The Measurement of Thermal Diffusivity in Conductor and Insulator by Photodeflection Technique

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Abstract. The purpose of this study is to estimate thermal diffusivies of high thermal diffusivity bulk material as well as low thermal diffusivity bulk material by using many types of fluid such as Ethyl alcohol and water. This method is studied by measuring amplitude and phase of photodeflection signal in various frequency modulations. The experimental setup consists of two laser lines: 1) a pump laser beams through a modulator, varied frequency, controlled by lock-in amplifier and focused on sample surface by lens. 2) a probe laser which parallels with the sample surface and is perpendicular to the pump laser beam. The probe laser deflection signal is obtained by a position sensor which controlled by lock-in amplifier. Thermal diffusivity is calculated by measuring the amplitude and phase of the photodeflection signal and compared with the thermal diffusivity of a standard value. The thermal diffusivity of SGG agrees well with the literature but the thermal diffusivity of Cu is less than the literature value by a factor of ten. The experiment requires further improvement to measure the thermal diffusivity of Cu. However, we succeed in using ethyl alcohol as the coupling medium instead of CCl_4 which is highly toxic.

1. Introduction

Thermal diffusivity, one of the most important parameter of the thermal characterization of materials, is scientific and industrial interest. There are several photothermal methods such as photoacoustic, photothermal reflection, etc. which have been successfully used for measuring thermal diffusivity. Photodeflection or mirage technique, which is nondestructive and noncontact, is also the powerful and highly precise method to determine thermal diffusivity. Nowadays, photodeflection is usually used to measure high diffusivity of thin film materials [1]. In the past, to improve the sensitivity of deflection signal they used Carbon Tetrachloride (CCl_4) as the coupling medium. CCl_4 is known to be highly toxic [2] and evaporates easily.

In this paper we propose a method which permits to determine thermal diffusivity of high thermal diffusivity bulk material as well as low thermal diffusivity bulk material by using many types of fluid such as Ethyl alcohol and water. This method is studied by measuring amplitude and phase of photodeflection signal in various frequency modulations.

2. Theory

There are 3 layers which are fluid (f), sample (s) and backing (b), to determine the temperature at the sample surface. We have to solve the heat diffusion equation in various media where the heat can propagate. These calculations are run by Rosencwaig and Gersho in 1976 [3] for the case of a photoacoustic detection have been extended to the case of mirage detection by several researches [4].
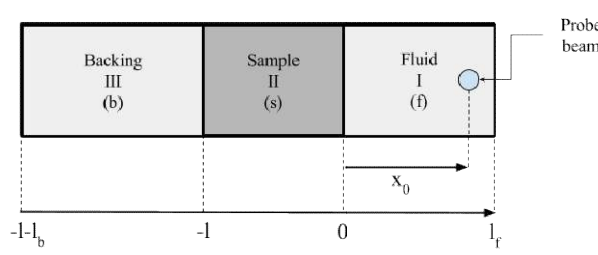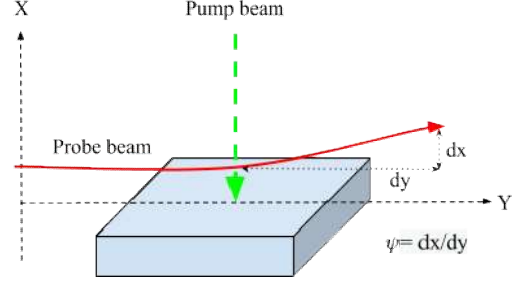
Figure 1. Geometry of the 1.D system

Figure 2. Schematic of the probe beam deflection

Considering the geometry shown in figure 1, as schematically outlined, an intensity-modulated light beam generates a periodic thermal wave propagates across the sample. In our model, only sample layer can absorb the incident pump beam with an absorption coefficient α. We will examine in the case of frequency measurement in order to determine one layer of sample [5]. We can write the modulated sample surface temperature (T_s) at $x_0 = 0$:

$$|T_s| = \frac{\alpha I_0}{2k_s(\alpha^2 - \sigma_s^2)}\left[\frac{(r-1)(b+1)\exp(\sigma_s x_0) - (r+1)(b-1)\exp(-\sigma_s x_0) + 2(b-r)\exp(-\alpha x_0)}{(g+1)(b+1)\exp(\sigma_s x_0) - (g-1)(b-1)\exp(-\sigma_s x_0)}\right] \quad (1)$$

Where $g = \frac{k_f \mu_s}{k_s \mu_f}, = \frac{k_b \mu_s}{k_s \mu_b}, r = (1-j)\frac{\alpha \mu_s}{2}$

Where $\mu_i = \left(\frac{D_i}{\pi f}\right)^{\frac{1}{2}}$ is the thermal diffusion length in the region i. D_i and k_i is thermal diffusivity and thermal conductivity respectively. x_0 is the distance between the sample surface and probe beam. The calculation of probe beam deflection is based on the schematic of figure 2.

$$n\frac{dx}{dy} = -\int_{-\frac{L}{2}}^{\frac{L}{2}}\frac{dn}{dx}dy \quad (2)$$

Where L is the width of the pump beam. Where n is the refractive index of the fluid. Deflection angle is dx/dy. This deflection angle ($|\psi|$) can be written as:

$$|\psi| = \frac{\sqrt{2}}{n}\frac{dn}{dT_f}\frac{L}{\mu_f}\left(Q_r^2 + Q_i^2\right)\exp\left(\frac{-x_0}{\mu_f}\right) \quad (3)$$

Where Q_r and Q_i are the real and imaginary part of T_s respectively.

Equation (3) is for general sample case. In case the sample is thermally thin ($\sigma_s d \ll 1$) and optically opaque ($\alpha \gg 1$) where $\sigma_i = (1+j)(\mu_i^{-1})$. The equation (3) can be written as [6]:

$$|\psi| = \frac{L}{n}\frac{dn}{dT_f}\frac{I_0(1-R_0)}{2K_s\langle b+g\rangle}\sqrt{\frac{D_s}{D_f}}\exp\left(-x_0\sqrt{\frac{\pi f}{D_f}}\right) \quad (4)$$

3. Experimental set-up

The experimental setup is described in figure 3. There are 2 laser lines. The first, a pump laser beam, a power I_0 =14 mW, 532 nm of wavelength, is modulated in various frequency by acousto-optic modulator driver (AOM) which is controlled by lock-in amplifier as SR830 then focused beam at the sample surface by 75 mm focal length double-convex lens. The diameter of the pump beam is 1.06 µm. The second, a He-Ne gas laser probe beam, 632.8nm of wavelength, 0.14 mW of power, is focused by 25.4 mm focal length double-convex lens. The diameter of the probe beam, intersects with the pump beam, is approximately 0.64 µm. It is paralleled the sample surface through the fluid and

intersect with pump laser beam. We cannot see the laser beams directly but we observed the amplitude from the log-in amplifier. If the probe beam overlaps the pump beam, the amplitude will be highest value. In case that we measured them at the same frequency. The probe laser deflection signal is obtained by a position sensor as quadrant photodiode with amplifier circuit related to the lock-in amplifier measure the deflection of probe beam. Computer reads the amplitude and phase signal from the lock-in amplifier for plotting the graph amplitude versus square root of frequency modulation.
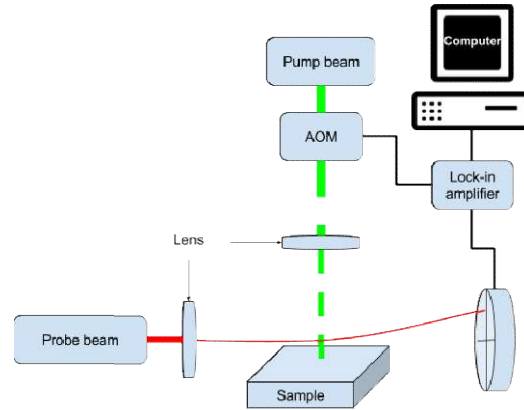

Figure 3. Experimental set-up

The sample uses as Sigradur type G (SGG), Copper (Cu). Their thermal diffusivity and their thickness are $D_{SGG} = 5.4\text{-}6\times10^{-2}$ cm^{2}s^{-1}, $D_{Cu} = 11.1\times10^{-1}$ cm^{2}s^{-1}, $-l_{SGG} = 1.9$ mm, $-l_{Cu} = 0.25$ mm. In the case of SGG, the fluid and backing media is ethyl alcohol. Its thermal diffusivity is $D_f = D_b = 8.52\times10^{-4}$ cm^{2}s^{-1}. In the case of Cu, the fluid and backing media is water, its thermal diffusivity is $D_f = D_b = 0.143\times10^{-6}$ cm^{2}s^{-1}. The skimming distance (x_0) is 36 μm for SGG and 18 μm for Cu. To determine the thermal diffusivity of SGG and Cu, we have to know properties of SGG and Cu which show in Table 1.

Table 1. Properties which use for determining SGG and Cu

Properties	SGG	Cu	Ethyl alcohol	Water
Thermal conductivity (k)	0.063 W/cm·k	3.86 W/cm·k	1.65×10^{-3} W/cm·k	5.91×10^{-3} W/cm·k
Thermal absorption (α)	1.43×10^{5}cm^{-1}	1.92×10^{4}cm^{-1}	-	-
Refractive index	-	-	1.361	1.333
dn/dT_f	-	-	-4.09×10^{-4} deg^{-1}	-9.4×10^{-5}deg^{-1}

4. Result and Discussion

We proved our calculation of equation (3) which was corrected by comparing with reference's calculation as in equation (4). According to figure 4, it shows our SGG's theoretical calculation comparing with reference's calculation. The slope of graphs are similar because SGG is thermally thin ($\sigma_s d \ll 1$) and optically opaque ($\alpha \gg 1$). Therefore, we are quite sure that our calculation is correct. In the other hand, in figure 5, the slope of graphs are different because Cu is not thermally thin like SGG.

According to figure 6, it shows the experimental results and theoretical variation for several of thermal diffusivity of SGG properties. We found that the trends of varying thermal diffusivities are different except 1×10^{-2} and 6×10^{-2} cm^{2}s^{-1} which are slightly different. The Experimental results are correspond with D = 5.57×10^{-2} cm^{2}s^{-1}. The experimental results and theoretical variation for several

thermal diffusivity of Cu properties are shown in figure 7. We found that the trend of varying thermal diffusivity is different. There is the noise at frequency at 50, 100, 150, 200 Hz. We cannot measure the results because of electricity frequency noise. We obtained values for frequency range 35 to 200 Hz since thermal diffusion length of Cu which its thickness is 0.25 mm. We presuppose that the experimental results are in micro voltage range which is too little amount so it is very hard to obtain the precise experimental result. The experimental results are correspond with $D = 1.22 \times 10^{-1}$ cm^2s^{-1}. The thermal diffusivity of SGG and Cu from the experiment and literature are given in Table 2. Phase variation of photothermal signal of SGG and Cu are shown in figure 8. In the case of SGG, the value obtained from experiment is slightly different from value of literature. In the case of Cu, the authors selected the coupling medium from the dn / dT value, which used to be Carbon tetrachloride but it is prohibited in Thailand. Therefore, Ethyl alcohol is needed instead. However, the Ethyl alcohol cannot be used in Cu's case because the Ethyl alcohol is a good solvent. Moreover, the surface of copper is coated by black ink in order to reduce some reflection. So, if we use the Ethyl alcohol, the ink coated on the copper surface will dissolve. We hypothesized that the Thermal diffusivity of Cu values of experimental results are inaccurate because we cannot use Ethyl alcohol as coupling medium and that black ink causes discrepancy.
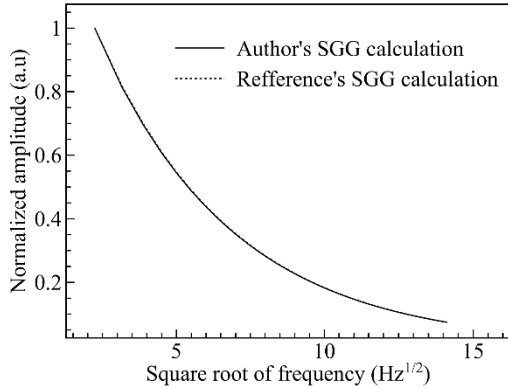

Figure 4. SGG's theoretical Variation of general case as presented in equation (3) vs specific case as presented in equation (4)
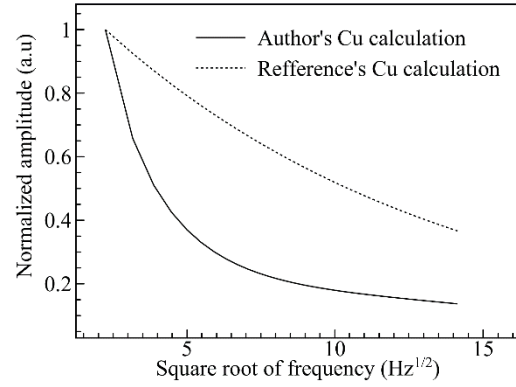

Figure 5. Cu's theoretical Variation of general case as presented in equation (3) vs specific case as presented in equation (4)
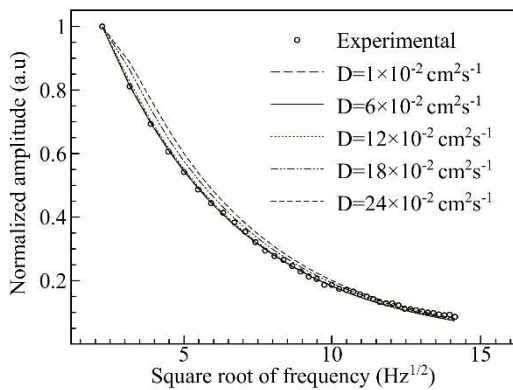

Figure 6. Variation of the normalized amplitude of photothermal signal vs the square root of the frequency modulation for several thermal diffusivity of SGG properties.
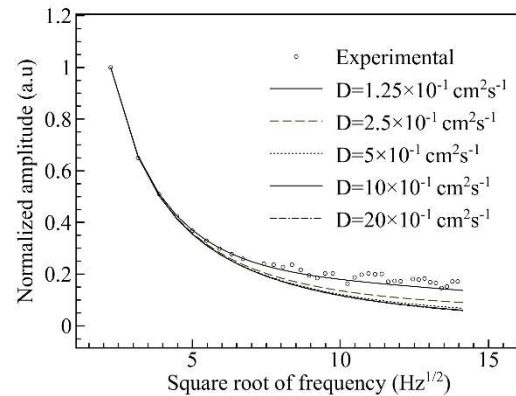

Figure 7. Variation of the normalized amplitude of photothermal signal vs the square root of the frequency modulation for several thermal diffusivity of Cu properties.
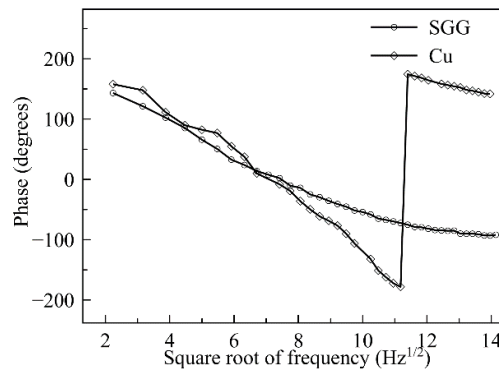
Figure 8. Variation of phase of photothermal signal vs the square root of the frequency modulation for several thermal diffusivity of SGG and Cu properties.

Table 2. Thermal diffusivity ($cm^2 \cdot s^{-1}$)

Material	Experiment	Literature
SGG	5.57×10^{-2}	$5.4\text{-}6 \times 10^{-2}$ [7, 8]
Cu	1.22×10^{-1}	11.1×10^{-1} [9]

5. Conclusion

In this paper we succeed in theoretical calculation of general case for one layer of bulk material which can be widely using. Our calculation corresponds to the result of our experimental set-up (in the case of SGG). It means that our experiment can determine the thermal diffusivity of bulk material by using frequency measurement of photothermal deflection technique. Moreover, we succeed in using ethyl alcohol as the coupling medium instead of CCl_4 which is highly toxic. To best of our knowledge, this is the first time Ethyl alcohol is used as a coupling medium in photodeflection technique and the first time photodeflection technique has been set to measure thermal diffusivities of materials in Thailand. The frequency measurement is easier than offset measurement because there is no need to translate sample. Therefore, this success can reduce experimental set-up size in order to make it more portable.

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