Infrared Physics & Technology 73 (2015) 130–140

Contents lists available at ScienceDirect

Infrared Physics & Technology

journal homepage: www.elsevier.com/locate/infrared

Infrared sequence transformation technique for in situ measurement of thermal diffusivity and monitoring of thermal diffusion

Huilong Dong, Boyu Zheng, Feifan Chen *

State Key Laboratory of Precision Measurement Technology and Instrument, Department of Precision Instrument, Tsinghua University, Beijing 100084, PR China

HIGHLIGHTS

- The IRSTT was proposed to perform the in situ measurements of thermal diffusivity.
- The thermal diffusivities were automatically evaluated with DRLSE formulation.
- Measurement results in case of varying excitation incidence angles were reported.
- Thermal diffusions of PCBs were monitored with the calculated peak curve sequences.

ARTICLE INFO

Article history:
Received 30 July 2015
Available online 26 September 2015

Keywords:
Thermal diffusivity
IR sequence transformation
In situ measurement
Angle-adjustable excitation
Thermal diffusing visualization

ABSTRACT

An infrared (IR) sequence transformation technique for visualization of thermal diffusion process and in situ measurement of radial thermal diffusivity is reported. It consists of heating the sample surface instantaneously by an angle-adjustable Gaussian beam and recording the temperature evolution by an IR camera. Compared to common techniques requiring the excitation beam to be fixed approximately perpendicular to the measurement surface, the proposed method allows a dynamic adjustment of the excitation incidence angle according to the actual operating space, which contributes to a fast and efficient in situ measurement approach. To achieve this, a new heat transfer model considering the elliptical distortion of the Gaussian beam caused by tilted incidence is established. Through decoupling analysis it is discovered that the area s surrounded by the maximum temperature curve $r_{Tmax}(\theta)$ grows linearly over time. The thermal diffusivity can be obtained from the growth rate at any incidence angle. Based on this s-time relation, an automatic thermal diffusivity characterization framework which involves extracting the $r_{Tmax}(\theta)$ sequence through a distance regularized level set evolution (DRLSE) formulation is proposed. For verification, samples of 304 stainless steel, titanium and zirconium are measured with the excitation incidence angles ranging from 30° to 60°, and the relative deviations from the literature values are -6.28% to 3.27%, -3.22% to 5.79%, and -1.61% to 4.03% respectively. Besides, the thermal diffusion process of two typical printed circuit boards (PCBs) are monitored and analyzed visually with this technique.

1. Introduction

Along with the development of system on chip (SOC) and system in a package (SIP) techniques in the past 15 years, electronic devices are integrated towards microminiaturization. The increasing packaging density leads to a number of engineering application problems, among which the poor heat dissipation performance within limited space is urgent to be solved. The in situ measurement of thermal diffusivity is of great importance for evaluating the heat dissipation performance and guiding thermal structure design. Since the last century, a number of techniques for thermal diffusivity measurements have been developed, among which the periodic methods [1–11] and pulse techniques [12–25] fetch considerable attention for their characteristic advantages.

Among the group of periodic techniques, the photothermal reflectance method [2–7] developed recently features heating the sample surface with a modulated light power. The thermal diffusivity is characterized based on the phase lag – $(\text{frequency})^{1/2}$ relation. Specifically, thermal diffusivity measurements of bulk materials [2], thin films [3], multi-layered structures [4–6] and superconductor [7] using this technique have been reported. Another periodic technique, the frequency modulated thermal wave imaging (FMTWI) method [8–11] proposed more recently has been validated to be effective for measuring the radial thermal

* Corresponding author.
E-mail addresses: donghl11@mails.tsinghua.edu.cn (H. Dong), Zhengby12@mails.tsinghua.edu.cn (B. Zheng), cff@mail.tsinghua.edu.cn (F. Chen).

http://dx.doi.org/10.1016/j.infrared.2015.09.021
1350-4495/

diffusivity of extremely thin samples and anisotropic structures. The thermal diffusivity is obtained from the phase images of the whole measurement surface instead of one fixed point. Moreover, the measurement time consumption can be reduced effectively by using a chirp excitation signal instead of frequency scan [8].

On the other side, pulse techniques are also widely used for fast and simple measurements. Specifically, Parker's flash method [12] measures the axial thermal diffusivity by heating the front surface of a sample instantaneously and extracting the maximum temperature time of the rear surface. It has been widely utilized in the past several decades [13–15], and has been developed to measure the radial thermal diffusivity [16–21]. As the IR thermography with high resolution and frame frequency has been developing rapidly, the full-filed temperature can be recorded instead of one-point temperature. The thermographic technique presented by Cernuschi et al. [22], which consists of heating the sample surface with a pulsed Gaussian beam and detecting the temperature field with an IR camera, can measure the in-plane thermal diffusivity of solids. The high-precision thermal diffusivity is obtained from the time-varying temperature spatial distribution [22,23].

For most of these conventional methods, the heat source is assumed as circular in their theoretical models. On account of this, the excitation beam always needs fixed to be perpendicular [2,16–22,24] or at a narrow incidence angle [25] to the sample surface. The tilted excitation beam produces an elliptical heat source on the measurement surface, in which case more error sources might be introduced [24]. So far, few reports about the measurement results in case of varying excitation incidence angles have been published.

In this proposed IR sequence transformation technique, the excitation beam incidence angle can be dynamically adjusted according to the actual measurement space without introducing the system error. An active in situ measurement system can be rapidly assembled by placing the angle-adjustable excitation source on the same side of the temperature detector. (Such configuration is known as the front face technique in Ref. [24]). To achieve this, a new theoretical model is established considering the elliptical distortion of the excitation beam caused by non-perpendicular incidence. From this model, the area surrounded by the maximum temperature curve $r_{Tmax}(\theta)$ is discovered to grow linearly over time. The thermal diffusivity can be characterized by the area growth rate at any incidence angle. Furthermore, a $r_{Tmax}(\theta)$ sequence can also be obtained, providing a visualized method to monitor the thermal diffusion process and heat flow distribution. For verification, both isotropic and anisotropic samples are measured, and the measurement results at different excitation incidence angles are discussed in detail.

2. Theory

Before we establish the heat transfer model in case of varying incidence angles, an ideal model with the Gaussian beam fixed perpendicular to the sample surface is discussed. As in Fig. 1(a), assuming that an isotropic and homogenous thin-film sample is irradiated by an instantaneous laser beam with circular Gaussian intensity distribution, the temperature filed evolution can be described by a simplified two-dimensional heat conduction equation in the polar coordinate system:

$$\frac{1}{\alpha}\frac{\partial T(r,\theta,t)}{\partial t}=\frac{\partial^2 T(r,\theta,t)}{\partial r^2}+\frac{1}{r}\frac{\partial T(r,\theta,t)}{\partial r}+\frac{1}{r^2}\frac{\partial^2 T(r,\theta,t)}{\partial \theta^2} \tag{1}$$

where α is the thermal diffusivity, T is the temperature, t is the time, r and θ are the radial distance and polar angle respectively. The Gaussian heat source center is set as the coordinate origin, then the corresponding boundary condition of Eq. (1) can be expressed as:

$$T(r,t)|_{t=0}=\frac{2Q}{\pi\rho c L R_C^2}\exp\left(\frac{-2r^2}{R_C^2}\right) \tag{2}$$

where R_C is the radius of the Gaussian laser beam (defined as the distance at which the beam intensity reduces by a factor of $1/e^2$), ρ is the density, c is the specific heat capacity, L is the thickness, and Q is the total energy absorbed by the sample. Eq. (1) coupled with the boundary condition of Eq. (2) can be satisfied by the solution form of:

$$T(r,t)=\frac{Q}{\pi\rho c L}\frac{1}{0.5R_C^2+4\alpha t}\exp\left(-\frac{r^2}{0.5R_C^2+4\alpha t}\right) \tag{3}$$

Eq. (3) describes the temperature field evolution after perpendicular Gaussian beam heating. As the shape of Gaussian beam's projection on the sample surface is circular (see Fig. 1(a)), the temperature response is clearly independent of the angular coordinate θ.

Actually, a flexible in situ measurement system requires the temperature detector and the heat source to be located on the same side of the sample. Therefore the Gaussian beam is necessitated to be non-perpendicular to the sample surface and the incidence angle has an adjustable range correspondingly, as shown in Fig. 1(b). As a result of non-perpendicular incidence, the projection shape is ellipse instead of circle. Specifically, the boundary condition of Eq. (1) for tilted Gaussian beam heating can be expressed as follows:

$$T(r,\theta,t)|_{t=0}=\frac{2Q\cos\varphi}{\pi\rho c L R_C^2}\exp\left[\frac{-2r^2}{R_E(\theta)^2}\right] \tag{4}$$

where

$$R_E(\theta)=\frac{R_C}{\sqrt{\cos^2\varphi\cos^2\theta+\sin^2\theta}} \tag{5}$$

and φ is the incidence angle of the Gaussian beam. Seen from the boundary condition Eq. (4), the initial temperature field distribution is a binary function with variables of r and θ, indicating that the temperature field varies with both r and θ. It is difficult to solve the 2D heat conduction equation Eq. (1) coupled with Eq. (4) directly. Nevertheless, it can be seen that Eq. (4) shows the same function form as Eq. (2), except the Gaussian beam radius item $R_E(\theta)$ in $\exp\left[-2r^2/R_E(\theta)^2\right]$. Introduce $R_E(\theta)$ to correct the Gaussian index item of Eq. (3), and then the solution of Eq. (1) bounded by Eq. (4) can be estimated as follows:

$$T(r,\theta,t)\approx\frac{Q\cos\varphi}{\pi\rho c L}\frac{1}{0.5R_C^2+4\alpha t}\times\exp\left[-\frac{r^2}{0.5\left(R_C\Big/\sqrt{\cos^2\varphi\cos^2\theta+\sin^2\theta}\right)^2+4\alpha t}\right] \tag{6}$$

Different from Eqs. (3) and (6) describes the temperature filed evolution after instantaneous Gaussian beam heating with a variable incidence angle of $\varphi(0^\circ\leqslant\varphi<90^\circ)$. It is noteworthy that by substituting $\varphi=0$ into Eq. (6), function $T(r,\theta,t)$ will be simplified to Eq. (3).

Fig. 2(a) and (b) shows the computed temperature fields at $t=0.05$ s and $t=0.5$ s respectively. Here $T(r,\theta,t)$ is computed by fixing $\varphi=46^\circ, \alpha=9.32\times10^{-6}\ \mathrm{m^2\ s^{-1}}, \rho=4500\ \mathrm{kg/m^3}, c=522$