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Localisation of heat sources in electronic circuits by microthermal laser probing [1]

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Abstract — In this work we present an original method for detection and localisation of heat sources at microscopic scale upon integrated circuits. The methodology is based upon thermoreflectance and interferometry, which allows us the measurement of surface temperature and dilatation with resolution better than micrometer. The heat sources are transistors electrically activated. The optical probes we have build act as a thermal antenna sensitive to the presence of thermal wave emitted by the heat source. By a set of three measurements of the phase of the thermal wave we are able to localise the heat source which generates the wave. This methodology is applied to microelectronics to detect and localise faults in CMOS integrated circuits. © 2000 Éditions scientifiques et médicales Elsevier SAS

laser metrology / thermoreflectance / thermoelasticity / microelectronics / Joule effect / heat transfert / fault detection / integrated circuits

Nomenclature

d	surface displacement amplitude	m
d_0	surface displacement amplitude at the origin	m
I	electrical current intensity	A
k	wave vector	m^{-1}
R	surface reflectivity	
t	time	s
T	temperature	°C
T_0	surface temperature amplitude at the origin	°C
r	polar variable	m
r_i	radius	m
x, y, z	Cartesian coordinates	m
α, δ	damping coefficient	m^{-1}
β, γ	propagation coefficient	m^{-1}
ϕ, φ	phase shift	rad
Δd	thermal dilatation	m
κ	thermoreflectivity coefficient	K^{-1}
λ	thermal conductivity	$W \cdot m^{-1} \cdot K^{-1}$
ΔR	reflectivity variation	
ΔR_i	uncertainty of the radius	m
ΔT	temperature variation	K

1. INTRODUCTION

In recent work [1] we have shown that in microelectronic circuits a fault acts as a heat source which dissipates additional heat into the device. A circuit with defects produces a set of microscale heat sources distributed upon the surface of the component. The purpose of this paper is to validate a fault detection and localisation procedure based upon a set of measurements of the surface temperature variation or the normal surface displacement at three fixed locations upon the component distant from the heat source. Hot spot localisation by distant sensors has already been proposed [2] but with no experimental validation, to our knowledge. In the test circuit we have built, a fault is simulated by the activation of a MOS transistor which acts as a heat source.

For the particular case of sine wave excitation the power dissipation of such a heat source has a sine wave

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time dependence. The propagation of the heat flux in the integrated circuit produces an oscillating temperature field at each point on the surface in the vicinity of the fault. The thermal properties of the material determine the amplitude and the phase of the temperature variation for a given frequency at a given location on the surface of the component. Thermal expansion of the component always accompanies temperature variations. The surface of the chip has therefore, at a given location, a displacement, normal to the surface, at the same frequency as the heat source. The amplitude and the phase of this surface movement depends upon the temperature distribution under the surface and the stress build up in the medium.

In this work, we study by laser probing both temperature distribution and deformation of the surface around a microscale heat source which simulates a fault upon an integrated circuit. We demonstrate that by a set of phase shift measurements of the thermal responses, performed at three fixed points upon the circuit, it is possible to localise the heat sources.

2. TEMPERATURE AND DILATATION MEASUREMENTS

We have developed an optical probe [3–5] dedicated to microelectronic applications. It includes a visualisation system with micrometric resolution. It allows temperature mapping and dilatation measurements upon integrated circuits at micrometric scale. It can measure the temporal behaviour of the temperature variation and transient surface displacement in the range DC to 125 MHz.

2.1. Principle of temperature measurement

The principle of temperature measurement is based on thermoreflectance. A temperature rise of a material leads to a variation of its optical constants such as the index of refraction. These changes of refractive index induce a change of the optical reflection coefficient (R). Over a very large range of temperatures (a few hundred K) the relative changes of the reflection coefficient can be assumed to be proportional to the temperature variation

$$\Delta T(t) = \kappa^{-1} \frac{\Delta R(t)}{R}$$

where κ is the temperature coefficient of the reflection coefficient,

$$\kappa = \frac{1}{R} \frac{\partial R}{\partial T}$$

The knowledge of κ allows one to determine the temperature variation. The measurement of $\Delta R(t)/R$ is obtained through the measurement of relative variation of the reflected light intensity (I) from the circuit. The sensitivity of the apparatus is about 10^{-2} K. The lateral resolution is limited by the diffraction limit of the laser light and is about 1 μm.

2.2. Principle of dilatation measurements

Dilatation measurements are performed by laser interferometry. The optical bench is a high resolution stabilised homodyne Michelson interferometer. This interferometer allows absolute normal surface displacement measurements. The sensitivity is about 10^{-15} m and the lateral resolution is also 1 μm.

3. HEAT SOURCES

The integrated circuit test structure is made of 16 heat sources made of MOS transistors which can be activated separately. A set of 8 MOS transistors are indicated by numbers in *figure 1*. The circuit was designed at the Universitat Politècnica de Catalunya, it has been implemented with the BAE process of AMS which is a 1.2 μm mixed signal BICMOS technology. The active structures generate thermal waves when they are activated by a continuous sinusoidal current. The properties of the waves generated are assumed to be the same than the ones of thermal waves generated by a fault upon a digital CMOS circuit. The characteristics of the waves, wave vectors, for example, are used to localise the heat sources.

The MOS transistors have the gate connected to the drain. All the sources are connected to a common PAD. The drain electrode can be independently connected to an external power supply. Their $V-I$ characteristics are strongly nonlinear. The power deposited by Joule effect in the transistors is composed of lot of harmonics. Using a lock-in amplifier we detect the response at the electrical current frequency.

The first measurements where performed by activating the MOS transistor #6 (see *figure 1*) which is at the origin of the axes. A positive sine wave voltage at 1

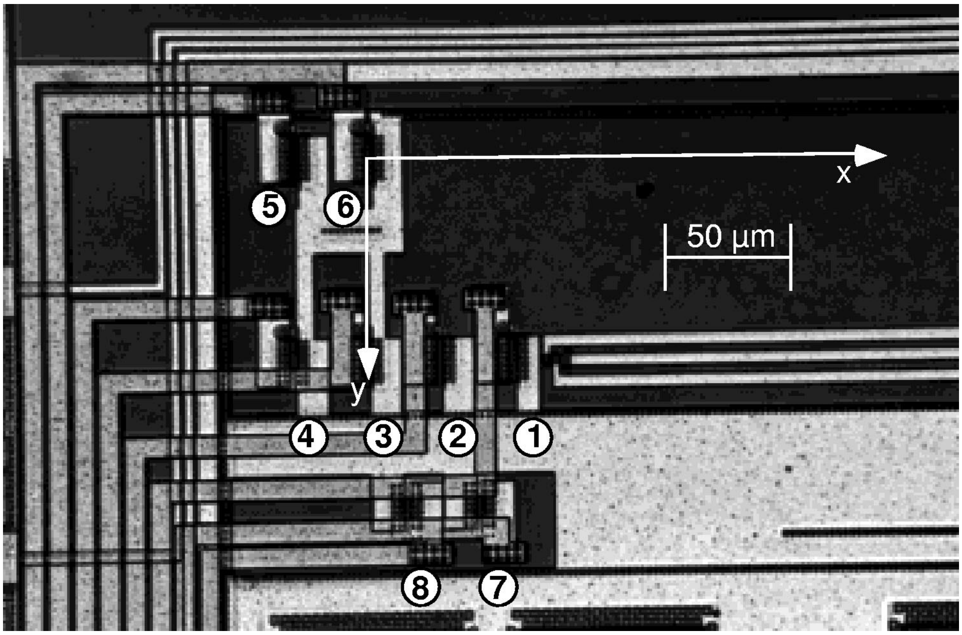

Figure 1. View of 8 MOS transistors upon integrated circuit test structure.

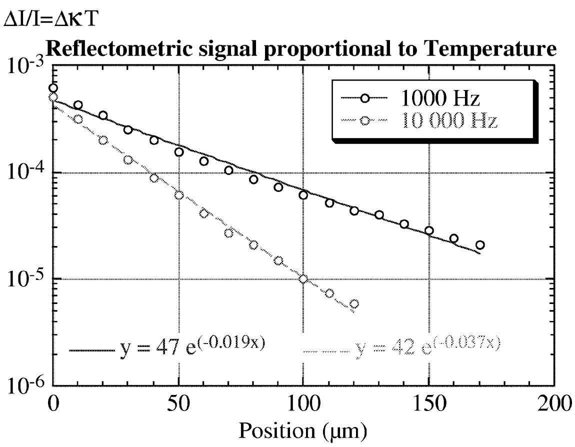

Figure 2. Magnitude of the sine wave thermoreflectometric (surface temperature) signal at 1 kHz and 10 kHz along the x-axis starting from the heat source.

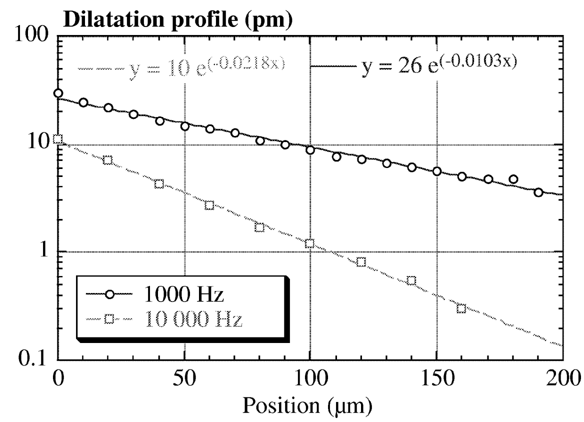

Figure 3. Magnitude of the sine wave surface displacement profile signal at 1 kHz and 10 kHz along the x-axis starting from the heat source.

and 10 kHz frequency is applied. Both interferometric and reflectometric responses have been measured as a function of the distance to the source along the x-axis. A total distance of 200 µm has been explored. *Figure 2* shows the magnitude of the reflectometric signal and *figure 3* the surface dilatation. The reflectometric signal is related to the temperature by the following relation:

$$\frac{\Delta I}{I} = \frac{\Delta R}{R} = \kappa \Delta T$$

The profile of *figure 2*, in arbitrary units because the thermoreflectance coefficient κ is not known for this sample, shows clearly the surface temperature exponential decay with distance to the source. *Figure 3* shows the interferometric measurements providing the absolute surface displacement amplitudes, they are of a few picometers (10^{-12} m). An exponential decay is here also clearly observed, both figures are fitted by an exponential function. This property is characteristic of a diffusion process. It is interesting to note that the diffusion length fitted on

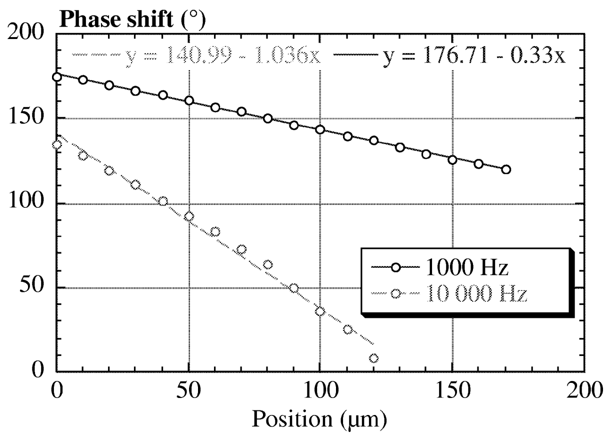

Figure 4. Phase shift of the reflectometric signal at 1 kHz and 10 kHz versus the distance to the heat source.

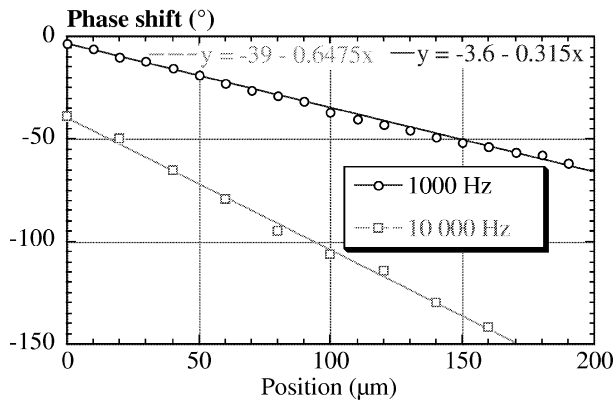

Figure 5. Phase shift of the surface displacement at 1 kHz and 10 kHz versus the distance to the heat source.

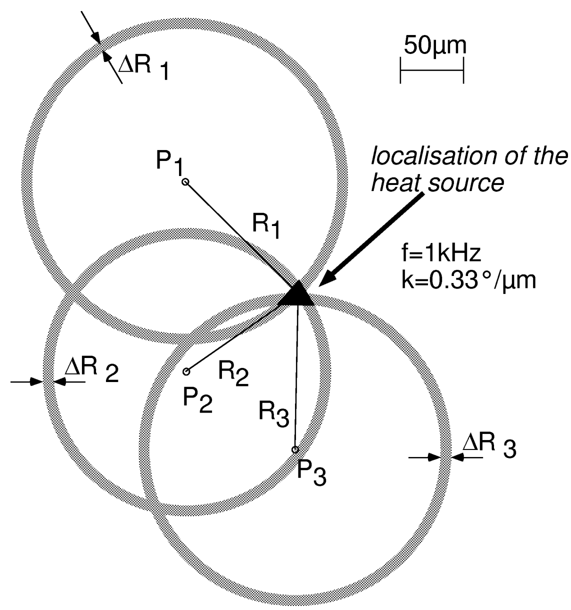

Figure 6. Sketch of the localisation of microscale heat source.

the graphs has not the same value for the dilatation and temperature profiles. We know that the diffusion length of the temperature is easily related to the thermal diffusivity of the material and to the excitation frequency [6]. The interpretation of the diffusion length of the dilatation profile is more complicated because the amplitude and the phase of the surface displacement results from the temperature field under the surface. Indeed, the temperature field produces surface displacement through thermomechanical actions in the material. Even if modelling thermomechanical effects is difficult, we see the amplitude of the thermoelastic wave to be led by an exponential decay as does the temperature. Therefore, from a strict measurement point of view, the only difference between the thermal and the thermoelastic behaviours is the value of the attenuation coefficient which is larger for the temperature than for the dilatation. This makes the detection of faults by laser interferometry possible and allows a broader detection area than with laser reflectometry. At 1 kHz, a detection range of 400 µm is possible by interferometry, while it is limited to about 150 µm for reflectometry.

The use of a lock-in amplifier allows to measure the phase of the responses with respect to the sine wave current applied to the heat source. The results are shown in *figures 4* and *5*. In both cases a linear decay is clearly observed. Again this is the signature of a propagation phenomenon. That is the reason for which the harmonic propagation of heat is called thermal wave propagation. A wave vector can be identified by a linear fit on the plots. The wave vector of the reflectometric signal shows a square root dependence versus frequency where the dilatation follows another linear decay. Here too, a range of more than 400 µm is possible for detecting faults.

The isotropic propagation scheme was tested by performing measurements like those from *figure 2* and *3* in y-axis direction. Identical results were observed. In all cases temperature and dilatation measurements can be fitted by the following expressions:

$$\Delta T(r,t) = T_0\,\mathrm{e}^{-\alpha r}\,\mathrm{e}^{\mathrm{j}(\omega t - \beta r + \varphi_0)}$$

for the temperature and

$$d(r,t) = d_0 \mathrm{e}^{-\delta r}\,\mathrm{e}^{\mathrm{j}(\omega t - \gamma r + \phi_0)}$$

for the dilatation, where T_0 and d_0 are respectively the temperature and the surface displacement at the origin.

ω is the pulsation of the electrical current. φ_0 and ϕ_0 are the phases of reflectometric and interferometric signals upon the heat source. The phases are determined by a measurement upon the heat source as it is shown in *figures 4* and *5*. α and δ are the attenuation coefficients. α^{-1} would be equal to the diffusion length of the temperature in a 1D propagation model. β and γ are the propagation coefficients.

3.1. Localisation of micrometric heat sources

The linear decay of the phase shift of both reflectometric and interferometric responses presented in *figures 4* and *5* have been used to determine the position of heat sources. This can be performed by measuring the phase of the wave at three fixed positions, P_1, P_2 and P_3 (see *figure 6*). The phase shift undergone by the travelling wave at a given location P_1 allows to localise the heat source upon a circle centred in P_1. Two other measurements done at two other locations P_2 and P_3 allow the univocal localisation of the heat source at the intersection of three circles, this is well known and called triangulation. By the knowledge of the excitation frequency (f) and using the calibration of *figures 4* or *5* we extract the wave vector (k) of the thermal wave. The radii of the three circles are

$$R_i = \frac{\varphi_i}{k}, \quad i \in \{1, 2, 3\}$$

ΔR_i takes a 5 % uncertainty of the phase measurements into accounts. The principle of the method is shown in *figure 6*.

In order to use these results for the localisation of an unknown heat source it is of course better to use the phase of the thermal signal than the amplitude, to determine the

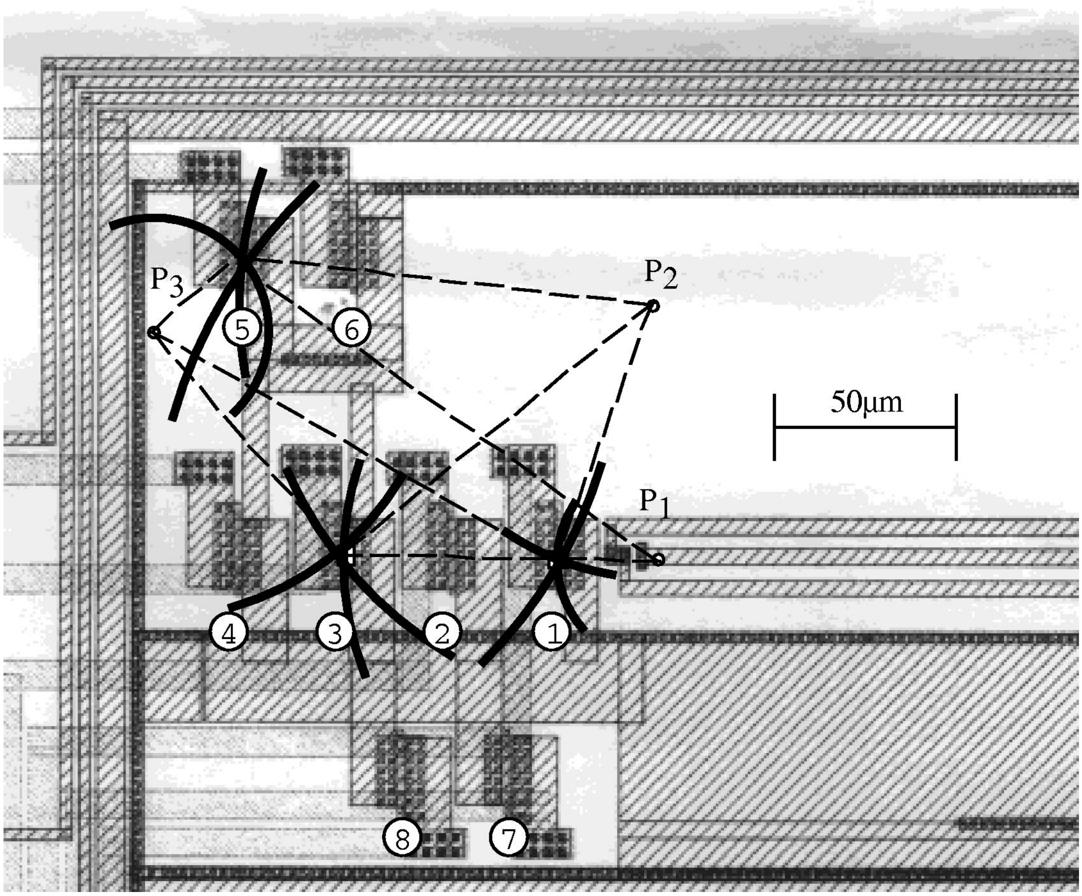

Figure 7. Localisation of heat sources upon IC.

distance to the heat source, as the phase is independent of the amplitude of the temperature variation at the source. The temperature amplitude of the fault is, of course, not known in a real situation. The triangulation method is, for practical reasons, much faster to detect a hot pot than surface scanning. Moving the laser spot from one point to another and make a measurement takes a few seconds. Three point measurements are incomparably faster than mapping the whole sample.

4. APPLICATION OF THE METHODOLOGY UPON AN IC

The measurements have been performed upon the chip described in *figure 1*. The CAD outline of the region containing the 8 MOS transistors is presented in *figure 7*. The phase shift measurements have been performed on the surface dilatation signals at the points P_1, P_2 and P_3 (*figure 7*). The sources 1, 3 and 5 have been successively supplied. The circles represent the phase shifts converted in metric values using the wave vector from *figure 5*. The width of the tracing represents 5 % uncertainty on the measurement. The activated sources are uniquely localised with a precision of a few micrometers.

5. CONCLUSION

We have demonstrated the possibility of detecting and locating heat sources upon CMOS integrated circuits by laser sensing with a micrometric resolution. This methodology can be applied to the detection of electrical faults in ICs using integrated thermal sensors implemented upon the die. The method we propose is based upon triangulation from three measurements at fixed points. The detection range of defect by surface displacement laser probing is typically of the order of 400 μm. The methodology will further be tested upon fault detection using integrated thermal sensors implemented upon the tested die itself.

On the other hand, the methodology has to be generalised to the case of many sources acting simultaneously. This is under study.

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