DIFFERENT NON DESTRUCTIVE PHOTOTHERMAL DEFLECTION TECHNIQUES TO DETERMINE THERMAL PROPERTIES OF BULK SEMICONDUCTORS

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ABSTRACT

In this paper we will describe and compare different non destructive Photothermal Deflection methods easy to develop and not expensive which permit the determination of the thermal diffusivity of bulk semiconductor material. The first method consists to draw the experimental amplitude and phase of the photothermal deflection signal versus square root modulation frequency. The sample placed in air is heated thanks to a modulated pump uniform beam. The only difference between the first and the second method is that in the second method the sample is covered by a thin graphite layer. We show in this study that the first method is only sensitive to the thermal diffusivity of the sample however the second method is sensitive for both thermal diffusivity and thermal conductivity. Finally the third method which is a spectroscopic one consists to draw the experimental phase and amplitude of the photothermal signal versus wavelength at a fixed modulation frequency. The sample is immersed in a CCl₄ filled cell. In this study we show that the phase signal saturate for high and low optical absorption coefficient values. The phase difference between the two saturated regions is function of the thermal diffusivity of the sample.

Key words: Photothermal Deflection Technique, thermal diffusivity, thermal conductivity.

Nomenclature

ν Modulation frequency (Hz)
N₀ Refractive index of the fluid
φ Phase of the photothermal deflection (rad)
Z₀ Distance between the probe beam axis and the sample surface (m)
Kᵢ Thermal conductivity of i media (Wm⁻¹K⁻¹)
Dᵢ Thermal diffusivity of i media (m²S⁻¹)
α Sample’s optical absorption coefficient (m⁻¹)
1. Introduction

During the past few years, the application of the photothermal deflection technique which have the advantage of being non-destructive has been considerably involved [1-3]. The aim of this technique is in the first time to detect the thermal wave generated by the sample’s optical absorption of a modulated light beam which will propagate into the sample and in the surrounding fluid inducing a temperature gradient then a refractive index gradient and in a second time to study the deflection of a laser probe beam skimming the sample surface and crossing the inhomogeneous refractive index region. This deflection may be related to the thermal properties of the sample.

Several methods based on the Photothermal Deflection Technique or the so-called “Mirage Effect” have been developed to determine the thermal diffusivity of materials with high precision [4-6]. The most used technique consists to heat the sample by a modulated laser pump beam and to draw the experimental in phase signal versus the distance \( x \) between the pump beam and the probe beam axis at a fixed modulation frequency \( \nu \). The obtained curves cut the \( x \) axis in two points distant from \( d \). The linear curve \( d = f(1/\sqrt{\nu}) \) whose slope depends on the thermal diffusivity will allow determining it.

In this work, we present and compare three different methods applied to bulk semiconductor such as GaSb samples in order to determine their thermal diffusivity. The two first methods deal with the analysis of the photothermal signal variation versus modulation frequency where the sample is placed in air and heated by a modulated light coming from a Halogen Lamp (uniform heating case).

In the second method the sample is covered with a thin graphite layer where interest will be discussed later. The third method is a spectroscopic one and consists to draw the photothermal deflection signal versus wavelength at a fixed modulation frequency where the sample is immersed in a CCl\(_4\) filled cell. The thermal diffusivity of bulk GaSb samples is obtained by fitting the experimental curves.

2. Theoretical model

To obtain the expression of the probe beam deflection \( \psi \) [7], we must know the temperature distribution in the fluid so we have to determine the temperature elevation at the sample surface by resolving the heat diffusion equation in the different media and assuming the continuity conditions of temperature and heat flow at the different interfaces. As the sample surface is uniformly heated so a one dimension heat treatment is sufficient.

In the first method, we have to consider only three media: fluid, sample and backing. We assume that both fluid and backing are optically non-absorbing media for the incident light. So the obtained temperature elevation at the sample surface \( T_0 \) [7] is given by:

\[
T_0 = -E \frac{[(1 - r)(1 + b) \exp(\sigma_s l_s) - (1 + r)(1 - b) \exp(-\sigma_s l_s)] + 2(r - b) \exp(-\alpha l_s)]}{[(1 + g)(1 + b) \exp(\sigma_s l_s) - (1 - g)(1 - b) \exp(-\sigma_s l_s)]}
\]

(1)

Where \( E = A/(\alpha^2 - \sigma_s^2) \), \( b = K_f\sigma_b/K_s\sigma_s \), \( g = K_f\sigma_f/K_s\sigma_s \) and \( r = \alpha/\sigma_s \)

\[
\sigma_i = (1 + j)/\mu_i, \quad \mu_i = (D_i/\pi \nu)^{1/2}
\]
\( \alpha \) is the optical absorption coefficient of the sample and \( \nu \) is the modulation frequency. \( K_i, D_i \) and \( \mu_i \) are respectively the thermal conductivity, the thermal diffusivity and the thermal diffusion length of the \( i \) medium. Here the index \( i \) take the subscripts \( s, f \) and \( b \), respectively, for the sample, fluid and backing.

When we deposit a thin graphite layer on the sample (second method) we must take it into account in our theoretical model. So we have to consider four media which are fluid, graphite layer, sample and backing. In this case, only the graphite layer is considered as an absorbing media of the incident light and so play the role of a heat source.

The periodic temperature elevation \( T_0 [8] \) in this case will be given by:

\[
T_0 = E [(1 - b) e^{-\alpha_i l_f} \left[ (1 - r)(1 - c) e^{\sigma_i l_f} + (1 + r)(1 + c) e^{-\sigma_i l_f} \right] - 2(1 + r c) e^{-\alpha_i l_f} \left[ (1 - r)(1 + c) e^{\sigma_i l_f} + (1 + r) e^{-\sigma_i l_f} \right] - 2(1 - r c) e^{-\sigma_i l_f} \left[ (1 + b) e^{\sigma_i l_f} + (1 + g)(1 + c) e^{\sigma_i l_f} + (1 - g)(1 - c) e^{-\sigma_i l_f} \right] - (1 - b) e^{-\sigma_i l_f} \left[ (1 + g)(1 - c) e^{\sigma_i l_f} + (1 - g)(1 + c) e^{-\sigma_i l_f} \right]]
\]

(2)

By applying the ray equation to calculate the probe beam deflection one can obtain the complex expression of the deflection \( \Psi [7] \):

\[
\Psi = |\Psi(z_0)| \exp(j \Phi)
\]

(3)

where \( |\Psi(z_0)| = -\frac{L}{n_0} \frac{dn}{dT} \frac{\sqrt{2}}{\mu_f} |T_0| \exp(-z_0/\mu_f) \) and \( \Phi = \frac{z_0}{\mu_f} + \theta + \frac{\pi}{4} \)

are the amplitude and phase of the photothermal deflection signal whereas \( |T_0| \) and \( \theta \) are respectively the amplitude and phase of the sample’s surface temperature.

\( z_0 \) is the distance between the probe beam and the sample surface.

3. Experimental set-up

For the thermal study, the experimental set-up is described in [7] is composed essentially of a power 100W Halogen lamp which light is modulated thanks to a mechanical chopper of type SR540 and then focused on the sample surface. A He–Ne Laser probe beam of wavelength 632.8 nm skimming the sample surface at a distance \( z_0 \) is deflected and its deflection will be measured by a photodetector of four quadrants (QD50T) connected to a lock-in amplifier (EG&G5210). Via the intermediary of IEEE bus, a PC microcomputer sets the modulation frequency of the mechanical chopper and reads the amplitude and phase of the signal from the lock-in and finally draws their variation according to the square root of modulation frequency. For the optical study we interpose between the halogen lamp and the mechanical chopper a Monochromator (Jobin Yvon HR250) and we plot the amplitude and phase variation of the photothermal signal versus wave length at a fixed modulation frequency.
4. Experimental results

The thermal study in the two first methods consists in drawing the logarithm of the amplitude and phase variation versus square root modulation frequency. The best coincidence between experimental and theoretical curves will give the best values of thermal properties.

4.1 First method

If we plot the theoretical logarithm of the amplitude and phase variations versus modulation frequency at a fixed value of the thermal diffusivity and for different values of the thermal conductivity one can notice that the obtained curves are confused so the photothermal signal is insensitive to the thermal conductivity in this case. However, if we vary the thermal diffusivity at a fixed value of thermal conductivity (fig. 1), one can notice that both the logarithm of amplitude and phase variations are very sensitive to $D_s$. Then increasing the thermal diffusivity of the sample we remark that the theoretical phase maximum moves towards high frequencies. Therefore, the best value of the thermal diffusivity $D_s$ is only obtained for the best coincidence between the experimental curves and the corresponding theoretical ones.

In fig. 2 are represented the experimental logarithm of the amplitude and phase variation obtained respectively for an undoped, Te-doped and Zn-doped GaSb sample. The corresponding theoretical curves which best coincide with experimental ones are obtained for values of thermal diffusivity reported in table 1.

4.2 Second method

Here, the samples of Gallium Antimonide are covered by a graphite layer of thickness 1.6μm for the undoped and Te-doped GaSb and 4μm for the Zn-doped. To determine the sensitivity of our experimental set-up towards the thermal properties we have plotted in figs. 3-a and 3-b respectively the theoretical logarithm of amplitude and phase variations for different couples ($K_s, D_s$) of an undoped GaSb sample.

We notice from these curves that both the logarithm of amplitude and phase, unlike in the first method, are very sensitive as well as to $K_s$ and to $D_s$ which prove the interest of this method.

![Fig. 1: Theoretical and experimental curves giving the variations of the logarithm of the amplitude (a) and phase (b) according to the square root modulation frequency for different values of $D_s$ of an undoped GaSb at a distance $z_0=95\mu m$.](attachment:fig1.png)
Fig. 2: Experimental curves and corresponding theoretical ones giving the variations of the logarithm of the amplitude (a) and phase (b) according to the square root modulation frequency of an undoped, Te-doped and Zn-doped GaSb samples at a same distance $z_0=95\,\mu m$.

Fig. 3: Experimental and theoretical curves giving the variations of the logarithm of the amplitude (a) and phase (b) according to the square root modulation frequency of an undoped GaSb on which we have deposed a thin graphite layer of a thickness 1.6 $\mu m$ at $z_0=215\,\mu m$ for 1: $(k_s=5\,W.m^{-1}.K^{-1}, D_s = 2.1\times10^{-5}m^2.s^{-1})$, 2: $(k_s=35.2\,W.m^{-1}.K^{-1}, D_s = 2.1\times10^{-5}m^2.s^{-1})$ and 3: $(k_s=35.2\,W.m^{-1}.K^{-1}, D_s = 10^{-5}m^2.s^{-1})$.

We notice also and as in the first method that the theoretical phase maximum moves towards high frequencies when the thermal diffusivity increases.

The theoretical curves which fit best the experimental ones are obtained for the couple $(k_s=35.2\,W.m^{-1}.K^{-1}, D_s = 2.1\times10^{-5}m^2.s^{-1})$.

Now in order to verify that the couple $(K_s, D_s)$ which we have founded is unique, we have plotted respectively in figs. 4-a and 4-b the logarithm of the amplitude and the phase versus square root modulation frequency for two fixed values of $z_0$. The coincidence between the theoretical curves and the experimental ones is obtained for the same couple $(K_s, D_s)$ which prove its uniqueness. A similar study was made for the Te-doped and the Zn-doped.
In figs. 5-a and 5-b are represented the experimental and the corresponding theoretical curves of respectively the logarithm of the amplitude and the phase versus square root modulation frequency for each samples at a same distance \( z_0 = 95 \mu m \). We notice from these figures the good agreement between the experimental and the theoretical curves for both the logarithm of amplitude and phase variation. The three samples thermal diffusivity and thermal conductivity values so deduced are reported in Table 1.

![Fig. 4](image)

**Fig. 4:** Experimental curves and corresponding theoretical ones giving the variations of the logarithm of the amplitude (a) and phase (b) according to the square root modulation frequency for two values of \( z_0 \) of an undoped GaSb covered by a graphite layer of thickness 1.6 \( \mu m \).

![Fig. 5](image)

**Fig. 5:** Experimental curves and corresponding theoretical ones giving the variations of the logarithm of the amplitude (a) and phase (b) according to the square root modulation frequency of an undoped, Te-doped and Zn-doped GaSb samples at a same distance \( z_0 = 215 \mu m \).
Fig. 6: Experimental (a) curves giving the variations of the phase according to wavelength and corresponding theoretical one (b) according to absorption coefficient of an undoped, Te-doped and Zn-doped GaSb samples at a fixed modulation frequency $\nu = 18.5$ Hz.

### 4.3 Third method

Our study in this method consists to plot the phase variation of the photothermal signal near the band gap region versus wavelength. The experimental corresponding curves obtained for each sample are shown in fig. 6. From this figure, one can notice that the phase saturates above and below the gap energy. The phase difference $\Delta \Phi$ between these two saturated zones is a function of the thermal diffusivity which may be determined by comparison of the theoretical phase difference with the corresponding experimental ones. The obtained thermal diffusivity values are listed in table 1.

<table>
<thead>
<tr>
<th>Samples</th>
<th>$Ds \times 10^{-5}$ x m$^2$. S$^{-1}$</th>
<th>$Ks$ (W m$^{-1}$. K$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>First method</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>undoped GaSb</td>
<td>2.13 ± 0.05</td>
<td>---</td>
</tr>
<tr>
<td>Te-doped GaSb</td>
<td>3.15 ± 0.05</td>
<td>---</td>
</tr>
<tr>
<td>Zn-doped GaSb</td>
<td>2.67 ± 0.05</td>
<td>---</td>
</tr>
<tr>
<td><strong>Second method</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>undoped GaSb</td>
<td>2.10 ± 0.03</td>
<td>35.2 ± 0.5</td>
</tr>
<tr>
<td>Te-doped GaSb</td>
<td>3.10 ± 0.03</td>
<td>48.4 ± 0.5</td>
</tr>
<tr>
<td>Zn-doped GaSb</td>
<td>2.71 ± 0.03</td>
<td>23.1 ± 0.5</td>
</tr>
<tr>
<td><strong>Third method</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>undoped GaSb</td>
<td>2.07 ± 0.10</td>
<td>---</td>
</tr>
<tr>
<td>Te-doped GaSb</td>
<td>3.90 ± 0.20</td>
<td>---</td>
</tr>
<tr>
<td>Zn-doped GaSb</td>
<td>2.70 ± 0.15</td>
<td>---</td>
</tr>
</tbody>
</table>
5. Conclusion

In this work, we have investigated the thermal diffusivity for an undoped GaSb, Te-doped and Zn-doped using three different methods based on the photothermal deflection technique by fitting the experimental curves and we have compared their sensitivity to the thermal properties especially the thermal diffusivity. In fact: while the first and the third methods are sensitive only to the thermal diffusivity, the second method depends on both thermal diffusivity and thermal conductivity. By depositing a thin graphite layer on the sample (second method), we have shown one simple and chip method applied for bulk semiconductors which allow to determine simultaneously the thermal diffusivity and the thermal conductivity with good precision.

6. References