INCREASING THE ACCURACY OF STRUCTURE FUNCTION BASED EVALUATION OF THERMAL TRANSIENT MEASUREMENTS

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ABSTRACT

The *Structure functions* based evaluation of the thermal transient measurements is now a broadly accepted way for the characterization of the time dependent behavior of the heat flow path. The usual way of generating structure functions considers one main heat flow path. By using a large mathematical tool set it generates for this path the Rth-Cth map of the structure. This enables an easy detection of partial thermal resistances in the heat flow path, with which we can determine the values of e.g. interface thermal resistances, etc. The accuracy that we can obtain with this methodology, working on simulated results is in the order of 2-5%. In this paper we present a methodology that enhances the accuracy of the structure function based evaluation method in case of measured thermal transient curves. In this procedure on one hand we measure the thermal transients for the system to be characterized and on other hand we measure the "parasitic" heat flow path, that influences our measurement. From the processing of the two measurements theoretically the error-less structure function of the measured structure can be generated. In this paper we present this methodology with mathematical details, and prove it with measured results.

KEY WORDS:
Thermal transient measurements, structure function evaluation, thermal conductivity measurement, interface thermal resistance measurement

NOMENCLATURE

d_i		denominator coefficients
G	[W/K]	thermal conductance
k	[W^2s/K^2]	value of the differential structure function
n_i		numerator coefficients
R	[K/W]	thermal resistance
s	[1/s]	$j\omega$: complex frequency
Z	[K/W]	impedance

Greek symbols

τ	[s]	time constant
ω	[1/s]	frequency

Subscripts

e	error component of the thermal resistance or impedance
Σ	cumulative values

INTRODUCTION

The structure function based evaluation of the thermal transient response functions [1] opened new avenues in the thermal transient testing of microelectronics structures. With the help of the structure functions die attach failures of packages can be determined [2], and they can be used to determine partial thermal resistances in a heat flow path [3]. The structure functions can be obtained by direct mathematical transformations from the measured or simulated thermal transient response functions of the system.

Structure functions [1] are "graphical" representations of the RC-model of thermal systems. In case of essentially one-dimensional heat-flow (such as longitudinal flow in a rod or radial spreading in homogeneous material layers, or even in cylindrical or spherical spreading) structure functions can be considered as direct models of the thermal system. In practical cases the *cumulative structure function* is directly constructed from the Cauer-network equivalent RC model of the thermal system (Figure 1) as follows. The thermal resistance between the *n*-th element of the model network and the heat source (driving point) is

$$R_\Sigma = \sum_{i=1}^{n} R_i \qquad (1)$$

and the cumulative thermal capacitance is

$$C_\Sigma = \sum_{i=1}^{n} C_i \qquad (2)$$

where R_i and C_i denote the element values of the i-th stage of the Cauer-type model network. Plotting the $C_{\Sigma\,n}$ vs. R_Σ values results in the *cumulative structure function* (Figure 2). It can be proved, that the derivative of $C_\Sigma(R_\Sigma)$, the *differential structure function*

$$k = \frac{dC_\Sigma}{dR_\Sigma} \qquad (3)$$

is proportional to the square of the cross-sectional area of the conducting path. We obtain such Cauer-ladders from Foster-models that are directly calculated from the discretised time-constant spectrum of the thermal system.

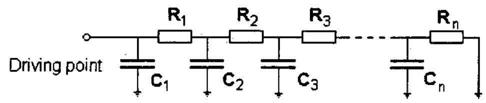

Figure 1: Cauer-type network model of a thermal impedance.

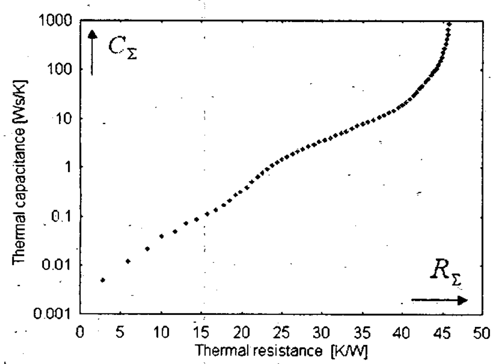

Figure 2: Cumulative structure function of a heat-flow path. The left-hand side corresponds to the driving point, the right-hand side to the ambient.

Several methods have been developed to measure thermal material parameters, based on the structure function evaluation [4]. In these measurements it is exploited that the values of the structure functions and their slopes depend, among others, on material parameters. If we know the geometric parameters we can determine from the structure functions the material parameters from fast and simple thermal transient measurements.

The structure functions are one-dimensional representations of the heat flow path. One dimensional heat flow can be forced in most of the practical cases in order to facilitate the structure function evaluation, but there is always a certain error in these measurements. This stems from the fact that there is always a certain amount of parasitic heat flow, that is moving in other directions than the considered one dimension.

In this paper we present a procedure that can be used to consider the parasitic heat flow that is always present in the case of structure function evaluation based measurement methods, and enables correcting the measured results.

THE SUGGESTED CORRECTION METHOD

The common feature of the structure function based material parameter measuring methods is that one dimensional heat flow is forced in the examined structure, by the application of appropriate boundary conditions. Heat is switched on at the $t=0$ time instant at a spot in the structure, then the temperature of the same spot is recorded as the function of time, until steady state is reached. From the measured transient curves the *structure functions* are determined by direct mathematical transformations.[5]

As was mentioned in the introduction, besides the main heat flow path, where we force the one dimensional heat flow, there are always more or less important *parallel heat flow paths* where a part of the heat is lost. This lost heat is responsible for the error of the measurements. The path of this lost heat is shown in Figure 3.

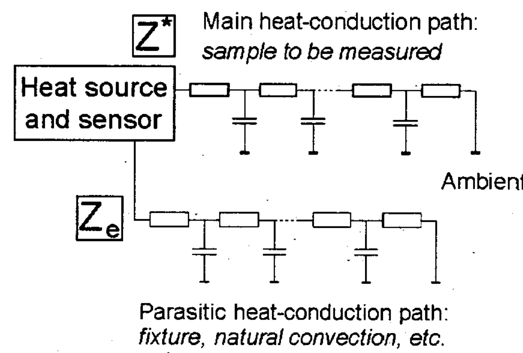

Figure 3: The main (Z*) and the parallel parasitic (Z_e) heat-flow paths in case of structure function based thermal material parameter measurements

A simplified case is discussed first, when the parasitic heat flow is considered with a single R thermal resistance while measuring a $Z(s)$ thermal impedance. This $Z(s)$ impedance is constituted by the "ideal" $Z^*(s)$ thermal impedance *to be identified* and the thermal impedance of the shunting heat-flow path.

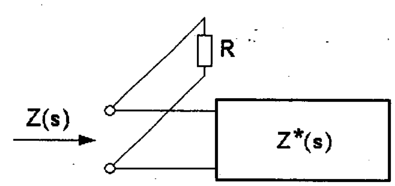

Figure 4: "Ideal" $Z^*(s)$ thermal impedance to be identified together with a shunt thermal resistance R

The measured thermal impedance – described by a Foster-model derived directly from the time-constant spectrum – can be written as follows [6]:

$$Z(s) = \sum_{i=1}^{N} \frac{R_i}{1 + s\tau_i} \qquad (4)$$

where R_i and τ_i are the resistance and time-constant values of the Foster-stages, respectively, N is the number of the Foster stages, $s=j\omega$ is the complex frequency. Rewriting it into a quotient of two polynomials yields

$$Z(s)=\frac{n_0+n_1s+n_2s^2+...}{d_0+d_1s+d_2s^2+...}=\frac{\sum_{i=0}^{N-1}n_is^i}{\sum_{i=0}^{N}d_is^i} \tag{5}$$

where n_i and d_i are the coefficients of the numerator and denominator polynomials, respectively. In case of parallel impedances the effect of R can be easily accounted for if the impedances are replaced by their reciprocals:

$$\frac{1}{Z^*(s)}=\frac{1}{Z(s)}-\frac{1}{R}=\frac{\sum_{i=0}^{N}d_is^i}{\sum_{i=0}^{N-1}n_is^i}-\frac{G\sum_{i=0}^{N-1}n_is^i}{\sum_{i=0}^{N-1}n_is^i}=$$

$$\frac{\sum_{i=0}^{N-1}(d_i-Gn_i)s^i+d_Ns^N}{\sum_{i=0}^{N-1}n_is^i} \tag{6}$$

where $G=1/R$. The correction accounting for the effect of R is to be carried out in the phase of generating the structure functions, when the thermal impedance is available in the form as given by formula (4) – that is during the Foster-Cauer transformation of the RC model of the impedance [1]. According to (6) the following transformations need to be done in the coefficients of the denominator polynomials:

$$d_i^*=d_i-G\cdot n_i \qquad if \quad i=0..N-1$$
$$d_N^*=d_N \tag{7}$$

If the parallel branch is considered with a $Z_e(\omega)$ excess thermal impedance function, the corrected structure function may be constructed as follows:

$$\frac{1}{Z^*(s)}=\frac{1}{Z(s)}-\frac{1}{Z_e(s)} \tag{8}$$

where $Z_e(s)$ is the excess thermal impedance that is the source of the error. This is the thermal impedance represented by all the heat paths outside the measured path.

Knowing the value of $Z_e(s)$ the following correction has to be accomplished:

$$\frac{1}{Z^*(s)}=\frac{\left(\sum_0^N d_is^i\right)\left(\sum_0^{M-1}n_{ei}s^i\right)-\left(\sum_0^{N-1}n_is^i\right)\left(\sum_0^{M}d_{ei}s^i\right)}{\left(\sum_0^{N-1}n_is^i\right)\left(\sum_0^{M-1}n_{ei}s^i\right)} \tag{9}$$

where d_i and n_i represent the denominator and numerator coefficients of the measured impedance, while d_{ei} and n_{ei} represent those of the error thermal impedance function.

The procedure to be used in order to eliminate the systematic measurement error is now as follows:

1) Measure the transient response of the parasitic heat flow path, construct the structure function, or determine the total steady state thermal conductance of the parasitic path. Even in case of constructing the structure function a rough approximation, with some time constants only is sufficient.
2) Measure the transient response of the fixture with the sample inserted and construct the structure function, this time an accurate approximation is needed.
3) Make the corrections according to Eq.(7) or Eq.(9).
4) If there are several parasitic heat flow paths, repeat 1-3 for each of these.
5) Calculate the material parameters from the corrected structure function.

In this calculation we suppose that the parasitic heat flow path is *from the source different* from the main heat flow path. For most of the practical cases this is only an approximation, since the first part of the heat flow is frequently common for the main and the parasitic paths. It is extremely difficult however to determine the exact location, where the heat flow paths from the source branch off. For this reason we recommend to use the correction based on Eq. (9), since even though the formula may not be entirely correct physically in some cases, it is resulting even in these cases in more accurate measured parameter values than without the correction.

To demonstrate the importance of the correction method a simple example is presented: the application of the correction in the measurement of the effective thermal conductivity of printed circuit boards.

EXAMPLE: MEASURING THE EFFECTIVE THERMAL CONDUCTIVITY OF PATTERNED PCBs

The measurement of the effective thermal conductivity of boards is based on the evaluation of the *cumulative structure function.* The board to be measured is inserted in a fixture that is based on an isothermal ring (see
Figure 5). A transistor in the heater/sensor head acts both as heater and sensor. This arrangement assures radial heat-flow in the board between the tip and the isothermal ring. From the thermal transient of the heating/sensing transistor captured by

the T3Ster thermal transient tester equipment [7] the cumulative structure function is derived. The section of the structure function that corresponds to the radial spreading in the PCB is a straight-line segment next to the singularity, at the end of the function [4].

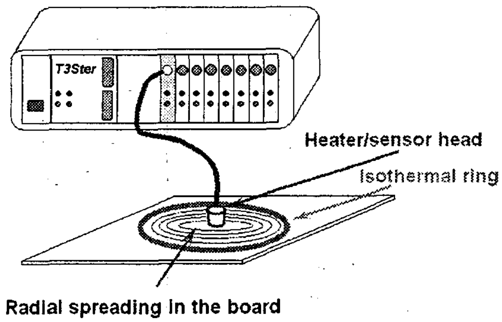

Figure 5: Schematic of the setup for measuring board thermal conductivity

In this measurement the natural convection and radiation taking place at the board surface causes a parallel heat-flow path on one hand, on the other hand the a parallel path is generated by the measuring fixture iself, via the powering structure as shown in Figure 6.

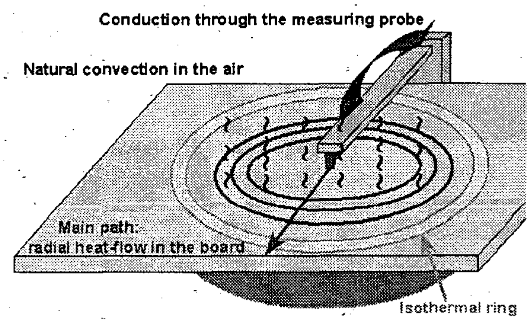

Figure 6: Parasitic parallel heat-flow paths in the effective board thermal conductivity measurement setup

The effect of all these can be lumped into a single shunting conductance. Both effects can be exactly identified if a calibration board is placed into the fixture and is measured in vacuum and in a still air chamber: the shunting conductance in the latter case is the correction value to be considered in all subsequent measurements of other boards.

In the following example the correction is done with the effect of the parasitic heat flow upward in the fixture only. The correction with the losses caused by the natural convection needs a measurement in a vacuum chamber, but can be done similarly.

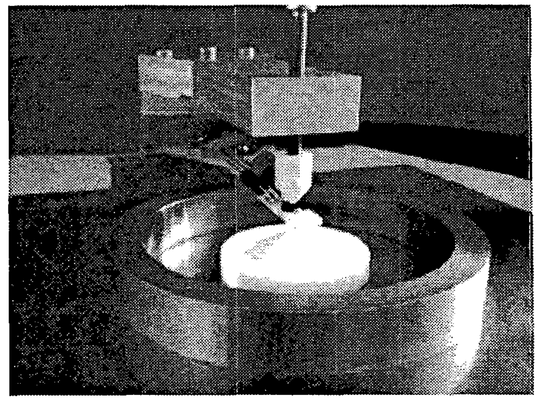

Figure 7 The fixture itself, without a sample

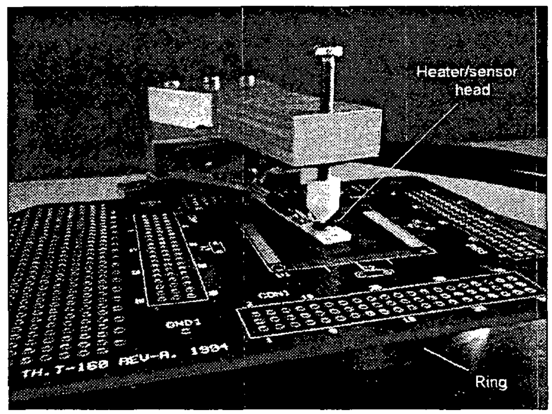

Figure 8 The measurement of a board of 4 different patterned layers

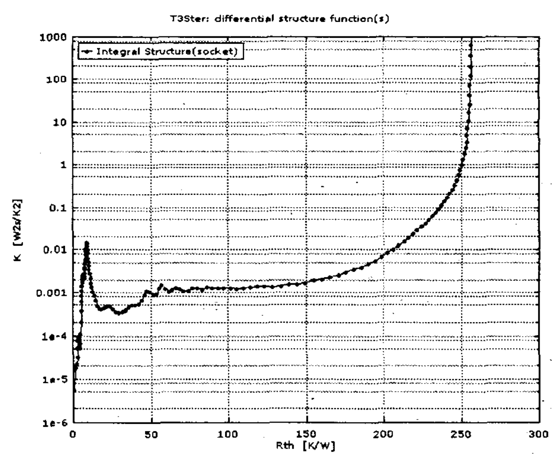

Figure 9 : The differential structure function of the fixture without the sample. The value of the parallel heat conduction represented by the fixture can be read from the right end of the figure: 1/257 W/K ~ 3.89*10^{-3} K/W

In Figure 9 the differential structure function of the fixture is presented, measured without a sample. The value of the parallel heat conduction represented by the fixture itself is the reciprocal of the (257 K/W) steady state thermal resistance of the fixture, readable at the right hand side end of the function, that is G=3.89 mK/W. This value was used in the correction formula of Eq. (4) for several measured samples, see **Table** 1.

Table[1] 1.

samples	Measured effective thermal conductivity w*lambda [W/K]	Corrected effective thermal conductivity w*lambda [W/K]	Change in the value, resulted by the correction %
sample_4a	0.01273	0.00889	30
sample_4b	0.01222	0.00856	30
Sample_6_via	0.01370	0.00955	30

The structure functions of the sample of the last row of Table 1 are presented in Figure 10. As it is shown in the table and in the figure the correction results in this case in an about 30% modification of the measured result, eliminating the error caused by the parallel heat flow paths.

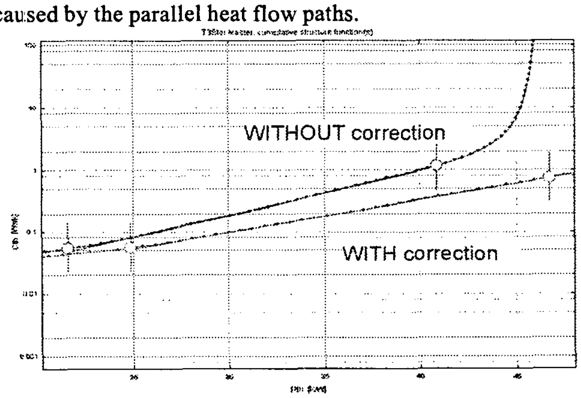

Figure 10 Enlarged details of the structure functions with and without correction

The advantage of the method is, that the necessary measurements to the correction have to be done only once for a given fixture, and the corrections after this can be done automatically by the measurement evaluation software, if the measurements are done in the same conditions.

MEASUREMENT OF THERMAL RESISTANCE OF INTERFACE MATERIALS

The measurement of the thermal resistance of interface materials [2] is based on the use of the *differential structure functions*. In the methodology, presented in [3] the sample to be measured is placed in a fixture, which has two separable parts, between which the sample to be measured has to be placed. The fixture itself is such, that it produces two well distinguishable sharp peaks in the differential structure function (A and B), and the sample to be measured has to be placed between the surfaces, represented by these peaks.

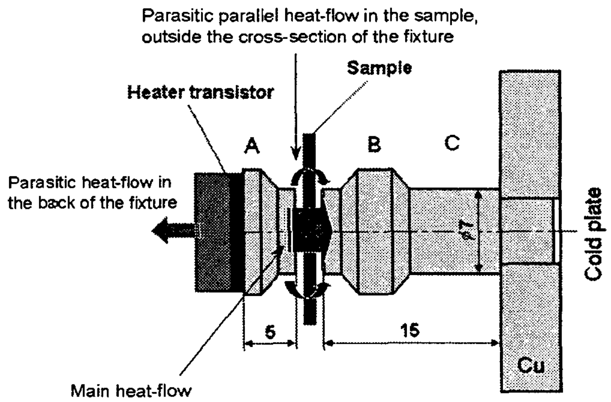

Figure 11: Fixture for measuring thermal resistance of interface materials, indicating possible parasitic heat-flow paths. The length unit is mm.

During the measurement first the reference function of the empty fixture is identified, then the one with the sample. The measurement principle is based on the shift of peaks in the differential structure function of the fixture as illustrated by Figure 11 and Figure 12.

The peak corresponding to section B shifts with respect to the peak belonging to section A as a sample is inserted into the fixture. The physical arrangement, together with the main and parasitic parallel heat-flow paths is also shown in Figure 11. All the heat, that leaves the transistor and arrives to the ambient on a path, which is different from the main path across the sample, is a loss for the measurement and has to be considered in the evaluation.

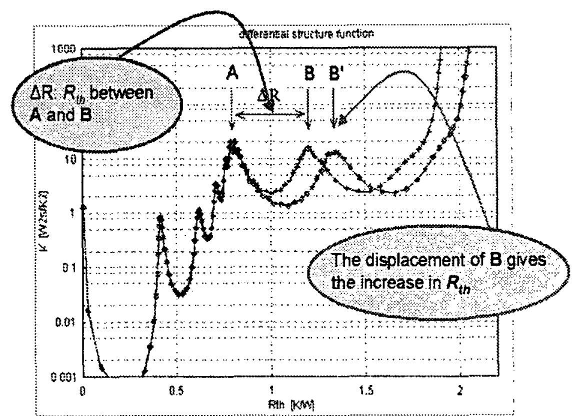

Figure 12: Displacement of peak B in the differential structure function gives the thermal resistance of the sample

[1] In the table the sample_4 samples were measured on a board of 470μm, sample_6 was measured on a board of 1510μm thickness, patterned on both surfaces, measured at different locations. The sample_6_via contains a thermal via. w is the thickness of the samples.

The losses can be accounted for if we measure the thermal resistance represented by the parasitic heat flow without the fixture, and correct the structure function with this value according to the procedure described above. The convection losses can be also calculated, if we measure the structure once in vacuum, this will be discussed in the next section in details.

The measured and the corrected results are presented in Figure 13. As we can see from this figure the correction for the parallel losses results in an about 18% increase in the measured thermal resistance value.

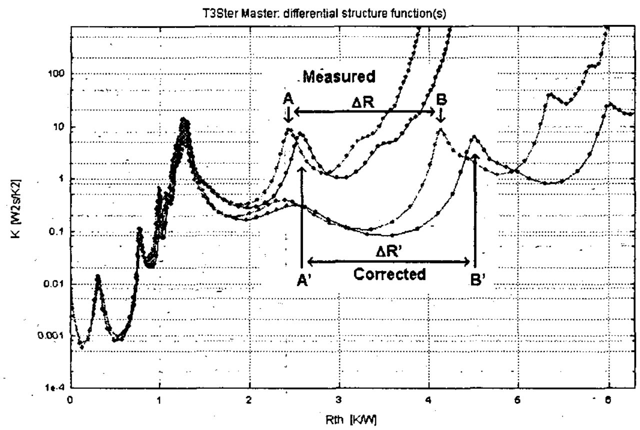

Figure 13: The corrected structure function of the thermal resistance meter

With a simple set of experiments in a vacuum chamber we have demonstrated, how the effect of natural convection and radiation as well as parasitic heat-flow via the electrical connections of the heating and measuring transistor influence the value of the measured material parameters. [8],[9]. In those experiments natural convection and radiation was eliminated by the physical setup of the measurement, and the effect of the "fixture" was considered with our new correction method, the textbook values of material parameters could be obtained.

CONCLUSIONS

In this paper we demonstrated, that it is possible to consider the thermal impedance of shunting branches in case of structure function based measurements. This option is very important when in case of structure function based indirect measurement of materials thermal properties we want to diminish the effect of parasitic heat-flow paths. Such parasitic paths always do exist even in case of special fixtures accurately designed to assure one-dimensional heat-flow. Parasitic effects are e.g. natural convection, radiation losses and conduction through the fixture itself, which considerably influence the results of measurement.

The method can be used to eliminate the effect of the systematic measurement errors, present in all the cases, when we use the structure function based evaluation to determine thermal material parameter values from fast and simple thermal transient measurements.

With the presented methodology the thermal conductivity was measured on an Inconel 600 thermal conductivity standard, in the framework of the Profit project. [10] We have measured 16.1W/mK, while the textbook value is 15W/mK. In the evaluation of the measurement only the simpler correction of Eq. (6) was used, and the effect of the convection and radiation was not corrected, only that of the measuring head. This way, with a very simple and fast measuring procedure we could determine the thermal conductivity of an arbitrary shape and size material with only 7% error. With some additional small efforts this error can be further decreased. We hope to be able to report such results at the time of the Conference presentation.

REFERENCES

[1] V. Székely and Tran Van Bien: "Fine structure of heat flow path in semiconductor devices: a measurement and identification method", *Solid-State Electronics*, V.31, pp.1363-1368 (1988)

[2] M. Rencz, V. Székely, A. Morelli, C. Villa: "Determining partial thermal resistances with transient measurements and using the method to detect die attach discontinuities", SEMITHERM, March 1-14 2002, San Jose, CA,USA, Proceedings pp 15-20

[3] M. Rencz, V. Székely: "Measuring partial thermal resistances in a heat flow path", *IEEE Transactions On Components and Packaging Technologies*, Vol 25, No 4, Dec. 2002, pp 547-553

[4] V. Székely, M. Rencz, S. Török, S. Ress: "Calculating effective board thermal parameters from transient measurements", *IEEE Transactions On Components and Packaging Technologies*, Vol 24, No 4, Dec. 2001, pp 605-610.

[5] V. Székely, M. Rencz: "Thermal Dynamics and the Time Constant Domain", *IEEE Transactions On Components and Packaging Technologies*, Vol.23, No.3, pp 687-594 (2000)

[6] G.C. Temes, J.W. Lapatra: Circuit Synthesis and design, McGraw-Hill, 1977

[7] http://www.micred.com/index1.htm

[8] M. Rencz, E. Kollár, A. Poppe, S. Ress: "Evaluation Issues of Thermal Measurements Based on the Structure Functions", 9th THERMINIC Workshop, 24-26 September 2003, Aix-en-Provence, France, pp. 219-224

[9] M. Rencz, A. Poppe, E. Kollár, S. Ress, V. Székely: "Increasing the accuracy of structure function based thermal material parameter measurements", *Submitted to IEEE Transactions On Components and Packaging Technologies*

[10] C. Lasance: The European project: PROFIT: Prediction of Temperature Gradients Influencing the Quality of Electronic Products, *Proceedings of the 17th SEMI-THERM Symposium*, 2001, pp 120-125