In the second step we measure the sample of the unknown thermal resistivity, contacted between the faces of the fixture the same way as the copper material was contacted before, assuring the possible lowest interfacial thermal resistance. We may expect that these values are more or less the same as for the case of the copper before. The difference of the two measurements will give now the value of the increased thermal resistance over the copper material—and the effect of the interface layers is eliminated.

The demonstrate the feasibility of the methodology the structure of Fig. 12 was simulated with SUNRED [12], [13] for two arrangements: first with a 1 mm thick 8 mm diameter Cu material placed in the fixture between the ***A*** and ***B*** faces, then another, slightly higher R_{th} piece of metal. The TherModel [13], [14] tool was used to calculate the structure functions from the simulated transient curves. The obtained differential structure functions are presented in Fig. 13.

On this figure, the differential structure function of the fixture of Fig. 12 is shown for the simulated two cases. In the first case there is a 1 mm thick copper between the faces of ***A*** and ***B***, in the second case another metal of similar size but with slightly worse thermal conductivity is placed between the faces of the fixture. The parameters of the second metal are as follows: thermal conductivity $\lambda = 100$ W/mK, 1 mm thickness and 8 mm diameter.

On the horizontal axis we see the cumulative thermal resistance values measured from the location of the dissipation (left

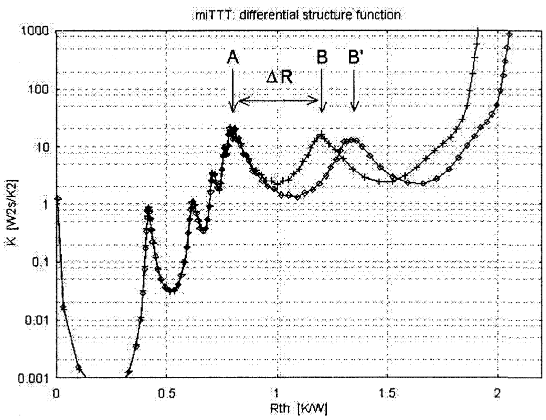

Fig. 13. Differential structure function of the heat flow path of the structure of Fig. 12. ***A*** and ***B*** refer to the appropriate regions of the fixture. The ***B***–***B′*** displacement on the horizontal axis gives the value of the inserted unknown thermal resistance over the known R_{th} value, measured first.

hand side) toward the ambient (right-hand side). On the vertical axis the K value is proportional to the square of the cross sectional area of the heat flow path at the respective location, see (2). On the curve of the differential structure function we may identify the peaks that we have expected: ***A*** and ***B*** refer to the middle of the appropriate broadenings of the copper fixture. The trench after the peak ***B*** refers to the ***C*** narrow neck of the structure before the final broadening that contacts the cold plate. The first peaks refer to the neighborhood of the transistor itself. The difference of the cumulative thermal resistances between ***A*** and ***B*** give the total thermal resistance between the middle of the broad regions of ***A*** and ***B***.

In the second case, when the second metal, that is the sample to be measured is placed between the ***A*** and ***B*** faces the repeated simulation and TherModel evaluation shows a displacement in the ***B*** peak, into ***B′***. If the sample is made of a good heat conductor material and of the size of the faces, the shape of the obtained new differential structure function is very similar to that of the first case, the fixture with the copper slab between the faces. In this second case however the value of $\Delta R'$ will increase from ΔR exactly with the R_{th} increase of the thermal resistance value of the sample to be measured over the value of the known R_{th}, measured first. From the differences of the two ΔR values, that means, from the value of the ***B***–***B′*** distance the small thermal resistance of the sample may be calculated. In the presented case the theoretical 0.147 K/W difference of the thermal resistances is in very good agreement with the distance of the ***B*** and ***B′*** peaks in Fig. 13.

There is however an inherent inaccuracy in the methodology in case of measurements: the value of the interface resistance is not constant, it is changing in the mounting–dismounting–remounting process. The standard deviation of this error may be however measured, and considered in the evaluation. With careful treatment of the interfaces, with the application of prescribed applied pressure the value of this standard deviation may be kept low.

Thermal resistances down to the magnitude of 0.2 K/Wcm^2 were measured with good repeatability and with about 10–15% standard deviation with this method. This accuracy is not bad, but we think that with further refinement of the fixture and the methodology the accuracy of the measurement may be further increased. We are currently working on the optimization of the fixture, and we consider developing a computer program that calculates the unknown R_{th} value automatically from the measured curves.

IV. Conclusion

From the presented examples we see that the structure function evaluation of the measured thermal transient results is a very useful method in the measurement of interfacial thermal resistance values. In the thermal qualification of packages it can be used to detect die attach failures or soldering failures. We have obtained good results in detecting the failures, but with the drawback that the structure function evaluation needs complete transient curves, that means curves that reach the steady state. Consequently, the speed of the structure function evaluation is not enough to assure applicability in in-line testing.

We have noticed however, that the characteristic time constants of the structure show significant differences in case of the different die attach failures, which suggests that there might be sufficient to determine only some of the shortest time constants to say something with confidence about die attach failures. These may be determined after a much shorter time (a few seconds) than the whole transient time, that is needed to calculate the structure functions. Currently we are working on developing the method toward this direction.

We have found that with the help of a dedicated fixture the method can be used to measure small thermal resistance values with good accuracy. In order to further increase the repeatability of the measurements we are working on the refinement of the mechanics of the fixture. But the results are already acceptable: thermal resistances in the order of 0.2 K/Wcm^2 can be measured with it on 1 cm $\times$ 1 cm large, 1 mm thick samples with the standard deviation of less than 10–15%. We expect considerable improvement in the standard deviation value with the new fixture, which will result in a decrease in the measurable value as well.

The measured results are accurate only if the sample is not larger than the area of the faces of the fixture, which is currently either 25 mm^2 or 50 mm^2. If the sample is larger there is a regular error in the order of some 1–15 percents in the measurement, depending on the geometrical ratios, material parameter values and the boundary conditions. This error may be calculated if we simulate the structure in parallel with the measurement, and the measured results can be corrected accordingly. We are also working on further developing the method in this direction.

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Dr. Székely received the Harvey Rosten Award of Excellence from the electronics thermal management community for his research results in thermal modeling in 2001.