International Journal of Heat and Mass Transfer 52 (2009) 4302–4307

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Effective thermal parameters of layered films: An application to pulsed photothermal techniques

Yu.G. Gurevich, I. Lashkevich, G. Gonzalez de la Cruz *

Departamento de Física, Centro de Investigación y de Estudios Avanzados del IPN, Apartado Postal 14-740, 07000 México, D.F., Mexico

ARTICLE INFO

Article history:
Received 25 September 2008
Accepted 31 March 2009
Available online 22 May 2009

Keywords:
Laser pulse
Heat diffusion
Thermal parameters
Layered-system

ABSTRACT

Pulsed photothermal techniques provide useful methods based on linear relations between measurable quantities to obtain the thermal diffusivity and thermal conductivity of homogeneous materials. In this work, the effective thermal parameters of two-layered films are defined starting from an homogeneous layer which at the surfaces, produces the same temperature fluctuations and the same photothermal signal that the composite heated by a fast pulse-laser. Our theoretical model predicts that the effective thermal parameters of the layered system can only be calculated in the limit when the laser pulse duration is smaller tan the characteristic time of each layer, respectively. The temperature distribution is calculated in each layer by using the Fourier integral and the time-dependent one-dimensional heat diffusion equation with appropriate boundary conditions according to the experimental conditions. Within this approximation, we found an analytical expression for both, the effective thermal diffusivity and thermal conductivity which depend significantly on the thickness and the thermal parameters of each film.

1. Introduction

The measurement of thin film thermal conductivities and thermal diffusivities is a long standing problem in many areas of physics and engineering. As one example, we mention the interest in thermal parameters of dielectric thin film materials used for optical coatings. Another important field of interest is films used in thermal management applications with semiconductor circuits. Such measurements also gained a tremendous interest in connection with the development of thin film diamond-like materials promising excellent thermal properties [1].

The methods used to measure the thermal conductivity are divided in two groups: the steady-state and the nonsteady-state methods. In the first one, the sample is subjected to a constant heat flow and the thermal conductivity (κ) is directly measured after equilibrium has been reached. In the second group, a periodic or transient heat flow is established in the sample and the thermal conductivity is not directly measured yet, but the thermal diffusivity (α). In the case of homogeneous samples, the thermal conductivity is then calculated from the thermal diffusivity.

On the other hand, the determination of effective properties, such as thermal, elastic, dielectric etc., of inhomogeneous systems has long been an important research subject since these effective properties are critical in design and control parameters for successful applications of the inhomogeneous system. Basically, the effective properties are a function of the constituent properties, interfacial characteristics between the different materials of the composite, volume fractions and microstructure of the system. Here, microstructure means the shape, size orientation and spatial distribution of the inclusions.

In particular, layered films are used in numerous devices such as micro-electronic elements, thin-film superconductors, reactor walls and numerous other applications. In recent years, engineers and physicists have paid more attention to the technologies related with thin films because micro-electromechanical systems are required in various applications. At the same time, due to the advanced of short-pulse laser technologies and their application to modern microfabrication technologies, ultrashort pulse heating of thin film structures has been developed rapidly. For example, transient thermoreflectance, photothermal deflection, photoacoustic and optical heating and electrical thermal sensing methods have been well developed to measure thermal properties of thin films [2]. At present, the microfabricated devices method [3] and the 3ω method [4] are the main measurement techniques to obtain thermophysical properties of materials in such low dimensions and small scales.

In recent years, there has been some interest in the thermal characterization of two-layer systems using photothermal techniques. From the analogy between thermal and electrical resistances used in heat transfer problems, Manzanares et al. [5] calculated the effective thermal diffusivity of the two-layer system as a function of the filling fraction of the composite system, the

* Corresponding author.
E-mail address: bato@fis.cinvestav.mx (G. Gonzalez de la Cruz).

0017-9310/$ - see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ijheatmasstransfer.2009.03.068

Nomenclature

c	heat capacity per unit mass, J/Kg K	*Greek*	
d	thickness of one layer, m	α	thermal diffusivity, m^2/s
d_i	thickness of the i layer, m	κ	thermal conductivity, W/m K
I_0	intensity of incident laser radiation, J/m^2t	ρ	density, Kg/m^3
$Q(z,t)$	heat flux W/m^2	τ	laser pulse time duration, s
t	time, s	ω	frequency, s^{-1}
$T(z,t)$	temperature distribution, K		
z	coordinate direction, m		

thermal diffusivities and the ratio of the thermal conductivities of each layer. More recently, the effective thermal diffusivity and conductivity of layered systems have been analyzed solving the one-dimensional heat diffusion equation for each layer with appropriate boundary conditions at the interface and at the surface of the composite according the photothermal experiments. Then, the effective parameters of the inhomogeneous system were calculated from an homogeneous material, with the same boundary conditions at the surface, which produce the same physical response under an external perturbation in the detector device [6,7]. These effective parameters, of course, depend strongly on the experimental set up and how they are measured. For example in photoacoustic experiments, depending on the position of the microphone there are two possible detection configuration: the microphone is at the front of the illuminated surface (close cell configuration) or it is at the rear opposite surface (open cell configuration). Thus, according to this consideration, the value of the effective parameters of the composite are not unique but depend on the experimental configuration [7].

In this paper, we present a theoretical investigation of transient heat transport in one and two layers for different laser pulse duration time τ. It is important to emphasize that in the theoretical models and photothermal experiments mentioned in Refs. [5–7], the incident laser radiation is periodically modulated by a chopper for different frequencies.

In order to obtain the effective thermal parameters, the heat diffusion equation is solved assuming that the sample is optically opaque, i.e., all the incident light is absorbed at the surface of the sample. The effective thermal parameters can be determinated by using the same boundary conditions for both, the one and two-layer samples according to the photothermal experiment and forcing the temperature fluctuation of the one (homogeneous sample) and two-layers be equal at the front and rear surfaces. We show that the effective thermal diffusivity and thermal conductivity obtained from the front-surface illumination and the rear-surface are different, the temperature fluctuations for one and two-layer systems are the same if the laser pulse duration is smaller than the characteristic time of the layered composite. It is important to mention the in this work the effects of the interface thermal resistance and lagging [8] on the heat transport in the layered systems are neglected. These latter effects, the electron–phonon interaction and carrier diffusion influence will be considered elsewhere. Interfacial thermal resistance has been show that is important in layered systems with structures that varies on the length scale of several nanometers heated by a short laser pulse. The thermal conductance of many solid–solid interfaces have been studied experimentally but the range of observed interface properties is much smaller than predicted by simple theory [9–11].

The results presented in this work show that in general an effective thermal parameters for two-layer systems cannot be defined as in photothermal experiments when the heat diffusion in the composite system is created by a periodic light beam.

2. Theoretical model

It is well known that heat transport in solids is carried out by various quasiparticle systems (electrons, holes, phonons, etc.), the interactions between these quasiparticles are such that each of these systems are describes by their own temperature and the physical conditions at the boundaries of the sample may be formulated separately for each quasiparticle system [12]. However, for small effective cooling length of the quasiparticles systems as compared with the sample dimensions and strong interaction between them, the system of quasiparticles can be described by the single particle approximation and the coupled heat-diffusion equations reduce to the usual diffusion equation [13]. For simplification, we shall consider a sample with the form of parallelepiped. On one of the surface ($z = 0$) there is an incident pulsed laser excitation, the other one at $z = d$ is maintained at constant temperature T_0, and the lateral faces are adiabatically isolated. In this geometry the one-dimensional heat diffusion equation is given as

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

where the thermal diffusivity α is given by $\alpha = \kappa/\rho c$, κ the thermal conductivity ρ the density and c the heat capacity of the sample, respectively.

Let us assume that a rectangular laser pulse with an arbitrary duration τ and intensity I_0 is incident on the surface of a layer sample of thickness d, and thermal parameters α and κ. In addition, we consider for simplicity that the one-layer system is optically opaque, i.e., the total laser radiation is completely absorbed on the surface and converted into heat, see Fig. 1(a). Then, the temperature fluctuations $T(z, t)$ in Eq. (1) should be supplemented by boundary conditions at the surface of the sample and some initial conditions. In transient heat transport experiments, the most common mech-

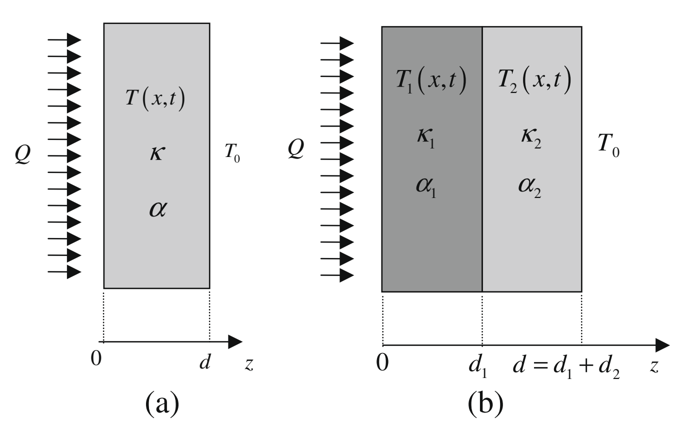

Fig. 1. Geometry for (a) a one-layer system with effective thermal conductivity κ and effective thermal diffusivity α and (b) two-layer system characterized by a thermal conductivity κ_l, and thermal diffusivity α_l for $l = 1,2$.

anism to produce a heat pulse is the absorption by the sample of an intense pulsed laser beam. It is clear that when the intensity of the radiation is fixed, the light-into-heat conversion at the surface of the sample can be written as

$$-\kappa \frac{\partial T(z,t)}{\partial z}\bigg|_{z=0} = Q(t)$$
$$Q(t) = \begin{cases} Q_0 & 0 \leqslant t \leqslant \tau \\ 0 & \tau \leqslant t \leqslant \infty \end{cases} \tag{2}$$
$$T(z,t)|_{t\leqslant 0} = T_0$$
$$T(z,t)|_{z=d} = T_0$$

Here $Q(t)$ is proportional to the incident light intensity, Q_0 = const., and at $z = 0$ describes the temporal form of the heat pulse during the time τ; the surface at $z = d$ remains at the ambient temperature T_0.

In terms of the Fourier integral the heat pulse at the surface of the layer can be expresses as

$$Q(t) = \frac{1}{2\pi}\int_{-\infty}^{\infty} C(\omega,t)d\omega$$
$$C(\omega,t) = \int_{-\infty}^{\infty} e^{i\omega(t-\gamma)}Q(\gamma)d\gamma = \int_{0}^{\tau} e^{i\omega(t-\gamma)}Q_0 d\gamma \tag{3}$$
$$= -\frac{iQ_0}{\omega}(1-e^{-i\omega\tau})e^{i\omega t}$$

The general solution of Eq. (1) for the temperature fluctuation associated with the heat-transient diffusion can be written as

$$T(z,t) = T_0 + \Delta T(z,t) = T_0 + \int_{-\infty}^{\infty}(M(\omega)e^{\sigma z} + N(\omega)e^{-\sigma z}))e^{i\omega t}d\omega \tag{4}$$

with $\sigma = (1+i)\sqrt{\omega/2\alpha}$ and the coefficients $M(\omega)$ and $N(\omega)$ can be found using the boundary conditions defined by Eq. (2). Then finally Eq. (4) is given by

$$T(z,t) = T_0 - \frac{i}{2\pi}\frac{Q_0}{\kappa}\int_{-\infty}^{\infty}\frac{(1-e^{-i\omega\tau})}{\sigma\omega}\frac{\sinh\sigma(d-z)}{\cosh\sigma d}e^{i\omega t}d\omega \tag{5}$$

Once we know the temperature distribution in the sample, we can calculate the response of the layer due to the laser pulse heating using one of the several alternative detection techniques, e.g., 3ω method, time-domain thermoreflectance, scanning thermal microscope and lamp flash.

We now turn to the discussion of the effective parameters of layered systems. Let us consider the physical two-layer system of a material 1 of thickness d_1 and a material 2 of thickness d_2, both having the same cross section (see Fig. 1(b)). Let α_I the thermal diffusivity and κ_I the thermal conductivity of the material I (I = 1, 2). Initially, the sample is at uniform temperature T_0, while the heat flux density distribution is zero. At time $t = 0^+$, there exist a short-pulse at the surface which induce a heat transfer in the layered medium. Furthermore, heat losses from the film surfaces are neglected during the short heating period. The system of heat-diffusion equations describing the heat transfer trough the various layers are given by Eq. (1) for each layer with the following boundary conditions

$$-\kappa_1 \frac{\partial T_1(z,t)}{\partial z}\bigg|_{z=0} = Q(t)$$
$$Q(t) = \begin{cases} Q_0 & 0 \leqslant t \leqslant \tau \\ 0 & \tau \leqslant t \leqslant \infty \end{cases}$$
$$T_1(z,t)|_{z=d_1} = T_2(z,t)|_{z=d_1} \tag{6}$$
$$\kappa_1 \frac{\partial T_1(z,t)}{\partial z}\bigg|_{z=d_1} = \kappa_2 \frac{\partial T_2(z,t)}{\partial z}\bigg|_{z=d_1}$$
$$T_2(z,t)|_{z=d_2} = T_0$$

For simplicity and in order to gain some insight in the physics about the effective thermal parameters of the layered system, the effects of the interface thermal resistance have been neglected in the third equation. The fourth equation represents the continuity of the heat flux at the interface of the two materials (energy conservation).

By solving the heat diffusion equation under the physical condition given by Eqs. (6), we find the complex temperature fluctuation for each layer as

$$T_n(z,t) = T_0 + \int_{-\infty}^{\infty}[M_n(\omega)e^{\sigma_n z} + N_n(\omega)e^{-\sigma_n z}]e^{i\omega t}d\omega,$$
$$\sigma_n = (1+i)\sqrt{\frac{\omega}{2\alpha_n}} \quad n = 1,2 \tag{7}$$

where

$$M_1(\omega) = \frac{i}{2\pi}\frac{Q_0}{\omega\sigma_1\kappa_1}\frac{1-e^{-i\omega\tau}}{D} \times e^{-\sigma_1 d_1}\left[\frac{\kappa_2}{\sqrt{\alpha_2}}\cosh\sigma_2 d_2 - \frac{\kappa_1}{\sqrt{\alpha_1}}\sinh\sigma_2 d_2\right]$$
$$N_1(\omega) = -\frac{i}{2\pi}\frac{Q_0}{\omega\sigma_1\kappa_1} \times \frac{1-e^{-i\omega\tau}}{D}e^{-\sigma_1 d_1}\left[\frac{\kappa_2}{\sqrt{\alpha_2}}\cosh\sigma_2 d_2 + \frac{\kappa_1}{\sqrt{\alpha_1}}\sinh\sigma_2 d_2\right] \tag{8}$$
$$M_2(\omega) = \frac{i\sqrt{2}}{2\pi(1+i)}\frac{Q_0}{\omega^{3/2}}\frac{1-e^{-i\omega\tau}}{D}e^{-\sigma_2(d_1+d_2)}$$
$$N_2(\omega) = -\frac{i\sqrt{2}}{2\pi(1+i)}\frac{Q_0}{\omega^{3/2}}\frac{1-e^{-i\omega\tau}}{D}e^{\sigma_2(d_1+d_2)}$$
$$D(\omega) = \frac{2\kappa_2}{\sqrt{\alpha_2}}\cosh\sigma_1 d_1\cosh\sigma_2 d_2 + \frac{2\kappa_1}{\sqrt{\alpha_1}}\sinh\sigma_1 d_1\sinh\sigma_2 d_2$$

As can be observed, the temperature distribution in each layer depends upon the thermal bulk parameters and the thickness of both layers. Since any photothermal experiments give only information of the effective thermal parameters but nothing about the thermal parameters and volume fraction of each material in the layered medium, it is necessary to find a mathematical expression for the effective thermal parameters (which are obtained from the experiment) as a function of the thermal characteristics and size of each component material in the composite.

Let us assume some one-layer system having the same geometrical form as the two-layer system with a thermal conductivity κ and thermal diffusivity α such that the photothermal signal of both systems (one and two-layers model) is the same for any time. With this model the effective thermal conductivity and thermal diffusivity are defined by the following relationships [7]:

$$T(z,t)|_{z=0} = T_1(z,t)|_{z=0}$$
$$T(z,t)|_{z=d-\varepsilon} = T_2(z,t)|_{z=d-\varepsilon} \quad \varepsilon/d << 1, \quad \varepsilon > 0 \tag{9}$$

Here the temperature fluctuation $T(z, t)$ for one-layer system is given by Eq. (5) with a thickness $d = d_1 + d_2$. The first equation describes the effective thermal parameters similar to those obtained in the closed photoacoustic cell (front-surface illumination) while the thermal parameters obtained from the second equation correspond to the open photoacoustic cell configuration (rear-surface). The temperature distribution in the second equation must be calculated inside the layer 2 since $T(z, t)$ and $T_2(z, t)$ are equal to T_0 at $z = d$. Because Eqs. (9) is valid for any time, in particular for $t = \tau$ and $t = 2\tau$ and for the pulse-laser incident on the front surface, the evolution of the surface temperature satisfies the following relationship:

$$\frac{T(0,2\tau)}{T(0,\tau)} = \frac{T_1(0,2\tau)}{T_1(0,\tau)} \tag{10}$$

Therefore the effective thermal diffusivity and thermal conductivity are given as

$$\frac{\int_{-\infty}^{\infty}(e^{i\omega\tau}-1)e^{i\omega\tau}\tanh\sigma_{eff}d\,\frac{d\omega}{\omega^{3/2}}}{\int_{-\infty}^{\infty}(e^{i\omega\tau}-1)\tanh\sigma_{eff}d\,\frac{d\omega}{\omega^{3/2}}}=\frac{\int_{-\infty}^{\infty}(e^{i\omega\tau}-1)e^{i\omega\tau}F(\omega)\frac{d\omega}{\omega^{3/2}}}{\int_{-\infty}^{\infty}(e^{i\omega\tau}-1)F(\omega)\frac{d\omega}{\omega^{3/2}}} \qquad (11)$$

$$\kappa_{eff}=\kappa_1\sqrt{\frac{\alpha_{eff}}{\alpha_1}}\frac{\int_{-\infty}^{\infty}(e^{i\omega\tau}-1)e^{i\omega\tau}\tanh\sigma_{eff}d\,\frac{d\omega}{\omega^{3/2}}}{\int_{-\infty}^{\infty}(e^{i\omega\tau}-1)e^{i\omega\tau}F(\omega)\frac{d\omega}{\omega^{3/2}}} \qquad (12)$$

with $\sigma_{eff}=(1+i)\sqrt{\omega/2\alpha_{eff}}$ and

$$F(\omega)=\frac{\frac{\kappa_2}{\sqrt{\alpha_2}}\sinh\sigma_1 d_1\cosh\sigma_2 d_2+\frac{\kappa_1}{\sqrt{\alpha_1}}\cosh\sigma_1 d_1\sinh\sigma_2 d_2}{\frac{\kappa_2}{\sqrt{\alpha_2}}\cosh\sigma_1 d_1\cosh\sigma_2 d_2+\frac{\kappa_1}{\sqrt{\alpha_1}}\sinh\sigma_1 d_1\sinh\sigma_2 d_2} \qquad (13)$$

Similar arguments can be used for rear illumination to calculate the effective thermal parameters of the two-layer composite. Using the second equation from Eq. (9), it leads

$$\frac{\int_{-\infty}^{\infty}\frac{(e^{i\omega\tau}-1)e^{i\omega\tau}}{\omega\cosh\sigma_{er}d}d\omega}{\int_{-\infty}^{\infty}\frac{(e^{i\omega\tau}-1)}{\omega\cosh\sigma_{er}d}d\omega}=\frac{\int_{-\infty}^{\infty}\frac{(e^{i\omega\tau}-1)e^{i\omega\tau}}{\omega D(\omega)}d\omega}{\int_{-\infty}^{\infty}\frac{(e^{i\omega\tau}-1)}{\omega D(\omega)}d\omega} \qquad (14)$$

and

$$\kappa_{er}=\sqrt{\alpha_2}\frac{\int_{-\infty}^{\infty}\frac{(e^{i\omega\tau}-1)e^{i\omega\tau}}{\omega\cosh\sigma_{er}d}d\omega}{\int_{-\infty}^{\infty}\frac{(e^{i\omega\tau}-1)e^{i\omega\tau}}{\omega D(\omega)}d\omega} \qquad (15)$$

As can be seen, Eqs. (11)–(15), in general, the effective thermal parameters have different values at different positions. These results have an important means because in any photothermal experiment the position of the detection technique will be essential, i.e., the effective thermal parameters of the layered composite will depend on two possible configurations; front or rear-surface illumination method. This latter conclusion has been considered in theoretical and experimental photoacoustic spectroscopy [7,14]. It is also interesting to note that the effective thermal parameters are not symmetric, i.e., they are different under exchange of the two layers and therefore the response of the layered system will be different if the laser pulse is incident on layer 1 or layer 2.

3. Discussion

We now turn to the discussion of the results obtained for one- and two-layer systems. It follows from the expressions (5) and (7) that the temperature distribution depends substantially on the relationship between the laser pulse excitation time τ and the characteristic thermal time of each layer. The two-layer material consists of Si on GaAs samples characterized with the following thickness and thermal parameters: $d_{Si} = 10^{-3}$ m, $\alpha_{Si} = 0.89\ 10^{-4}$ m^2/s, κ_{Si} = 154 W/mK, $d_{GaAs} = 3\ 10^{-3}$ m, $\alpha_{GaAsi} = 0.23\ 10^{-4}$ m^2/s, κ_{GaAs} = 46 W/mK. The characteristic thermal time at which the system responds to an external perturbation is given as $\tau_{Si} = d_{Si}/2\alpha_{Si}$ and $\tau_{GaAs} = d_{GaAs}/2\alpha_{GaAs}$. Therefore, the effect of the duration time of the laser pulse on the time evolution of the temperature at the front surface for one and two-layer system is showed in Fig. 2 in the range $\tau = \tau_{Si}/10 << \tau_{GaAs}$ Fig. 2a, and for $\tau_{Si} < \tau < \tau_{GaAs}$ Fig. 2b. As can be observed, when the heat-pulse time is larger than the thermal relaxation time of Si the temperature fluctuation at the surface for one and two-layer materials are, in general different for any time, i.e., in this situation is not possible to obtain some effective thermal parameters of the layered system however, when $\tau << \tau_{Si}, \tau_{GaAs}$ both temperatures coincide for any time and in particular for $t = \tau$ and 2τ, in this case the effective thermal parameters can be obtained from Eqs. (11) and (12) and they lead $\alpha_{eff} = \alpha_{Si}$ and $\kappa_{eff} = \kappa_{Si}$, the pulse laser converted into heat at the surface was chosen as $Q_0 = 10^4$ W/m^2 for both figures. Comparing the results of the short-pulse laser with the longer one, because of more energy diffusion into the deeper part of the film for longer laser pulses, the maximum temperature of the longer laser pulse is higher than that in the short laser pulse and in this case the evolution of the temperature on the surface of the layered system is strongly influenced for the thermal properties of both layers. On the other hand, for short laser pulse excitation the temperature fluctuation after the laser pulse has been extinguished, it attenuates rapidly to zero with increasing time such that at time $t = \tau + \tau_{Si}$ the temperature fluctuation is effectively fully damped out, under this situation thermal information is only obtained from the silicon layer. One of the characteristic peculiarities of the curves is the rapid increase of the temperature during the laser pulse and their decay after heat pulse duration. These results are qualitatively in good agreement with those obtained in Refs. [11,15]. The analysis of these peaks allows us to obtain information about the effective thermal parameters of the layered composite.

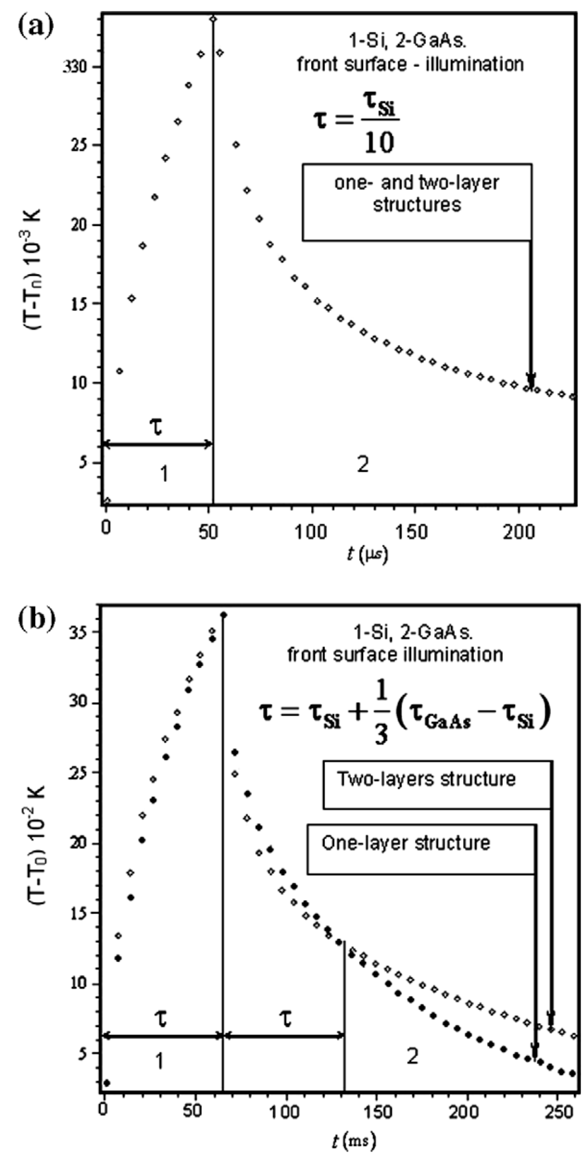

Fig. 2. Time dependence of the temperature fluctuation for one and two-layers system at the surface of the sample ($z = 0$) for (a) short laser pulse $\tau << \tau_{Si}$ and large laser pulse (b) $\tau_{Si} < \tau < \tau_{GaAs}$.

Finally as can be observed in Fig. 2(b), it is not possible to define an effective thermal diffusivity and thermal conductivity for the layered system due to the difference of both temperatures, for one and two-layer systems. This important result is different from that obtained in photothermal experiments where the incident radiation is modulated by a chopper and the effective thermal parameters of two-layer system can be defined for a wide range of modulation frequencies, see Refs. [7,12].

Fig. 3 shows the transient temperatures distribution in the layered system for different times when the laser pulse is incident onto the surface of the Si film, Fig. 3a, and when the laser radiation is absorbed and converted into heat by the GaAs surface sample, Fig. 3b. As can be seen the temperature distribution into the sample depends on what kind of surface of the composite is illuminated and in both cases the transient temperatures of the two-layered materials approach to steady-state temperature for deep distance from the surface of the sample. Note that the curves increase during the laser pulse excitation in the range $\tau/2 < t < \tau$ and subsequently the system returns to thermal equilibrium after the layered system reach its maximum value at $t = \tau$. This arise from the fact that after the laser pulse excitation the heat at the surface is transferred to the subsequent volume element in the sample by diffusion process. As we mentioned before, for laser pulse duration such that $\tau_{Si} < \tau < \tau_{GaAs}$, the evolution of the temperature distribution in the two-layer system as a function of the position is shown in Fig. 3a and b for various values of t before and after the laser pulse has been switched off. As can bee seen, in the range $0 < t < \tau$, the temperature decrease exponentially with increasing distance from the surface until it is damped out inside the layered system. On the other hand, when the laser pulse has been extinguished ($t > \tau$), the initial heating due to the excess of energy received during the laser excitation results in a diffusion process inside the sample. Note that the cooling of the sample occurs after the temperature fluctuation reaches its maximum value at $t = \tau$ in the region close to the surface of the sample ($0 < z < z_c$), in this range $T(z,\tau) > T(z, 2\tau)$, see Fig. 3a. Here z_c is defines such that $T(z_c, t_1) = T(z_c, t_2)$, $t_1 > t_2 > \tau$. However, the temperature distribution behavior changes notably towards greater times ($t > \tau$), i.e., there is an overheating with increasing distance from the surface of the sample ($z_c < z < d$) and in this condition $T(z,\tau) < T(z, 2\tau)$. This arises from the fact that after the laser pulse excitation has been switched off, the heat at the surface is transferred inside the sample by a diffusion process. This effect has been investigated in detail related with the transient heat transport by carriers in semiconductors [12].

On the other hand, for short laser pulse heating, the temperature decreases exponentially with increases distance from the surface it is completely damped in the region $0 < z < d_1$ and as a consequence all the thermal information is obtained from the illuminated first layer in the system.

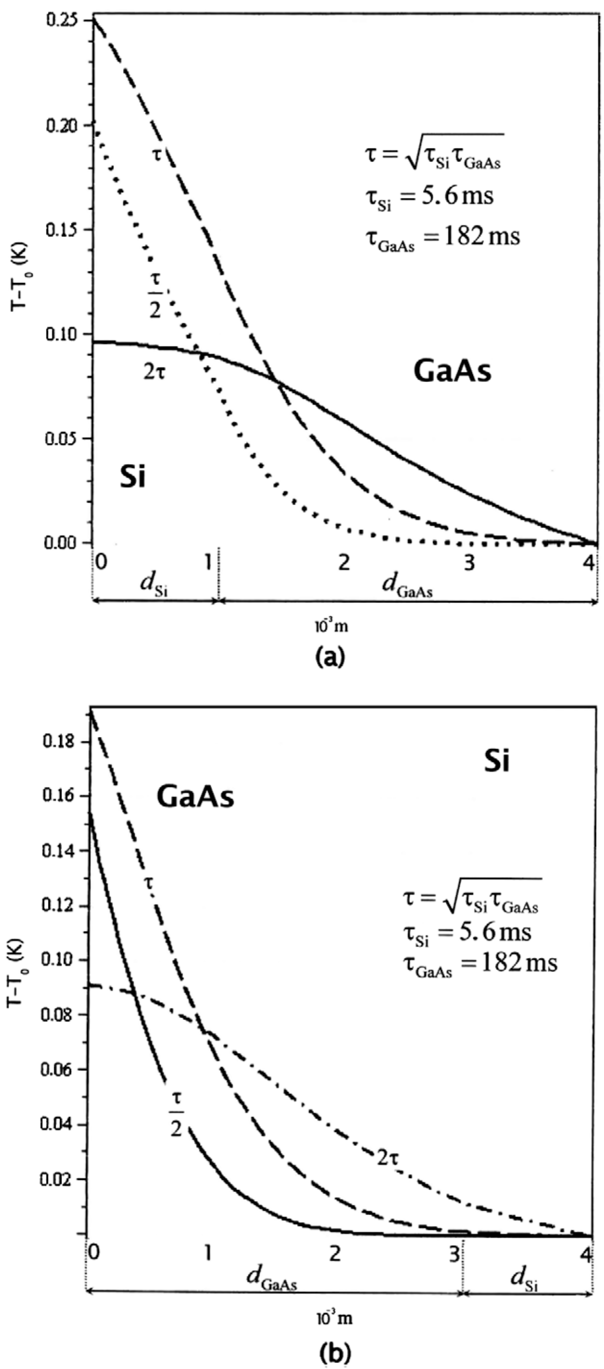

Fig. 3. Temperature distribution inside the two-layers system at different times and $Q_0 = 10^4$ W/m^2 for (a) Si front-surface illumination and (b) GaAs front-surface illumination.

4. Conclusions

A theoretical analysis of thermal pulse propagation in two-layer system has been studied. Using the boundary conditions which are in accordance with the experimental situation, we obtain the temperature distribution in each layer of the system. Thus the effective thermal parameters of the layered sample are calculated by assuming an homogeneous material characterized by some thermal properties which produces the same physical effects. Specific applications are showed for two-layer material composed by Si and GaAs films. The results presented in this work show that in general the effective thermal parameters for two-layer systems cannot be defined. This latter conclusion is completely different from that obtained in photothermal experiments when the heat diffusion in the composite system is created by a periodic light beam.

Acknowledgement

This work has been partially supported by Consejo Naional de Ciencia y Tecnologia (Conacyt).

References

[1] M. Reichling, H. Gronbeck, Harmonic heat flow in isotropic layered systems and its use for thin film thermal conductivity, J. Appl. Phys. 75 (1994) 1914.
[2] Jinbo Hou, Xinwei Wang, Jiaqi Guo, Thermal characterization of micro/nanoscale conductivity and non-conductivity wires based on optical heating and electrical thermal sensing, J. Phys. D Appl. Phys. 39 (2006) 3362.
[3] L. Shi, D. Li, Ch. Yu, W. Wang, D. Kim, Z. Yao, P. Kim, A. Majumdar, Measuring thermal and thermoelectric properties of one-dimensional nanostructures using a microfabricated device, J. Heat Transfer 125 (2003) 881.

[4] W.P. Risk, C.T. Rettner, S. Raoux, In situ 3ω techniques for measuring thermal conductivity of phase-change materials, Rev. Sci. Instrum. 79 (2008) 26108.
[5] A.M. Manzanares, A.C. Bento, H. Vargas, N.F. Leite, L.C.M. Miranda, Photoacoustic measurement of the thermal properties of two-layer systems, Phys. Rev. B 42 (1990) 4477.
[6] A. Salazar, A. Sanchez-Lavega, J.M. Terron, On the effective thermal diffusivity of fiber-reinforced composites, Appl. Phys. Lett. 80 (2002) 1903.
[7] N. Muñoz-Aguirre, G. Gonzalez de al Cruz, Yu.G. Gurevich, G.N. Logvinov, M.N. Kasyanchuk, Heat diffusion in two-layer structures: photoacoustic experiments, Phys. Status Solidi (b) 220 (1) (2000) 781.
[8] Ku-Chi Liu, Analysis of dual-phase-lag thermal behaviour in layered films with temperature-dependent interface thermal resistance, J. Phys. D Appl. Phys. 38 (2005) 3722.
[9] D.G. Cahill, W.K. Ford, K.E. Goodson, G.D. Mahan, A. Majumdar, H.J. Maris, R. Merlin, S.R. Phillpot, Nanoscale thermal transport, Appl. Phys. Rev. 93 (2003) 793.
[10] M.A. Panzer, K.E. Goodson, Thermal resistance between low-dimensional nanostructures and semi-infinite media, J. Appl. Phys. 103 (2008) 94301.
[11] Y.M. Lee, T.W. Tsai, Effect of interfacial contact conductance on thermo-elastic response in a two-layered heated by ultrashort-fast pulse-laser, J. Phys. D Appl. Phys. 41 (2008) 45308.
[12] A.F. Carvallo-Sánchez, G. Gonzalez de la Cruz, Yu.G. Gurevich, G.N. Logvinov, Transient heat transport by carriers and phonons in semiconductors, Phys. Rev. B 59 (1999) 10630.
[13] G. Gonzalez de la Cruz, Yu.G. Gurevich, Time-dependent heat diffusión in semiconductors by electrons and phonons, Phys. Rev. B 58 (1998) 7768.
[14] H. Vargas, L.C.M. Miranda, Photoacoustic and related photothermal techniques, Phys. Rep. 161 (1988) 3282.
[15] P. Suter, T. Graf, Photothermal thickness measurement of multilayered structures: an experimental and numerical analysis, J. Appl. Phys. 103 (2008) 33509.