TIME RESOLVED PHOTOTHERMAL DEFLECTION MEASUREMENT OF SEMICONDUCTOR MATERIALS THERMAL PARAMETERS

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ABSTRACT

A time resolved measurement of the thermaly induced surface deformation has been carried out using visible light-based photothermal deflection technique. Thermal conductivity coefficients were determined for several semiconductor materials. Problems of the experimental data interpretation with respect to the effect of 2D/3D heat source excitation and the potential advantages of the time resolved data are discussed.

Keywords: *Photothermal deflection spectroscopy, Heat transfer equation, Thermal parameters measurement*

1. INTRODUCTION

Photothermal deflection spectroscopy (PDS) belongs among the most popular optical contactless methods for both thermal and optical parameters determination. The method was developed at the beginning of eighties of the last century [1]. The measurement technique is based on the measurement of the dependence of laser probe beam vs. thermal excitation chopping frequency. The system operates on the pump and probe principle because the focused laser beam is used also as a thermal source for an initiation of the surface thermal deformation and it is chopped mechanically or acoustically to create interrupted thermal excitation. Generally the laser probe beam can be deflected by mirror-like surface flatness deformation, by passing through the thermal lens inside the tested material but it also may be inclined due to index of refraction gradient in the surface adjacent air boundary layer [2–4]. The detection response of the deformation/index of refraction changes is related to the thermal as well as temperature materials parameters. As the excited deformation and/or index of refraction changes are finite time processes the response signal is gradually depleted with growing frequency and the basic material thermal parameters can be extracted from such a relationship. From the point of view of the signal acquisition, the detection technique can be very sensitive due to the fact of using in such a reading scheme of the single-frequency synchronized detection. Thus, by the application of lock-in amplifier signal processing, information about the transient process of thermally excited change as a response to step-wise activation is irretrievably lost. However, as we have approved experimentally, the time dependence of the observed process can be evaluated with the aim to determine the basic material parameters. In the paper the analysis has been carried out on the possibility to develop the procedure of retrieval the thermal diffusion coefficient and/or coefficient of thermal conductivity of the semiconductor materials such as Si, GaAs, InP or GaP eventually including the materials deposited as a thin layer. We have tried to demonstrate potentiality of the recurrence signal acquisition and subsequent processing by averaging even without the necessity of lock-in amplifier technique.

2. THEORETICAL MODEL OF THERMAL SURFACE DEFORMATION

Gaussian laser beam light intensity distribution impinging perpendicularly the material surface can be expressed by following expression:

$$I = I_0 \exp\left(-\frac{2r^2}{w^2}\right) \tag{1}$$

where w is the radius of laser beam, I_0 is the intensity at the centre of the beam, $r = \sqrt{x^2+y^2}$ and the surface plane of the specimen coincides with the plane (x,y). Part of the illuminating light is reflected while the rest of ligh is absorbed into the material. Material absorption is described by the Beer-Lambert law, that is in the depth z under the surface the following intensity distribution can be observed

$$I = I_0 \mathscr{T} \exp\left(-\frac{2r^2}{w^2}\right) \mathrm{e}^{-gz} \tag{2}$$

where $\mathscr{T}$ is the intensity transmittance of the surface and g is the absorption coefficient of the material. A portion of light absorbed inside material can be considered as a thermal source, then $p = -\partial I/\partial z$ is the whole power of the heat supplied:

$$p = I_0 \mathscr{T} g \exp\left(-\frac{2r^2}{w^2}\right) \mathrm{e}^{-gz} \tag{3}$$

In the strong absorbing medium which were the materials that we are dealing with, the absorption coefficients were in the range $10^6\,\mathrm{m}^{-1}$ to $10^8\,\mathrm{m}^{-1}$ therefore the heat is generated only in thin surface film with the thickness of $l \approx 1/g$. It means the penetration depths of only $1\,\mu\mathrm{m}$ to $0.01\,\mu\mathrm{m}$ which is 2–3 orders less comparing the radius of illuminating laser beam spot ($w = 50\,\mu\mathrm{m}$). It is always indicated, that the temperature subsurface spreading into the material has shown exponential attenuation $\exp(-gz)$, the same as the exciting source. These geometrical conditions implie that the excitation is realized on the surface or perhaps inside the thin deposited layer, and moreover the heat propagation acts during the limited time interval of the order of ms. Accordingly it can be regarded as a surface process. Taking into account of these basic assumptions 2-D model of the heat propagation was applied in order to describe the transient process. For the sake of simplicity, even analytical model is applicable.

At the case of strongly absorbing medium on its surface $(z=0)$ $\mathrm{e}^{-gz} \approx 1$, everywhere outside this terms is zero. The volume density of the laser source thermal power can be written in the form:

$$p = I_0 \mathscr{T} g \exp\left(-\frac{2r^2}{w^2}\right) \tag{4}$$

Next, the heat propagation is governed by the heat transfer equation:

$$\nabla^2 T = \frac{1}{\kappa}\frac{\partial T}{\partial t} - p \tag{5}$$

where $\kappa = k/\rho c$ is the thermal difussion coeficient and k is the thermal conductivity, ρ is the material density and c is the thermal capacity. In the case of continual laser excitation, which was starting at the $t=0$, the solution can be found in the form [3]

$$T(r,t) = \frac{I_0 \mathscr{T} g w^2}{4k}\int_0^{t/\tau_c} \frac{1}{1+2\tau}\exp\left(-\frac{2w^2/r^2}{1+2\tau}\right)\mathrm{d}t \tag{6}$$

where we have used substitution for the time parameter

$$\tau_c = w^2/4\kappa \tag{7}$$

Although the exact determination of the induced surface deformation as a function of temperature is rather complex task of termomechanics, the values of displacements can be roughly assessed. With regard of relatively small temperature differneces the out-of-plane surface deformation is of the order 10^{-2} nm to 10^{-1} nm [5]. As a first approximation, let the local deflection $u(r)$ of the surface point is directly proportional to the temperature at the same point, that is

$$u(r,t) \propto T(r,t) \tag{8}$$

Deflection based measurement makes use the detection of the laser beam deviation as an effect of the induced surface deformation. The deviation angle is twice the angle between the deformed surface and the original flat position

$$\theta \approx \tan\theta = 2\frac{\mathrm{d}u}{\mathrm{d}r} = 2\frac{\mathrm{d}T}{\mathrm{d}r} \tag{9}$$

After the simple analytical adaptation by derivation with respect to r, we obtain the basic expression for the measured data interpretation:

$$\frac{\mathrm{d}T}{\mathrm{d}r} = \frac{I_0 \mathscr{T} g w^2}{kr}\left[\exp\left(-2r^2/w^2\right) - \exp\left(-\frac{2r^2/w^2}{1+2t/\tau_c}\right)\right] \tag{10}$$

As seen, it denotes that PSD signal is proportional to the radial temperature gradient.

3. EXPERIMENTAL REALIZATION

In our experiments, we have set traditional high sensitive optical scheme, often used for PSD measurements. The experimental arrangement is shown in Fig. 1. The solid state Nd:YAG laser with the output power 150 mW was used for excitation at the second harmonics wavelength 532 nm. At such a wavelength the absorption coefficient of all the material specimens evaluated is strong enough to prevent the deep depth penetration of the heat energy. Single frequency stabilized He-Ne CW laser with the output power of 1 mW was used as a probe laser for inclination angle reading. The mechanical chopper was placed at the position of focal plane of the lens L2 with focal distance 50 mm. By means of this lens a sufficiently small diameter in the focal waist of the exciting laser beam can be adjusted, in order to provide for a satisfactory rise time comparing the characteristic time duration of the transient thermal processes. Subsequently, the lens L4 focuses the beam onto the surface, where the diameter of the spot is about 80 µm. The beam of the probe was focused by the same lens onto the diameter 30 µm at the optimal position of 32 µm regarding the measuring sensitivity.

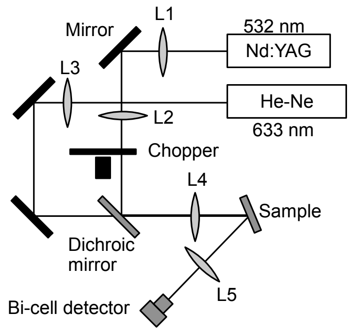

Fig. 1 Photothermal deflection experimental setup

After the reflection the probe beam was focused by the lens L5 onto the effective area of the bi-cell photodiode with differential detecting and amplifying circuit (PSD). The specimen was fixed in the adjusting holder with the possibility of two axes inclination. The quality of the useful signal is considerably related to the precise centering of the reflected measuring beam spot onto the effective bi-cell photodiode areas. When no excitation is applied the output signal has to be nearly zero.

The photodetector signal was recorded immediately by a digital oscilloscope Tektronix TDS 220 where also the averaging of the repeated excitation signals was accomplished. As we have found, the noise of the signal had a characteristic features of white noise, thus the applying of up to 64 repeated signal traces was possible resulting in ultimate noise elimination.

4. RESULTS AND DISCUSSION

The thermal conductivity of the several semiconductor materials has been measured with the next data evaluation. The recorded dependencies were evaluated by fitting using Lavenberg-Marquardt algorithm. The results of some measurements are summarized in Tab. 1. As seen the dispersion of the results obtained do not exceed 10 %. As we have recognize, the basic factor of the necessity is the inaccuracy in the defining of mutual position of the centers of probe and exciting beams. Fig. 2 and Fig. 3 illustrate the recorded time traces of the transient heating process where also the theoretical curves are plotted obtained by fitting. As it can be determined the time constant of the transient is approximately 2.5 times higher for GaAs in comparison with monocrystalline silicon.

Generally, the comparison of the time resolved method of measurement with that of standard thermal deflection spectroscopy has shown some of the advantageous of the former approach. Besides the possibility of measurements without the using of lock-in amplifier data processing, the acquirement of the time relationship between heating of the material and its deformation response can be used to study the thermal effects more effectively and reliably. Such an approach is enable also to give us information about the possible discrepancies between the true measured data and the interpretation expression when retrieving the evaluated values and thus to control the process.

Table 1 The basic thermal paremeters of semiconductor materials with comparison of the measured data

Material	Values from [6]				Measured
	k	c	ρ	κ	κ
	$\mathrm{W\,m^{-1}K^{-1}}$	$\mathrm{J\,kg^{-1}K^{-1}}$	$\mathrm{kg\,m^{-3}}$	$10^{-6}\,\mathrm{m^2s^{-1}}$	$10^{-6}\,\mathrm{m^2s^{-1}}$
GaAs	55	330	5 320	31.0	30.2
Si	130	700	2 329	80.0	75.2
InP	68	310	4 810	37.2	34.8
GaP	110	430	4 140	62.0	54.7

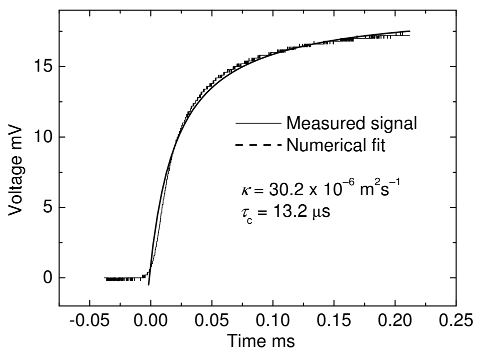

Fig. 2 Time dependence of deformation response for GaAs material

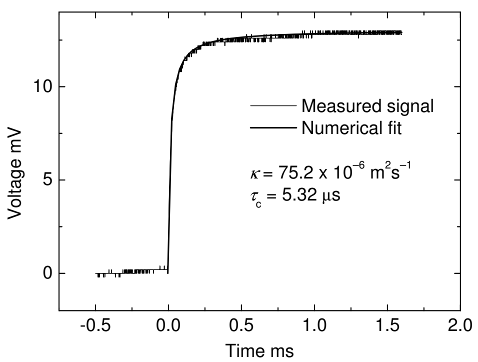

Fig. 3 Time dependence of deformation response for Si material

5. CONCLUSION

As we have acquired, the time resolved measurement of thermally induced surface deformation can be successfully carried into operation with the aim to evaluate the basic thermal or thermomechanical parameters of both the substrates and deposited thin films. The problem of handling with thin layers is overcame by control of depth of focus of the exciting laser beam. Using the large aperture number lens the heat source can be localized into thin depth region creating thus the “planar” 2-D source of excitation. Such an approach is offering good prospects for contactless thermal conduction characterization of micromechanical structures even with the multilayer structures.

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BIOGRAPHIES

Juraj Chlpík was born in Slovakia, in 1975. He recieved his first degree in physics from Faculty of Mathematics and Physics, Commenius University, Bratislava in 1999. Now, he is a PhD student. His research efforts are focused on applying of optical methods for investigation of thermomechanical properties of thin layers, modeling and numerical simulation of transient thermal processes.

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Martin Koleda was born in Slovakia, in 1982. He recieved his first degree in microelectronics in 2007. His diploma work was focused on photothermal deflection measurement of thermo-mechanical parameters of semicondactors. He works as a laser specialist.