Available online at www.sciencedirect.com

SCIENCE DIRECT®

International Journal of Heat and Mass Transfer 47 (2004) 3233–3244

International Journal of HEAT and MASS TRANSFER

www.elsevier.com/locate/ijhmt

Performance analysis of the transient thermo-reflectance method for measuring the thermal conductivity of single layer materials

Pavel L. Komarov, Peter E. Raad *

Department of Mechanical Engineering, Southern Methodist University, Dallas, TX 75275-0337, USA

Received 17 October 2003; received in revised form 6 February 2004
Available online 16 March 2004

Abstract

This work shows that the Fourier number (*Fo*) defines the shape and amplitude of the thermal response of a semi-infinite layer sample. The introduction of the responsivity, Rs, of the TTR method provides the ability to assess the performance of the thermal conductivity measurements. A simplified heat transfer analysis of a finite layer sample revealed that the properties ratio, $(\rho C_p K)_S/(\rho C_p K)_L$, and the layer thickness, h/δ_P, uniquely define both temperature response and measurement responsivity. If the material under test is the substrate, this work can help improve the measurement accuracy by selecting the appropriate thickness of the top layer. If the material is a layer on top of a known substrate, this work suggests that the accuracy of the TTR measurements can be fully maximized.

Keywords: Transient thermo-reflectance; Thermal conductivity measurements; Uncertainty minimization; TTR performance

1. Introduction

The high rate of innovation in the electronics and telecommunications fields has raised expectations for increased performance and functionality. Most advances have evolved from smart engineering and efficient manufacturing practices. Equally substantial gains, however, can be made from the introduction of innovative materials. Indeed, miniaturization and performance requirements have forced the use of existing materials beyond initially envisioned ranges and have spurred the development of special materials [1]. Knowledge of material properties is fundamental to the design process, especially for electronic and telecommunication devices, where performance depends heavily on electro-thermal interactions.

Higher performance is only possible by significant reductions in the size of active features, which in turn can increase heat generation densities to critical levels. With the use of submicron devices came the realization that bulk and thin-film thermal properties differ markedly [2]. However, since no universal behavior is expected for these differences and since they cannot be predicted from theory [3], the properties of each material must be measured individually. Also, as films are typically layered and deposition techniques differ by manufacturer, it is important to measure the interface resistance of stacked layers [4].

The transient thermo-reflectance method (TTR) [5] is preferred among the various experimental techniques [6] used to determine the thermal conductivity of thin-film and multi-layered materials. The main advantage of the TTR method is that it is a non-contact and non-destructive optical approach, both for heating a sample under test and for probing the variations of its surface temperature [7]. Because the method is non-invasive, it is attractive for the measurement of the thermal properties of thin-layer materials whose investigation by invasive

* Corresponding author. Tel.: +1-214-768-3043; fax: +1-214-768-4998.

E-mail addresses: pavel@engr.smu.edu (P.L. Komarov), praad@smu.edu, praad@mail.smu.edu (P.E. Raad).

0017-9310/$ - see front matter © 2004 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ijheatmasstransfer.2004.02.006

Nomenclature

Fo	Fourier number, $Fo = \alpha\tau/\delta_\lambda^2$
F	fluence of heating laser irradiation
h	thickness of a layer
h^*	minimal thickness of a *semi-infinite* layer
$I(t)$	heating irradiation intensity, Eq. (3)
k	extinction coefficient of a sample material
K	thermal conductivity of a sample material
$Q_{ab}(z,t)$	laser energy absorbed by a sample
R	reflectivity of a sample surface
Rs	responsivity of the TTR measurement of K
t	time
t_0	time at which heating laser intensity reaches its maximum value
T	non-dimensional time, $T = t/\tau$
$T_{0.1}(a)$	non-dimensional time at which $\widetilde{\Theta} = 0.1$
z	coordinate that is normal to a sample surface
Z	non-dimensional coordinate, $Z = z/\delta_\lambda$

Greek symbols

α	thermal diffusivity of a sample material, $\alpha = K/(\rho C_p)$
γ	absorption coefficient of a sample material, $\gamma = 4\pi k/\lambda$
δ_λ	light penetration depth of a heating laser, $\delta_\lambda = 1/\gamma$
δ_P	heat penetration depth during a cycle of heating laser pulse, $\delta_P = \sqrt{\alpha\tau}$
δ_H	heat penetration depth of the laser pulse energy into a sample while $\widetilde{\Theta} \geqslant 0.1$
Φ	ratio of substrate and layer material properties, $\Phi = (\rho C_p K)_S/(\rho C_p K)_L$
θ	temperature of a sample
θ^*	reference temperature, $\theta^* = F/(\rho C_p \delta_\lambda)$
Θ	non-dimensional temperature of a sample, $\Theta(Z,T) = \theta(Z,T)/\theta^*$
$\widetilde{\Theta}$	normalized temperature of a sample surface, $\widetilde{\Theta}(T) = \Theta(0,T)/\Theta_{max}$
λ	wavelength of a heating laser
ρC_p	specific heat of a sample material
σ_{Fo}	measurement uncertainty of Fo number
$\sigma_{\widetilde{\Theta}}$	measurement uncertainty of a normalized temperature
τ	pulse width of a heating laser

methods would present the difficulties of having to fabricate a measuring device into a sample, and then having to isolate and exclude the influence of the measuring device itself.

The basic principle of the transient thermal reflectance method is to heat a sample by laser irradiation and probe the changes in the surface reflectivity of the heated material. The schematic in Fig. 1(a) depicts the square heating and round probing spots produced by the TTR system built by the authors at SMU (http://engr.smu.edu/netsl). The source of energy in the TTR method is normally provided by a pulsed laser with short pulse duration. During each pulse, a given volume on the sample surface heats up to a temperature level above ambient due to the laser light energy absorbed into the sample. The heating area is specified by adjusting the pulsing laser aperture and the optics of the system. The depth of the volumetric heating, on the other hand, is determined by the optical penetration depth, which is a function of laser wavelength and surface material properties. The heating level through the light penetration depth (δ_λ) obeys an exponential decay law, as described later. After each laser pulse is completed, the sample begins to cool down to the initial ambient temperature. During this process, the probing CW laser light reflected from the sample surface at the heating spot center (probing spot in Fig. 1(a)) is collected on a

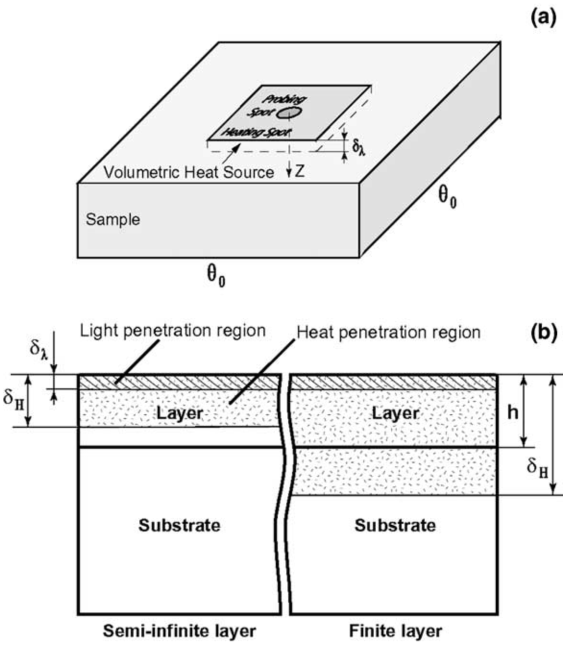

Fig. 1. Problem geometry and important parameters: (a) heating and probing spots on a sample; and (b) different heat penetration depths imply either semi-infinite or finite layer behavior.