The Aberrations of the AC Thermal Characteristics in the Presence of Solder Defects in Multilayer Microelectronic Structures

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***Abstract*—In this paper, the multilayer microelectronic structures have been modeled using AC thermal modeling approach. The influence of defects in solder layers on the thermal parameters of the structures has been investigated. It has been presented how an aberration in a solder layer that may result e.g. from the manufacturing flaw, can significantly affect the thermal characteristics of the structure thus aggravating the conditions of the heat transfer. The phenomena have been described in the qualitative and quantitative way. Furthermore, the applicability of the proposed modeling method for the purpose of determining the optimal frequency range in non-destructive device testing technique - lock-in thermography - has been demonstrated.**

***Index Terms*—AC thermal modeling, nondestructive testing, thermal impedance, heat transfer.**

I. INTRODUCTION

THE usual approach to heat transfer is confined to time-domain which adequate for a variety of purposes does not embrace all the phenomena. The exploration of frequency-domain ceases to be negligible when structures become relatively small, e.g. the microelectronic structures. In this case, the cut-off frequency becomes considerably high, these high frequencies penetrate the structure and the penetration no longer can be perceived as depthless. The periodic heat sources can be a result of some unwanted thermal couplings within the circuit [1] or energy waves purposely applied to the surface in order to pursue the non-destructive testing (NDT) i.e. lock-in thermography [2].

The dynamic approach is more and more frequently used to investigate thermal properties of electronic and microelectronic components. The nomenclature for AC thermal modeling is derived from the terminology in the electric domain as it implies the existence of the periodic sources. The numerical simulations performed in AC are not entirely realistic, as the genuine sinusoidal heat sources are of no existence. The method assumes superposition of AC and DC sources. The frequency domain is obtained by transforming the heat equation:

$$\nabla^2 T - \frac{C_V}{k}\frac{\delta T}{\delta t} = 0 \qquad (1)$$

$$\nabla^2 T - \frac{j\varpi C_V}{k} T = 0 \qquad (2)$$

The simulations are based on the electrothermal analogy. The thermal conduction is described with the same mathematical equations as the electrical conduction, hence it is possible to model the dynamic thermal behavior as an equivalent RC ladder network (Fig.1) [3] enhanced with boundary conditions. The lateral bounding planes are adiabatic and at the bottom surface the isothermal condition is assumed with the temperature equal to the reference temperature. The heat source is homogeneously spread at the upper surface of the structure. Cooling is accomplished by heat conduction towards a heat-sink, through a stack of materials.

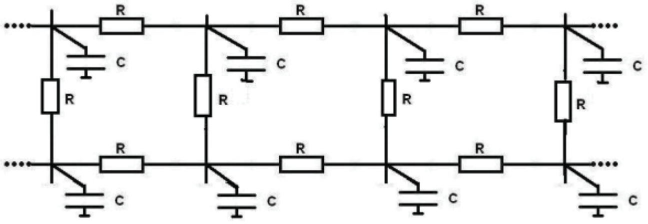

Fig. 1. The RC ladder network.

The results are presented using the thermal impedance $Z_{th}(j\omega)$ represented in a Nyquist plot. This is a curve where the imaginary part $\mathrm{Im}[Z_{th}(j\omega)]$ is plotted versus the real part $\mathrm{Re}[Z_{th}(j\omega)]$ using ω as a parameter. The thermal impedance of a microelectronic structure is defined as the junction temperature divided by the power dissipated in the same junction. It is expressed in K/W.

$$Z_{th}(j\varpi) = \frac{T(j\varpi)}{P(j\varpi)} \qquad (3)$$

II. THE ALTERATION OF THERMAL CHARACTERISTICS

The basic model of the analyzed problem is a two-layer structure with a solder layer in between (Fig.2). To simplify

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the simulation the thin solder layer can be treated as a perfect contact. The defect in this layer is introduced as a gap in material in the middle of the structure which then is gradually enlarged in the consecutive simulations. It has been assumed that the gap behaves like a perfect insulator, therefore it can be modeled as vacuum. The thermal parameters of the simulated structure are presented in the table (see Table I).

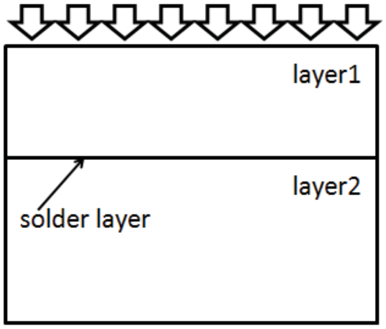

Fig. 2. The two dimensional structure.

TABLE I
THERMAL PARAMETERS OF THE LAYERS.

	k [W m^{-1} K^{-1}]	C_v [J m^{-3}K^{-1}]
Silicon	160	1,784 ×10^6
Solder	55	1,774 ×10^6
Alumina	22	2,98 ×10^6

The thermal characteristics presented as Nyquist curves (Fig. 3) are of almost circular shape. It can be easily noticed that even a minor gap in the solder layer has a significant impact on the thermal properties. However, the influence is restricted only to low frequencies. When we take a closer look at the higher frequencies region (Fig.4), we can see that above phenomenon can be easily explained. The lower the frequency, the deeper the penetration. Above certain certain frequency, the influence is no longer visible. The frequency, the fact that there is some variation in the internal structure at the depth of the solder layer, is no longer detectable. The frequency in the case of the analyzed structure is around 1 kHz.

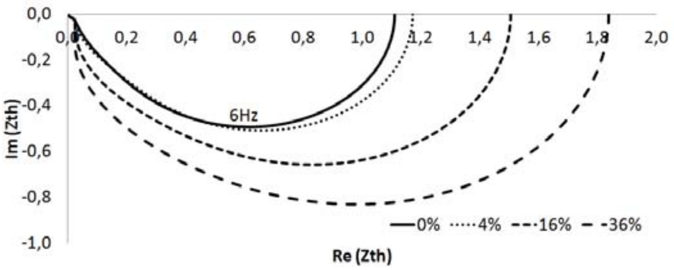

Fig. 3. The thermal characteristics.

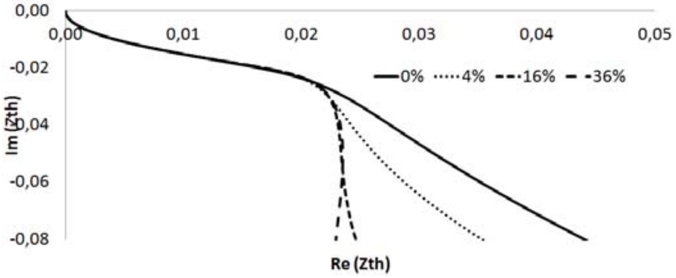

Fig. 4. The thermal characteristics – high frequencies region.

In the characteristics, the most conspicuous parameter is the thermal resistance $R_{th}=Z_{th}(j\omega=0)$ - the point in which the curve reaches the x-axis. The results show that e.g. an air gap of the size of around 25% of the cross-sectional area can give a 50% rise to the temperature at the upper layer of the structure by significant aggravation of the heat dissipation process (Fig. 5).

It is necessary to point out that the presented characteristics are made for the central point at the upper surface. Generally speaking, they depend on the location – they are not specific to the structure as a whole but they characterize a specific point of it. This reasoning is perfectly natural as cooling process obviously differs in cases when the heat source is situated above the area where the gap is located and when it is not. The simulations are made for a homogeneous power source at the upper surface dissipating the power of 1W.

As the thermal resistance is a function of location at the surface, it is possible to present it in a form of a thermal profile either two dimensional – cross-section of the structure or three dimensional (Fig. 6 and Fig. 7).

The simulations confirm that the thermal resistance distribution along the upper surface is uneven and significantly higher above gap. It means that heat transport (here the only considered mode is the heat conduction) is hindered in the areas, therefore leading to higher local temperature rises and possibly causing the malfunctioning of the device.

The AC modeling has however the advantage over the traditional approach to thermal simulations that apart from allowing determining the thermal resistance distribution, it also gives an insight into the frequency domain of the problem.

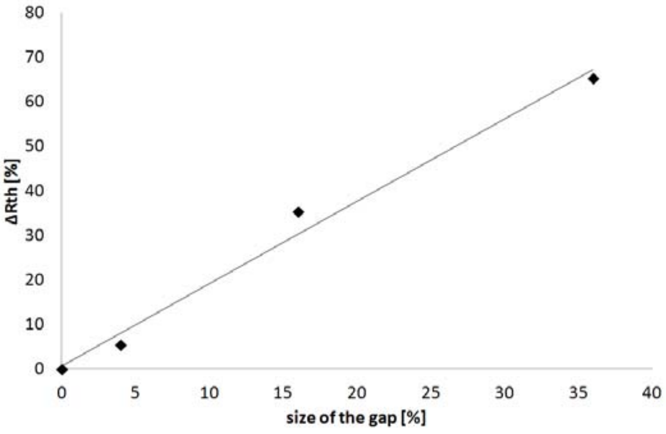

Fig. 5. The thermal resistance in function of the size of the gap in the solder layer.

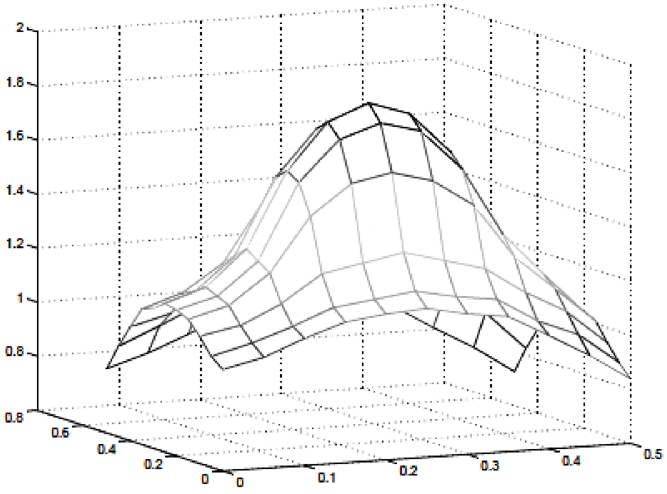

Fig. 6. The example of three dimensional thermal resistance distribution (for 36% size of the gap).

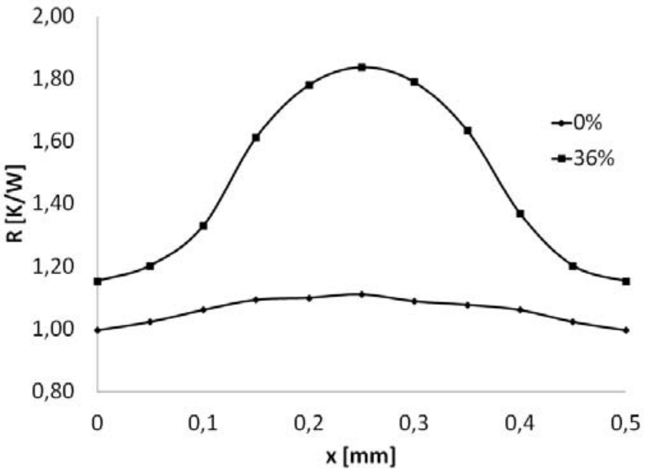

Fig. 7. The thermal resistance distribution at the surface of the structure for a gap situated in the middle (0% and 36% size).

III. Determining the Optimal Frequency

The method of non-destructive testing - lock-in thermography requires a periodic energy source applied to the surface of the device under test (i.e. thermal emitter, ultrasound, microwave, eddy current, flash lamp). The thermal response (the resulting local temperatures detected by IR-camera) is phase shifted as the energy wave is partially reflected from the areas of different thermophysical properties in relation to the surrounding material – e.g. the air gap in the solder layer. The result is analyzed in order to determine the internal structure of the device. The important requirement to derive internal inconsistencies within the object is that the input energy source uses an optimal frequency [4,5]. To assure the detectability of a defect, certain range of the frequencies needs to be used for testing.

The research indicates that the necessary information can be provided by means of the AC thermal simulations (Fig.8). The phase characteristic is just another representation of the same information as contained in the Nyquist curve of thermal impedance. It is easily noticeable that there is a certain range of frequencies for which the phase shift in each gap-size case is different. Using a frequency from the range for the purpose of lock-in thermography guarantees the correct detection of the gap in the solder layer. The phase characteristic also confirms that above the frequency of about 1 kHz, the detection of the gap is no longer possible, which was previously presented in the Nyquist curves.

The results indicate that not only the lock-in thermography can be used to detect the gaps in the structure but also, that the method of AC modeling can contribute to this method of non-destructive testing by giving a clear insight into what range of frequencies should be inspected in order to detect the inconsistency. As for the gap detection, we can see that by evaluating the phase shift of the local surface temperatures in relation to the input energy wave, the gap can be detected and moreover judging by the phase shift, the size of the gap can be distinguished (Fig. 8).

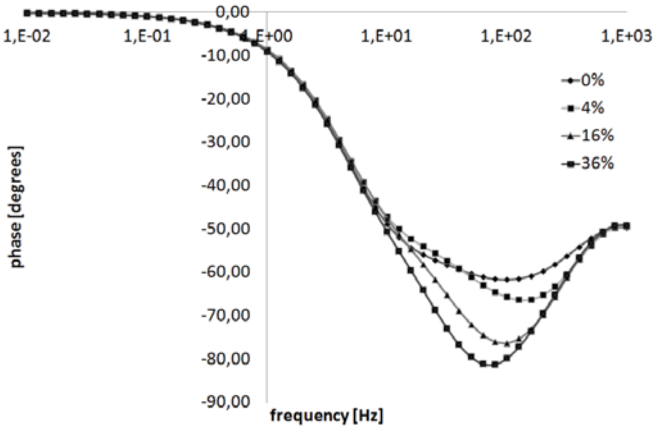

Fig. 8. The thermal resistance in function of the size of the gap in the solder layer.

IV. Conclusion

The influence of the discontinuities in the solder between two layers on the thermal parameters of the structure has been investigated. The novel approach of the AC thermal modeling and simulation instead of the traditional time-domain analysis has been adapted to the problem.

The simulations demonstrate how the existence of the material inconsistencies influences the thermal characteristics and hinders the conditions of heat dissipation (Fig. 5), which can lead to the device malfunctioning, faster ageing or even to the destruction of the device. The method allows determining the thermal resistance distribution over the upper surface of the device (Fig. 6 and Fig. 7).

The obtained results prove that the defects in the solder layer can be detected using lock-in thermography. Moreover, they indicate that AC thermal modeling can give a powerful insight into the frequency-domain in order to identify the optimal frequency range for the purposes of the method.

REFERENCES

[1] Vermeersch Bjorn, De Mey Gilbert: Thermal impedance plots of micro-scaled devices, Microelectronics Reliability 46 (2006) 174–177

[2] Gralewicz Grzegorz, Owczarek Grzegorz, Więcek Bogusław: Investigations of Single and Multilayer Structures Using Lock-In Thermography - Possible Applications, International Journal of Occupational Safety and Ergonomics (JOSE) 2005, Vol. 11, No. 2, 211–215

[3] Kawka Piotr, De Mey Gilbert, Vermeersch Bjorn: Thermal Characterization of Electronic Packages Using the Nyquist Plot of the Thermal Impedance, Components and Packaging Technologies, IEEE Transactions on , vol.30, no.4, pp.660-665, Dec. 2007

[4] W. Bai and B. S. Wong, Evaluation of defects in composite plates under convective environments using lock-in thermography, Meas. Sci. Technol. 12 (2001) 142–150

[5] Horny N. and Lannoy B.: Lock-in thermography with a focal plane array, INSTITUTE OF PHYSICS PUBLISHING MEASUREMENT SCIENCE AND TECHNOLOGY 14 (2003) 439–443

[6] Yunus Cengel: Heat and Mass Transfer: A Practical Approach, ISBN: 9780077366643

[7] Więcek Bogusław, De Mey Gilbert: Termowizja w podczerwieni, Podstawy i zastosowania, ISBN: 978-83-926319-7-2

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Her current research interests include AC modeling of heat transfer.