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Simultaneous measurement of the thermal conductivity and diffusivity of small size elements: application to the characterization of integrated circuit package samples

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Abstract—A new method for the simultaneous measurement of thermal conductivity and diffusivity, based on the analysis of the amount of heat which penetrates a sample, has been set up. Two metrological systems for integrated circuit package samples have been miniaturized. The first concerns resin samples and the other ceramic samples. A sensitivity analysis has led to the optimization of the process.

1. INTRODUCTION

THIS RESEARCH aims to develop a thermal measurement system for the design and exploitation of miniature electronic components. Except for the flash method, which requires heavy equipment, standard systems do not operate with small sample sizes measuring a few millimetres square and thick. We have chosen to set up a new method allowing the simultaneous measurement of the thermal conductivity and diffusivity of integrated circuit package samples as well as the miniaturization of the measurement devices used. This method concerns thermal insulating elements of the epoxy resin type and also better conductors of the ceramic type. The originality of the principle is that it is based on the analysis of the amount of heat which penetrates the sample. This report presents the method and the main experimental results.

2. THE PRINCIPLE OF THE SIMULTANEOUS MEASUREMENT OF THERMAL CONDUCTIVITY AND DIFFUSIVITY

2.1. *The simplified theoretical model* (*Fig.* 1)

A step cooling process from temperature $\theta_2(0)$ to $\theta_2(\infty)$ is carried out upon the cold side of the sample S initially penetrated by a heat flow P_1. The heat flow introduced from the hot side is therefore automatically controlled during the experiment to maintain its initial temperature θ_1.

The measurement consists of analyzing the change in the amount of heat which penetrates the hot side. A standard calculation gives the heat flow variation

$$\frac{P-P_1}{P_2-P_1} = 1+2\sum_{n=1}^{\infty}(-1)^n\,\mathrm{e}^{-n^2\pi^2(at/e^2)} \qquad (1)$$

where P_1 and P_2 denote its initial and final steady-state values. The integration of P leads to a theoretical expression of the amount of heat Q

$$\frac{Q-Q_1}{Q_2-Q_1} = 1-\frac{e^2}{6at}\left(1+\frac{12}{\pi^2}\sum_{n=1}^{\infty}\frac{(-1)^n}{n^2}\,\mathrm{e}^{-n^2\pi^2(at/e^2)}\right) \qquad (2)$$

in which $Q_1 = P_1 t$ and $Q_2 = P_2 t$. Q is a linear function of t after the transient event and the asymptotic value, Q_∞, is

$$Q_\infty = P_2 t - \frac{e^2}{6a}(P_2-P_1). \qquad (3)$$

The value of t_0, the point of the time axis which intercepts Q_∞, and the ratio Q_1/Q_2 determine the diffusivity

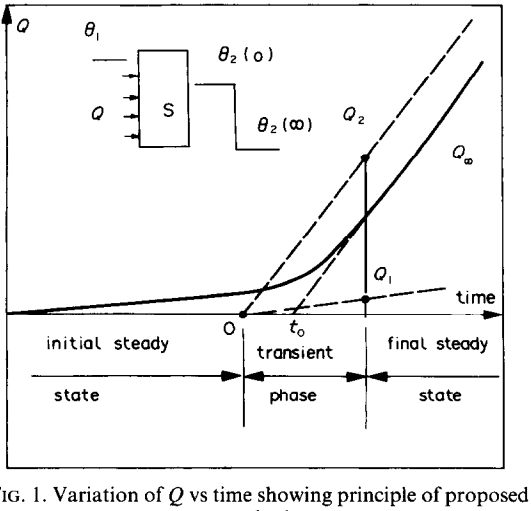

FIG. 1. Variation of Q vs time showing principle of proposed method.

NOMENCLATURE

a	thermal diffusivity, $\lambda/c\rho$	Q	amount of heat
Bi	Biot number, hl/λ	q	heat pulse energy
c	specific heat	R_c	thermal contact resistance
e	sample thickness	Δt	heat pulse duration
h	exchange coefficient	V	voltage.
I	current		
l	sample half square	Greek symbols	
n	pulse number	θ_1	hot side temperature of the sample
$\dot{n}_1$	initial pulse number per second	θ_2	cold side temperature of the sample
$\dot{n}_2$	final pulse number per second	θ_c	cold plate temperature
P	heat flow	θ_H	heating element temperature
P_1	initial heat flow	λ	thermal conductivity
P_2	final heat flow	ρ	density.

$$a = \frac{e^2}{6t_0}\left(1 - \frac{Q_1}{Q_2}\right). \tag{4}$$

The value of conductivity is given by the measurement of Q_2 and by the final temperature difference between the two sides of the sample

$$\lambda = \frac{e}{S}\frac{Q_2}{(\theta_1 - \theta_2(\infty))t}. \tag{5}$$

2.2. *Experimental model* (*Fig.* 2)

The sample S is fitted between an isothermal heating element H and a cold plate C the temperature of which passes from $\theta_c(0)$ to $\theta_c(\infty)$ by means of the successive circulation of two thermostated fluids. A conducting plate B, called the thermal barrier, acting as a guard, envelopes H and is separated from H, by an insulating space. The circulation of a thermostated fluid brings B to θ_B and a heat control system maintains H at this temperature in such a way that $\theta_H = \theta_B$ and $\theta'_H \simeq \theta_B$. The measured amount of heat is that which penetrates the sample.

The temperature deviation supplied by sensors giving θ_B and θ'_H controls the regulating system which synchronizes the emission of a series of short identical heat pulses. The succession of pulse trains has to be compatible with the theoretical model of continuous variation from the initial steady state. It has been shown that this is obtained if the damping of the periodic signal corresponding to the succession of pulse trains is higher than π at one seventh of the sample's thickness. It follows that control parameters must be selected in order to operate in the pulse train frequency range

$$f \geqslant \frac{50}{\pi}\frac{a}{e^2}. \tag{6}$$

If q is the energy of a heat pulse and n, the number of pulses produced between $t = 0$ and t, the dissipated amount of heat is $Q = nq$. The diffusivity measurement is consequently given by an energy ratio equivalent to a pulse number ratio. $\dot{n}_1$ and $\dot{n}_2$ denote the pulse numbers per second during the steady states.

The conductivity measurement requires, on the other hand, an accurate determination of q

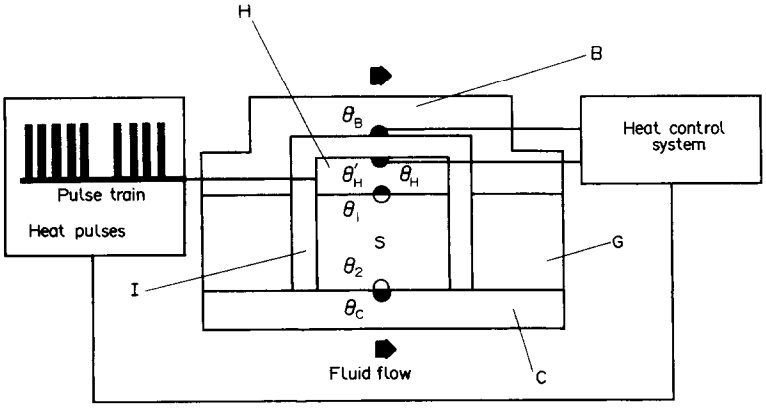

FIG. 2. Experimental model: S, sample; C, cold plate; G, lateral guard; B, thermal barrier; H, heating element; ⏳, location of temperature sensors; I, insulating space.

$$Q_2 = \dot{n}_2 q t. \tag{7}$$

Otherwise, the sample is laterally insulated by means of a soft guard G. It is adapted to the sample's thickness and provides by means of a simultaneous contact with B and C, the same temperature gradient as through the sample.

3. MODIFICATION OF THE THEORETICAL MODEL, DESCRIPTION OF THE METHOD FOR SIMULTANEOUS MEASUREMENT OF THERMAL CONDUCTIVITY AND DIFFUSIVITY

The theoretical model which has been presented to expose the principle of the method is too schematic. It has to be modified to take into account on the one hand, the unavoidable inertia of the cold plate C and, on the other hand, the imperfect contact between the sample and the elements C and H. These two peculiarities imply that the temperature θ_2 upon the cold side of the sample is not subjected to a step variation but to a quick and continuous evolution $\theta_2(t)$ from $\theta_2(0)$ to $\theta_2(\infty)$. The final value $\theta_2(\infty)$ is obtained after a duration corresponding to the end of thermal stability of the plate C. This duration is short but not always negligible compared to the time constant of the sample. Likewise, because of contact resistance, the temperature θ_1 upon the hot side of the sample evolves slightly with time. The recording of the temperature difference $\delta\theta(t) = \theta_1 - \theta_2$ and the use of Duhamel's theorem allow to take into account these overall variations and lead to the corrected expression giving heat flow

$$\frac{P-P_1}{P_2-P_1} = \Delta\theta + 2\sum_{n=1}^{\infty}(-1)^n \int_0^t e^{-n^2\pi^2(a(t-\tau))/e^2} \frac{d(\Delta\theta)}{d\tau} d\tau \tag{8}$$

where

$$\Delta\theta = \frac{\delta\theta(0)-\delta\theta(t)}{\delta\theta(0)-\delta\theta(\infty)}.$$

The corrected expression of the amount of heat Q may be deduced, by integration in relation to t

$$Q = P_1 t - (P_2-P_1)\int_0^t \Delta\theta\, d\tau - (P_2-P_1)\frac{e^2}{6a}\Delta\theta - 2(P_2-P_1)\sum_{n=1}^{\infty}(-1)^n \frac{e^2}{n^2\pi^2}\int_0^t e^{-n^2\pi^2(a(t-\tau)/e^2)} \times \frac{d(\Delta\theta)}{d\tau} d\tau. \tag{9}$$

The new asymptotic value Q_∞ becomes

$$Q_\infty = P_2 t - (P_2-P_1)\left(\frac{e^2}{6a} + t_c\right) \tag{10}$$

where t_c is a parameter which possesses time dimension and which is linked to the evolution of $(\theta_1-\theta_2)$ by the relation (Fig. 3)

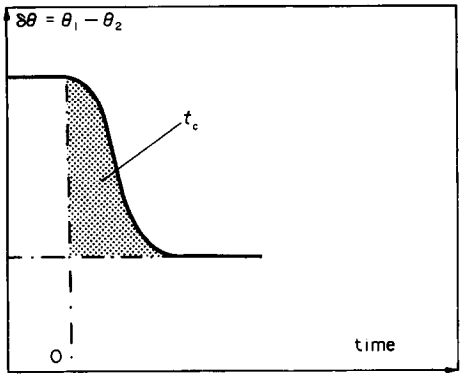

FIG. 3. Representation of the parameter t_c.

$$t_c = \int_0^\infty (1-\Delta\theta)\, dt. \tag{11}$$

The evaluation of t_c from experimental curves $\delta\theta(t)$ added to the time t_0, the point intersecting Q_∞ on the t-axis, and Q_1/Q_2 measurement give the new expression of diffusivity

$$a = \frac{e^2}{6\left(\dfrac{t_0}{1-Q_1/Q_2} - t_c\right)}. \tag{12}$$

This new model takes into account the inertia of the plate C and makes the determination of contact resistance between the sample and elements H and C unnecessary. This means that sensors must be implanted on each side of the sample. This requirement constitutes obviously an important drawback because the implantation is difficult.

If the approximate value of R_c is known and if, furthermore, $\lambda R_c/e \ll 0.04$ then, this implantation may be avoided. The direct measurement of the temperature differences of plates H and C allows the determination of λ and a by the following approximate relations:

$$a = \frac{e^2}{6\left(\dfrac{t_0}{1-Q_1/Q_2} - t_c'\right)}\left(1+4\frac{\lambda R_c}{e}\right) \tag{13a}$$

$$\lambda = \frac{e}{S}\frac{Q_2}{(\theta_H-\theta_c(\infty))t}\left(1+2\frac{\lambda R_c}{e}\right) \tag{13b}$$

where t_c' is a parameter similar to t_c, based on the difference $\delta\theta_{Hc} = \theta_H - \theta_c$ between the surface temperature of plates H and C.

This approximation is even more appropriate when the samples have a high internal resistance (epoxy resin for example) and when the contact resistances are weak.

One of the means to reduce these resistances is to

Table 1.

	Minimal value	Maximal value
2 mm square	10^{-5}	3×10^{-5}
12 mm square	5×10^{-5}	8×10^{-5}

ensure the planeness of the sample's sides and to use whenever possible a fluid or a conducting grease to improve the contact. An estimation of R_c may be thus obtained using the relation

$$R_c = \frac{0.7(\sigma_1+\sigma_2)}{\lambda_g} \quad (14)$$

where σ_1 and σ_2 are r.m.s. roughnesses of surfaces and λ_g the conductivity of grease. Table 1 gives some approximate values of R_c (in m^2 K W^{-1}).

4. EXPERIMENTAL ARRANGEMENTS (FIG. 4)

The experimental arrangement consists of a test device in which the sample is fitted, a heat control system with a stabilized power supply, a data acquisition and calculation processing system. In addition, two hydraulic valves are associated with two water flow thermostats, regulated at ±0.02°C, to carry out the temperature step.

The sample must be taken from the largest dimension of the package of the electronic component which is tested. There are two sorts of samples. The insulating epoxy resin type are flat and thin (1–3 mm thick). The conducting ceramic type are lengthened with small sections (4–10 mm^2).

Two miniature devices have been thus designed. A first device has been studied for samples of 12 mm square, the thermal gradient being established across the thickness. The second device has been provided for samples of 2 mm square, the thermal gradient being established across the length.

4.1. *Test device*

The heating element of the first device (resin samples) is an electrical resistance held in contact with B by means of an insulating ring. The heating element of the second device (ceramic sample) is a diode fitted between two copper elements. A cavity allows the embedding of the sample. A guide holds each component in position. A good contact pressure is obtained by compression of an alveolar material by means of a screw. The position of the crushing ensures the contact reproducibility.

The devices comprise four K thermocouples inserted on the surfaces of the conducting plates. In the case of important contact resistances, a thermoelectric element is mounted over the sample sides.

4.2. *Heat control system*

A generator and assembly unit produces a series of pulses by means of an 8 MHz quartz oscillator. Pulses are identical and reach their peak values after 15 ns. The differential voltage of thermocouples giving ($\theta_B=\theta'_H$) controls a logic gate which synchronizes the emission. An amplifier raises the output voltage level. The system can set and measure the heat pulse amplitude. It is possible to select its duration and that of

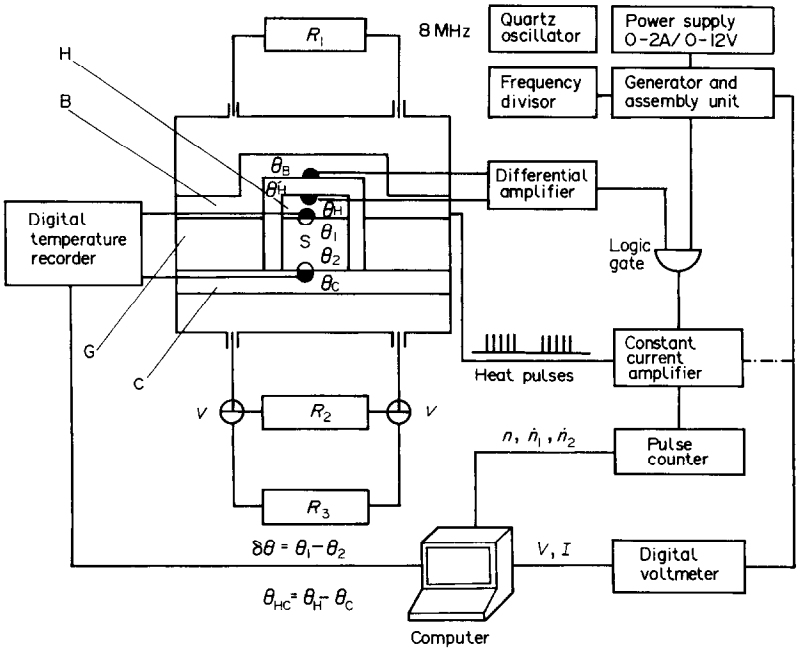

FIG. 4. Experimental arrangement.

the two successive emissions with a 200 μs step. If the pulse duration is Δt, its energy is $q = VI\Delta t$.

4.3. *Data acquisition and processing system*

It is composed of a temperature recorder for $\delta\theta = \theta_1 - \theta_2$ or $\delta\theta_{Hc} = \theta_H - \theta_c$ measurements, a pulse counter, a digital voltmeter for V and I measurements. Data are transmitted and processed on a computer.

5. OPTIMIZATION AND ACCURACY OF THE SIMULTANEOUS MEASUREMENT

5.1. *Optimization of the diffusivity measurement*

For extremely thin samples a few hundred micrometres thick, the temperature variations lead to a weaker sensitivity. In this case, the measurement of diffusivity carried out on the transient part of Q, which precedes the asymptotic phase, is more accurate. This is achieved by identifying experimental and theoretical curves, over the part $0.10 < (Q-Q_1)/(Q_2-Q_1) < 0.17$. The diffusivity value that minimizes the quadratic deviation $\|Q-Q_{measured}\|^2$ by an iterative method of the Newton–Gauss type is calculated. An initial value a_0 taken from the simplified model of Section 1 ensures rapid convergence. For example, the time measurement $t_{0.5}$ corresponding to half down variation of the heat flow and for which $(Q-Q_1)/(Q_2-Q_1) = 0.168$ gives directly

$$a_0 = 0.139\frac{e^2}{t_{0.5}}. \tag{15}$$

5.2. *Optimization of the samples for a conductivity measurement (Figs. 5–7)*

Because of imperfection of the guard systems, the temperature distribution within the sample is never strictly one-dimensional. The analysis of the difference between heat flow P dissipated in the sample and its theoretical value, denoted by P_0, necessary to maintain the same temperature difference, assuming there is no heat loss, allows the definition of the thickness compatible with an accurate λ measurement. The conduction and radiation transfer between the sample and its lateral guard is characterized by an exchange coefficient h. In the least favorable case, the guard temperature is considered uniform, equal to $(\theta_1+\theta_2)/2$.† The resolution of the heat conduction equation gives for a sample of $2l$ square

$$\frac{P-P_0}{P_0} = -1+2\frac{e}{l}Bi^4\sum_{n=1}^{\infty}\sum_{m=1}^{\infty} \times \frac{\sqrt{(u_n^2+u_m^2)}\left[\cosh\left(\frac{e}{l}\sqrt{(u_n^2+u_m^2)}\right)-1\right]}{(u_n^2+u_n+Bi)(u_m^2+u_m+Bi)u_n^2u_m^2\sinh\left(\frac{e}{l}\sqrt{(u_n^2+u_m^2)}\right)} \tag{16}$$

† In reality the temperature distribution in the guard follows a continuous variation from temperature θ_B to θ_C.

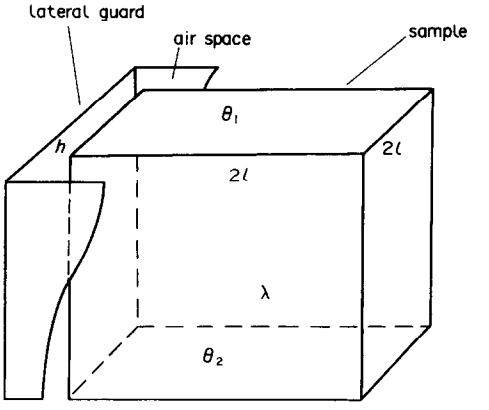

FIG. 5. Heat transfer between the sample and its lateral guard.

where u_n and u_m are roots of $u\tan u = Bi$ with $Bi = hl/\lambda$. Figures 6 and 7 allow the definition of sample sizes.

These calculations show that:

(a) for insulating samples, the semi-empirical approximate relation

$$\frac{P-P_0}{P_0} = 0.16\left(\frac{e}{l}\right)^2 Bi \tag{17}$$

permits the direct determination of thickness;

(b) for conductor samples, a rod model leads to an approximate expression which is slightly more complicated than the preceding relation and in which $(P-P)/P_0$ is expressed as a function of $(e/l)\sqrt{(Bi)}$. For $(P-P_0)/P_0 < 1\%$, limit values of thickness thus deduced are given as a function of λ in Table 2.

5.3. *Accuracy of simultaneous measurement*

Beyond bias introduces by deviation between experimental and theoretical model, accuracy of measurement is mainly related to random errors from the various parameters which occur. It may be shown that uncertainty on the measurement of a is given approximately by the expression

$$\frac{\Delta a}{a} \simeq 2\frac{\Delta e}{e} + \frac{Pt}{Pt-Q}\frac{\Delta t}{t} + 2\frac{Q}{Pt-Q}\frac{\Delta n}{n} + \frac{6a}{e^2}\int_0^t (1-\Delta\theta)\,\mathrm{d}\tau\frac{\Delta t_i}{t_i} \tag{18}$$

in which $\Delta n/n$ is the uncertainty of pulse count and $\Delta t_i/t_i$ the uncertainty from integration of the surface delimited by the temperature differences, $\delta\theta$ or $\delta\theta_{Hc}$, from 0 to t (Fig. 8).

Examination of each term indicates that optimal experiment is obtained for an initially isothermal sample ($Q_1 = 0$). This is not the case in practice. The first

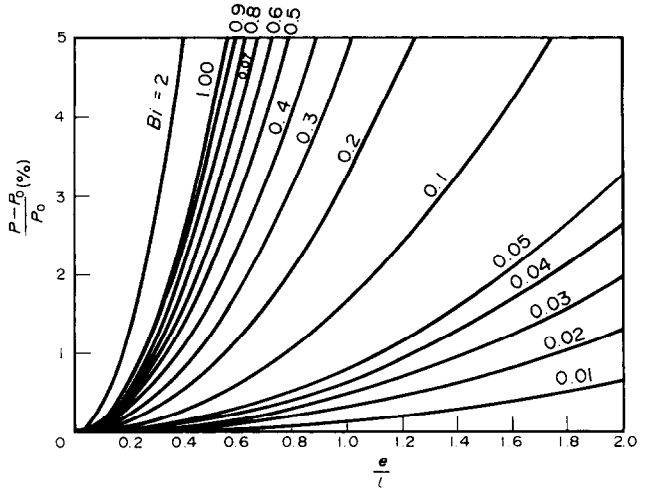

FIG. 6. $(P-P_0)/P_0$ (%) vs e/l for insulating elements of resin type (0.05 W m^{-1} K^{-1} $< \lambda <$ 5 W m^{-1} K^{-1}).

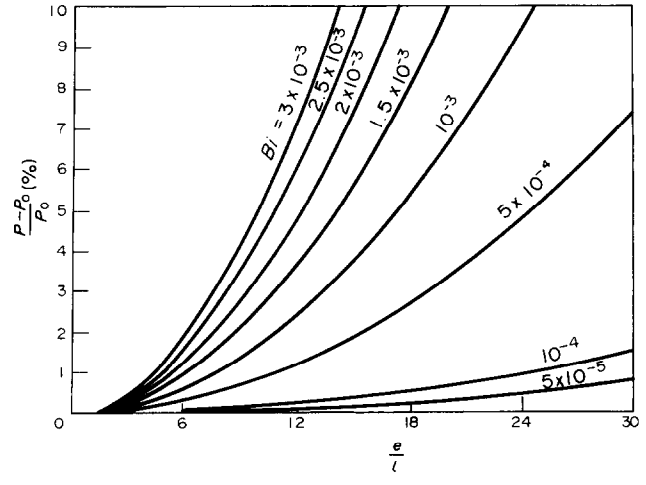

FIG. 7. $(P-P_0)/P_0$ (%) vs e/l for conductor elements of ceramic type (5 W m^{-1} K^{-1} $< \lambda <$ 50 W m^{-1} K^{-1}).

Table 2.

	Square (mm)					
	2	4	6	8	10	12
Conductor sample (mm)	$3.47\sqrt{\lambda}$	$4.9\sqrt{\lambda}$	$6\sqrt{\lambda}$	$6.94\sqrt{\lambda}$		
Insulating sample (mm)		$1.77\sqrt{\lambda}$	$2.16\sqrt{\lambda}$	$2.5\sqrt{\lambda}$	$2.79\sqrt{\lambda}$	$3.15\sqrt{\lambda}$

λ in W m^{-1} K^{-1}.

emissions of the pulse train are as a matter of fact too far apart for compatibility of the experimental signal with the continuous model of the heat flow ensured. To enable better conditions and if it is possible, the measurement is made with a low Q_1/Q_2 (of the order of 0.1) ensuring the correct pulse train frequency during the initial phase. It is the reason why it is worthwhile to use pulses as short as possible.

The uncertainties of $\Delta n/n$ and $\Delta t/t$ are low (of the order of 0.1%) compared to $\Delta e/e$ and $\Delta t_i/t_i$. It may be ensured $\Delta e/e \simeq 1\%$. To reduce $\Delta t_i/t_i$ requires a large number of data recordings from the temperature differences; accuracy of the numerical integration has to be better than 1%. In addition, a plate C carrying out to a shorter duration of temperature variation than time constant of the sample must be taken. If

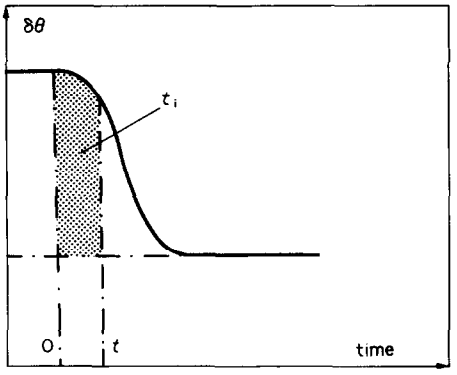

FIG. 8. Representation of t_i parameter.

Table 3. Some experimental results

Material	Plexiglas	Epoxy resin
Thickness (mm)	1.50	1.71
Heat pulse duration (μs)	200	200
q (mJ)	0.135	0.670
$\dot{n}_1$ (s^{-1})	474.5	221.7
$\dot{n}_2$ (s^{-1})	1566.4	835.8
P_2 (mW)	212	560
λ measured ($W\,m^{-1}\,K^{-1}$)	0.20	0.71
a measured ($m^2\,s^{-1}$)	1.13×10^{-7}	0.53×10^{-6}
λ standard ($W\,m^{-1}\,K^{-1}$)	0.19	
a standard ($m^2\,s^{-1}$)	1.1×10^{-7}	

$c'\rho'e'$ indicates the heat capacity of the plate C and h' the exchange coefficient of fluid flow, it may be shown that if $c'\rho'e'/h' \leqslant 0.1(e^2/a)$, the imprecision of the diffusivity measurement is about 3–4%.

The uncertainty of the measurement of λ is mainly due to errors from thickness, temperatures, pulse energy and from defect of the balance between the heating element and its thermal barrier. The precision of the measurement of λ is about 6–7%.

6. EXPERIMENTAL FINDINGS (TABLE 3, FIGS. 9 AND 10)

The heat control system gives a temperature equality of B and H of around ±0.02°C on briefly transient events. Pulse durations of 200 μs have been used. The measurement of Plexiglas material is consistent with its reference characteristics. The results obtained on a package resin and on stainless steel 18/10 (thermal properties similar to ceramic materials) are satisfactory.

The diffusivity measurement on transient and asymptotic states does not show a significant deviation over the thickness range 1–2 mm. Thinner samples should be used to perceive sensitivity differences. The conductivity measurement is sensitive to the pulse train frequencies. The criterion of Section 2 has been checked experimentally. This must be respected in order to eliminate the systematic errors which may exceed 10%. In practice, it is sufficient to scan several pulse durations and amplitudes to find the correct frequency. A pulse count lasting a few minutes during the steady states gives $\dot{n}_1$ and $\dot{n}_2$. It is difficult to obtain $\dot{n}_2$ higher than $5\dot{n}_1$ because of the

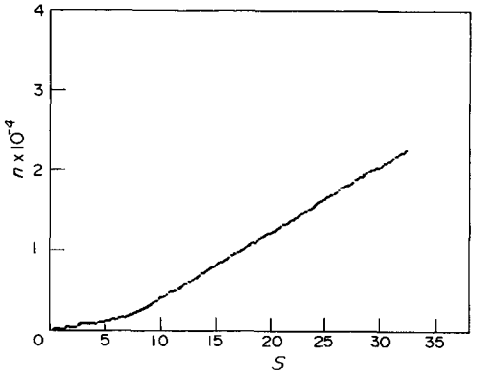

FIG. 10. Pulse number variation on resin sample (t_c = 1.26 s).

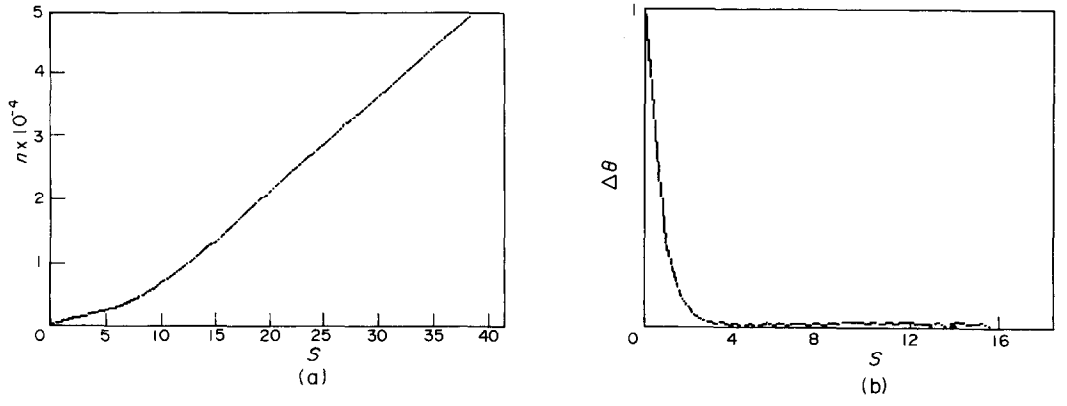

FIG. 9. Variation of pulse number (a) and relative temperature difference (b) on Plexiglas sample (t_c = 0.806 s).

frequency imposed on $\dot{n}_1$ and the final temperature difference which has to be about 5–10°C for measurement of λ. This is the reason why the heat control system has been adapted to cut up the signal into smaller units. In the future, 10 μs pulse durations may be used.

7. CONCLUSION

An original method of simultaneous conductivity and diffusivity measurement, based on the analysis of the amount of heat which penetrates a sample, has been developed. This has allowed the setting up of an efficient heat control system through the generation of short pulses. Its sensitivity and the precision of pulse counting give the diffusivity measurement at 3–4% and the conductivity at 6–7%.

Two measurement devices in accordance with the theoretical model, have been miniaturized for microelectronic component package samples. A sensitivity analysis has led to the optimization of the method. Moreover, this method is suitable for other materials used in electronics such as insulating deposits or substrates several hundred micrometres thick.

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MESURE SIMULTANEE DE LA CONDUCTIVITE ET DE LA DIFFUSIVITE THERMIQUE D'ELEMENTS DE DIMENSIONS REDUITES: APPLICATION A LA CARACTERISATION D'ECHANTILLONS DE BOITIERS DE CIRCUITS INTEGRES

Résumé—Une méthode originale de mesure simultanée de la conductivité et de la diffusivité thermique, fondée sur l'analyse de la quantité de chaleur qui pénètre dans un échantillon, a été mise au point. Deux dispositifs métrologiques pour la caractérisation d'échantillons de boitiers de circuits intégrés ont été miniaturisés. L'un concerne des échantillons de résine, l'autre des échantillons de céramique. Une analyse de sensibilité a conduit à l'optimisation du procédé.

GLEICHZEITIGE MESSUNG DER WÄRMELEITFÄHIGKEIT UND DER TEMPERATURLEITFÄHIGKEIT KLEINER ELEMENTE: ANWENDUNG AUF DIE CHARAKTERISIERUNG VON CHIPS

Zusammenfassung—Es wird ein neues Verfahren zur gleichzeitigen Messung der Wärmeleitfähigkeit und der Temperaturleitfähigkeit vorgeschlagen, das auf der Untersuchung der Wärmemenge beim Durchgang durch eine Probe beruht. Zwei meßtechnische Systeme für integrierte Schaltkreisanordnungen wurden miniaturisiert. Das erste besteht aus Harz, das zweite aus Keramik. Eine Untersuchung der Empfindlichkeit hat zu einer Optimierung des Prozesses geführt.

ОДНОВРЕМЕННОЕ ИЗМЕРЕНИЕ ТЕПЛОПРОВОДНОСТИ И ТЕМПЕРАТУРОПРОВОДНОСТИ ЭЛЕМЕНТОВ МАЛОГО РАЗМЕРА: ИСПОЛЬЗОВАНИЕ ДЛЯ ОПРЕДЕЛЕНИЯ ХАРАКТЕРИСТИК ОБРАЗЦОВ ПАКЕТОВ ИНТЕГРАЛЬНЫХ СХЕМ

Аннотация—Разработан новый способ одновременного измерения тепло- и температуропроводности на основе анализа количества тепла, поступающего в образец. Изготовлены две миниатюрные метрологические системы, применяемые в образцах пакетов интегральных схем. Первая система используется для смол, а вторая—для керамических образцов. Осуществлена оптимизация процесса измерения.