Applications of temperature phase measurements to IC testing

J. Altet a,*, J.M. Rampnoux b, J.C. Batsale c, S. Dilhaire b, A. Rubio a, W. Claeys b, S. Grauby b

a Department of Electronic Engineering, Universitat Politècnica de Catalunya, Campus Nord UPC, Building C4 Cl. Jordi Girona 1-3, Barcelona 08034, Spain
b Centre de Physique Moléculaire Optique et Hertzienne, Université Bordeaux I, 33405 Talence Cedex, France
c Laboratoire Énergétique et Phénomènes de Transfert, LEPT, ENSAM et CNRS, 33405 Talence Cedex, France

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Abstract

This work analyses the applicability of silicon surface temperature phase measurements as a test observable when a device acting as a heat source dissipates a modulated power function. Specifically, this paper considers two different functions: the phase shift of the temperature waveform as a function of frequency and distance, and the slope of the temperature phase shift versus distance as a function of frequency. Different cases are analyzed in order to show the potential of both functions, including experimental results obtained from a specific integrated circuit (IC). The conclusions will show that samples of the phase function can be used to locate devices acting as heat sources, and that the slope function can be used to extract information regarding the heat flow path in the IC, and, therefore, regarding the structure of the IC.

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1. Introduction

Defects in the structure of an integrated circuit (IC) may have implications at the thermal and electrical levels, shortening the life of the devices. Detecting such defects is an important issue in both manufacturing and in the application field scenarios.

The term thermal testing comprises all the techniques that use temperature as a test observable.

Fig. 1 shows a block diagram of the electrical model of a thermal testing procedure [1]. The temperature monitoring system can be off-chip (as depicted in the figure) or on-chip, built-in with the circuit under test (CUT). Focusing on this model, if the boundary conditions are assumed to be constant, a change in temperature at the monitoring points indicates an alteration of either the power dissipated by the devices or the IC packaging structure. Therefore, the aim of a thermal testing procedure is to detect either defects in the electronic realisation of the circuit that alter the power dissipated by its devices, or defects in the packaging structure. The specific target is chosen depending on the nature of the temperature measurements carried out and the characteristics of the temperature-measuring systems.

Recently, research has been carried out on thermal testing strategies. Most of the work published so far is based on temperature amplitude measurements when the devices acting as heat sources dissipate a step power function. Examples in [2,3] are aimed at detecting defects in the electronic circuits, whereas [4–8] are oriented towards the analysis of the package. Another approach would be to measure amplitude and/or phase of the temperature waveform when the power dissipated is a modulated function. Examples of this strategy can be found in [9–11].

The goal of the present paper is to discuss the applications of spot thermal phase measurements performed on the surface of an IC to the thermal testing of ICs, whether it be in order to test the electronic circuit or the package structure. The advantage of phase measurements is that they do not need amplitude calibration.
The paper is organized as follows: Section 2 presents the principle of the technique, temperature phase measurements for the thermal testing of ICs. Section 3 mathematically analyses what information can be extracted from a CUT with temperature phase measurements. The experimental results are given in Section 4. Section 5 concludes the paper.

2. Principle of the technique

If a device in an IC dissipates a power function with sinusoidal fluctuations of frequency $f$, the AC component of the temperature at a monitoring point placed on the surface of the silicon at a distance $r$ from this heat source can be generically written as:

$$T(r, t) = A(r, f) \cdot e^{i(2 \pi f r - \varphi(r, f))}$$

where $t$ is time, $A(r, f)$ is the amplitude and $\varphi(r, f)$ is the phase shift of the temperature waveform.

Figs. 2 and 3 show the experimental results of the function $-\varphi(r, f)$, as a function of $r$ for different values of $f$. In both figures, the heat source is an NMOS transistor sized 10 $\mu$m/1.2 $\mu$m. The IC was fabricated by AMS, with its 1.2 $\mu$m silicon BiCMOS process. The package is a ceramic 48 pin dual-in-line. Although the shape of this heat source is rectangular, due to the high thermal conductivity of the silicon, the isotherms are spheres a few tens of microns away from the heat source [3]. The measurements in Fig. 2 were obtained with a laser thermoreflectometer, whereas the measurements in Fig. 3 were obtained with a built-in differential temperature sensor. More details on the measurement techniques and the IC sample can be found in Section 4 and in [12].

As can be seen, the phase shift shows a linear behaviour with the distance $r$. Therefore, we can use the function $S(f)$, defined as the slope of $\varphi(r, f)$ versus $r$:

![Fig. 1. Block diagram of a thermal testing procedure. Electrical model.](image1)

![Fig. 2. Reflectometric phase measurements as a function of the distance $r$ from the heat source for different frequency values. Frequency multiples of 50 Hz have been avoided to reduce coupling from the electrical network.](image2)

![Fig. 3. Phase measurements (built-in differential temperature sensor) as a function of the distance $r$ from the heat source for different frequency values. Frequency multiples of 50 Hz have been avoided to reduce coupling from the electrical network.](image3)
\[ S(f) = \frac{\partial \varphi(r,f)}{\partial r} \]  
\[ S(f) \approx \frac{\varphi(r_1,f) - \varphi(r_2,f)}{r_2 - r_1} \quad r_2 > r_1 \]  

Exponentially, the function \( S(f) \) can be approximated by differential phase measurements:

\[ S(f) \approx \frac{\varphi(r_1,f) - \varphi(r_2,f)}{r_2 - r_1} \quad r_2 > r_1 \]  

Differential phase measurements reject common noise and make measurements independent of the sensor's transfer function.

Temperature phase measurements for thermal testing consists in obtaining samples of either \( \varphi(r,f) \) or \( S(f) \) (or both) to obtain information on the CUT.

3. Application of \( \varphi(r,f) \) and \( S(f) \) to the thermal testing of ICs: theoretical analysis

The purpose of the following cases is to analyse what information that can be extracted from the functions \( \varphi(r,f) \) and \( S(f) \) can be used for the thermal testing of ICs.

3.1. Case I: One-dimensional (radial) heat flow. Semi-infinite homogeneous material

Let us consider a homogeneous semi-infinite material with adiabatic top boundary conditions. A semi-spherical heat source is placed on the top of the material (Fig. 4a), its power dissipation being a sinusoidal function of frequency \( f \). Although this structure is unrealistic as a model of an IC from a thermal point of view, due to its simplicity, a closed form for the surface temperature can be found [13]:

\[ T(r,t) = \frac{C}{r} \cdot e^{-\sqrt{\pi f/D}} \cdot e^{i(2\pi f t - \varphi(r,f))} \]

\[ \varphi(r,f) = r \sqrt{\frac{\pi \cdot f}{D}} \]

where \( C \) is a constant, \( D \) is the thermal diffusion constant of the media, \( t \) is time and \( r \) is the distance from the heat source centre. If the radius of the heat source is much smaller than \( (4\pi f/D)^{1/2} \), the constant \( C \) can be approximated by \( P/2\pi nk \) where \( P \) is power source amplitude and \( k \) the thermal conductivity.

In this case, the phase shift depends only on the physical properties of the material, the distance from the heat source and the frequency. Therefore, phase measurements can be used to either estimate the distance between the heat source and the monitoring point or to measure the thermal diffusivity of the material. A precedent of using phase measurements for the thermal characterisation of materials is the \( 3\omega \) method [14].

The slope of the phase shift versus \( r \) can be calculated directly from (4):

\[ S_\varphi(f) = \sqrt{\frac{\pi \cdot f}{D}} \]  

3.2. Case II: One-dimensional (radial) heat flow. Semi-infinite heterogeneous material

Fig. 4b depicts a heterogeneous semi-Infinite material with the following structure: a semi-spherical heat source centred in a semi-sphere of radius \( R \) of one material (material 1) followed by a semi-infinite extension of another material (material 2). The temperature at the surface of material 1 can be obtained with the method of thermal quadrupoles [15] and computed with Matlab®.

Let us name \( \varphi_{II}(r,f) \) as the phase shift of the temperature waveform obtained at the surface of material 1 and \( S_{II}(f) \) to its slope versus \( r \).

Fig. 5 shows the functions \( S_{II}(f) \) computed when material 1 is silicon and material 2 is aluminium. Three different values of \( R \) are considered: 300, 3000 and 30 000 \( \mu \)m. All these functions are compared with the \( S_\varphi(f) \) obtained in the previous case—Eq. (5)—considering silicon only.

Let us analyse the data of this figure. \( S_\varphi(f) \) is a straight line of slope 1/2 when drawn in a log–log chart. This is due to the square root operator present in (5). For high frequency values, no difference exists between the functions \( S_{II}(f) \) and \( S_\varphi(f) \), as the attenuation of the temperature amplitude increases with distance and frequency (e.g. Eq. (4)). If the power dissipated by the heat source has a sufficiently high frequency, almost all the
energy is confined inside material 1. In such circumstances:

\[ \phi_{II}(r,f) - \phi_I(r,f) \approx 0 \]  

Therefore, high frequency phase measurements in case II have the same application to thermal testing as case I.

For lower frequencies, the function \( \phi_{II}(r,f) \) is affected by the presence of material 2. The exact value of the frequency at which the function \( \phi_{II}(r,f) \) differs from \( \phi_I(r,f) \) depends on the value of \( R \) and can be seen through the functions \( S_{II}(f) \). If we name \( f_s \) as the value of frequency at which \( S_{II}(f) \) separates from \( S_I(f) \), from Fig. 5 we can derive:

\[ f_s \propto \frac{1}{R^2} \]  

The use of function \( S_{II}(f) \) allows the determination of the range of frequencies for which \( \phi_{II}(r,f) \) can be used with the same conditions as \( \phi_I(r,f) \), as well as the distance \( R \) between the heat source and the material transition in the conducting path.

Let us now consider that material 1 and material 2 only differ in one parameter: they have the same specific heat and density, but a different thermal conductivity \( k_2 \) and \( k_1 \):

\[ k_2 = m \cdot k_1 \]  

where \( k_1 \) and \( k_2 \) are, respectively, the thermal conductivities of material 1 and material 2 and \( m \) is a multiplying factor.

Fig. 6 shows how this material transition affects the function \( S_{II}(f) \). The slope function is calculated for different values of \( m \). In all the cases, \( R \) is set to 3000 μm.

When \( m = 1 \), \( S_{II}(f) \) behaves as \( S_I(f) \), as material 2 is identical to material 1. In all the other cases \( f_s \) is the same. However, the way the \( S_{II}(f) \) function changes depends on the thermal properties of material 1 and material 2. Thus, the function \( S_{II}(f) \) can be used to characterise material transitions in the thermal path.

### 3.3. Case III: Two-dimensional heat flow. Finite homogeneous material

The IC structure is more complicated than the simple models used in the previous cases: heat flow is not radial, following spherical coordinates, and the thermal path has boundary conditions.

In this case, we will model the silicon die with a cylinder (radius \( R \), height \( H \)) with adiabatic boundary conditions at the top and lateral sidewalls and isothermal bottom boundary condition. Fig. 7 shows a drawing of the analysed structure. A circular heat source of radius \( r_s \) is placed on the top centre of the cylinder.

As in the previous case, the surface temperature can be found with the method of thermal quadrupoles [15]. Let us name \( \phi_{III}(r,f) \) as the phase shift obtained at the surface of the cylinder and \( S_{III}(f) \) as its slope versus \( r \). We will focus on the issue of \( r \) verifying \( r_s < r < R \).

Cylindrical structures such as the one used in this section have already been used in the literature in order to thermally analyse ICs [16], as they reduce the complexity of the solution of the heat transfer equation. To illustrate that cylindrical structures are also suitable for temperature phase analysis, Fig. 8 compares the \( S_{III}(f) \) function obtained with a cylinder of dimensions \( R \times H = 1692 \text{μm} \times 400 \text{μm} \), a heat source of radius \( r_s = 22 \text{μm} \), and a slope function \( S_{III}(f) \) obtained at the surface of a parallelepiped of dimensions \( W \times L \times H = 3000 \text{μm} \times 3000 \text{μm} \times 400 \text{μm} \) with a centred rectangular heat source of dimensions \( w \times l = 40 \text{μm} \times 40 \text{μm} \). The dimensions were chosen to set the area and volume of
the silicon dies and the area of the heat sources in both structures as equal. As Fig. 8 shows, both structures generate similar slope results throughout the frequency range analysed.

To analyse how the functions \( u_{III}(r, f) \) and \( S_{III}(f) \) are affected by the boundary conditions, let us define the following dimensionless units:

\[
R^* = \frac{R}{r_s} \quad (9)
\]

\[
H^* = \frac{H}{R} \quad (10)
\]

Fig. 9 shows how lateral boundary conditions affect the function \( S_{III}(f) \). Three cylindrical structures are analysed: \( R^* = 10, 100 \) and \( 1000 \). In all of them, \( H^* = \infty \) to ensure that the bottom boundary condition does not affect the slope function. The three computed \( S_{III}(f) \) functions are compared with the \( S_1(f) \) (Eq. (5)). As can be seen, there is good agreement among all the functions for high frequency values. Thus, in this frequency range, function \( \varphi_{III}(r, f) \) has the same applications as function \( \varphi_1(r, f) \). The lateral boundary condition causes the behaviour of functions \( S_{III}(f) \) to split from the one of \( S_1(f) \). If we call \( f_s \) again as the splitting frequency value:

\[
f_s \propto \frac{1}{(R^*)^2} \quad (10)
\]

Figs. 10 and 11 show the effect of both boundary conditions for two different values of \( R^* \). As can be seen, for high frequency values, all the functions behave as the \( S_1(f) \) obtained in the first case. For lower values of \( f \), \( S_{III}(f) \) splits from the \( S_1(f) \). The bottom boundary condition introduces a unity slope split in the \( S_{III}(f) \) function. Depending on the sizes of the silicon die and the heat source, the first split from the \( S_1(f) \) is due either to the lateral or to the bottom boundary conditions.
3.4. Case IV: Two-dimensional heat flow. Finite heterogeneous material

Fig. 12 shows the IC model used in this case: two cylinders, both with the same radius $R$ but with different height ($H_1$ and $H_2$). The contact between both cylinders is characterised by its thermal contact resistance $R_c$ [K/W]. The boundary conditions are the same as in case III.

Let us name $u_{IV}(r, f)$ and $S_{IV}(f)$ as the phase shift computed at the surface of the upper cylinder and its slope versus $r$ respectively.

As in the previous cases, if the heat source dissipates a power function of sufficiently high frequency, no differences exist between the $S_{IV}(f)$ and $S_{I}(f)$ functions, and therefore between the $\varphi_{IV}(r, f)$ and $\varphi_{I}(r, f)$ functions. For lower frequencies, both the material transition and the boundary conditions affect the phase shift at the surface of the structure. For example, Fig. 13 shows four $S_{IV}(f)$ functions obtained in a structure of dimensions: $R = 300$ µm, $H_1 = 400$ µm, $H_2 = 100$ µm, $r_s = 10$ µm. The thermal contact resistance values considered are: $R_c = 0, 10^{-6}, 10^{-5}$ and $10^{-4}$ K/W. As the dimensions of all the analysed structures are the same, the splitting frequency has the same value in all the graphs. The differences in the behaviour of the $S_{IV}(f)$ functions in the low frequency range is caused by the different thermal contact resistances considered in each case.

4. Experimental results

An IC sample that was specially designed to characterise thermal couplings was used as a CUT. In this IC sample, several individually controllable heat sources (MOS transistors with sizes of $(10 \mu m)/(1.2 \mu m)$, connected in diode configuration) were positioned along with BiCMOS differential temperature sensors. The technology’s features are silicon substrate, two layers of metal and the sample is coated with oxide and passivation layers. The power supply voltage ($V_{dd}$) can be increased up to 5 V.

Two different techniques were used in order to perform phase measurements and differential phase measurements: a laser thermoreflectometer and a built-in differential temperature sensor.

Thermoreflectance exploits the proportionality between the variation of a material’s reflection coefficient and the surface temperature changes of the material. If a laser beam is focused on a silicon surface and the reflected light is monitored with a photodiode, variations in current $I$, generated by changes of the reflection coefficient, can be related to the variations of the temperature, $\Delta T$, of the area on which the laser is focussed [17]:

$$\Delta T = \psi^{-1} \frac{\Delta I}{I}$$  \hspace{1cm} (11)

The constant $\psi$ depends on the material and the light wavelength, and typical values can be found in the relevant literature. However, when the laser beam reaches the silicon surface through silicon dioxide and passivation layers, this coefficient is affected by a scaling factor that can be greater or smaller than unity, depending on the thickness of these layers [18]. Usually, a calibration stage is needed in order to obtain the exact value of $\psi$. 
The advantage of phase measurements is that they are not affected by these layers. Results reported in [19] show the laser probe to be a fast surface thermometer (dc to 150 MHz) with an excellent lateral resolution (1 µm) and large dynamics (ΔT from $10^{-2}$ to $10^{-3}$ K).

The built-in differential temperature sensor is a variation of a classical BiCMOS operational transconductance amplifier (OTA) and its schematic is shown in Fig. 14. The output voltage of this sensor presents a variation proportional to the difference in temperature between the bipolar transistors $Q_1$ and $Q_2$ [20]. Its sensitivity depends on its biasing. For instance, typical simulated analyses provide a sensitivity of $-2.7 \text{ V/}^\circ\text{C}$ when a current of 23 µA flows through $M_{le}$. The exact value of the sensitivity can be obtained with a calibration procedure. Again, phase measurements do not require this calibration stage.

Fig. 15 shows the layout of the sensor. Some heat sources are in the photograph as well. By activating the different heat sources sequentially, phase measurements can be extracted as a function of the distance between the heat source and the location of the closest bipolar transistor.

Figs. 2 and 3 show the phase measurements performed with a laser thermoreflectometer and a built-in differential temperature sensor respectively. In the case of Fig. 2, the laser beam has a diameter of 3 µm over the silicon die. The bipolar transistors are the smallest available with current technology. Therefore, the measurements can be assumed to be at one spot of the silicon surface. Fig. 16 shows the derived function $S(f)$.

As can be seen, the $S(f)$ function measured behaves as $S_I(f)$ for frequencies higher than 120–130 Hz. For values higher than this splitting frequency, the phase shift follows Eq. (4) and can be used either to obtain the distance between the monitoring point and the heat source, if the thermal physical properties of the IC substrate are known, or to thermally characterise this substrate if the distance of the heat source monitoring point is known. Actually, in [11], with the same IC sample used in this paper to obtain the phase measurements of Figs. 2 and 3, the location of a heat source in a layout was carried out with three point phase measurements (Fig. 17). In that work, the heat source dissipated a periodic 1 kHz power function. Now, thanks to the

![Fig. 14. Schematic of the built-in differential temperature sensor.](image1)

![Fig. 15. Detail of the IC layout: built-in temperature sensor and heat sources.](image2)

![Fig. 16. Comparison of the experimental values of $S(f)$ and the function $S_I(f)$ for $R_c = 10^{-4}$ K/W.](image3)
function $S(f)$ we can calculate the frequency up to which the measured phase behaves like the $\psi(r,f)$ model. This has important applications to IC diagnosis: if we do not know a priori the location of the heat source we want to identify, we have to select several temperature monitoring points. The lower the frequency at which we activate the heat source, the less the temperature is attenuated with distance and the larger the spacing between the monitoring points.

In Fig. 16, the measured $S(f)$ is compared with one of the $S_{IV}(f)$ functions of Fig. 13. As can be seen, good agreement exists between the measured and analytical data when the $R_c$ is $10^{-4}$ K/W.

5. Conclusions

This paper analyses the use of phase measurements and differential phase measurements performed at the surface of the IC substrate for the thermal testing of ICs. The analytical results have shown that:

High frequency phase measurements can be used to either locate devices acting as heat sources in an IC layout or to characterise the thermal properties of the substrate.

Differential phase measurements can be used to determine the frequency range where the phase shift function behaves as it does in the spherical homogeneous case. The way the slope functions split from the spherical homogeneous case can be used to determine the distance from the boundary conditions if the heat source has a large size compared to the substrate area, or to characterise the thermal path and the IC structure if the heat source has a small size compared with the silicon die.

Experimental results have shown examples of phase and slope measurements, and their application to the location of heat sources in an IC layout.

The technique for determining the distance from the heat source to heterogeneities on the heat path by using temperature slope measurements can be used to detect defects in electronic devices at both die and package levels. The feasibility of integrating sensors in the chip allows an automatic and continuous checking of the integrity of the structure, so it can be used to predict the reliability of components.

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