Thermal diffusivity of light-emitting diode packaging material determined by photoacoustic piezoelectric technique*

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Thermal property is one of the most important properties of light-emitting diode (LED). Thermal property of LED packaging material determines the heat dissipations of the phosphor and the chip surface, accordingly having an influence on the light-emitting efficiency and the life-span of the device. In this paper, photoacoustic piezoelectric (PAPE) technique has been employed to investigate the thermal properties of polyvinyl alcohol (PVA) and silicon dioxide, which are the new and the traditional packaging materials in white LED, respectively. Firstly, the theory of PAPE technique has been developed for two-layer model in order to investigate soft materials; secondly, the experimental system has been set up and adjusted by measuring the reference sample; thirdly, the thermal diffusivities of PVA and silicon dioxide are measured and analysed. The experimental results show that PVA has a higher thermal diffusivity than silicon dioxide and is a better packaging material in the sense of thermal diffusivity for white LED.

Keywords: thermal diffusivity, photoacoustic piezoelectric technique, two-layer model, LED packaging material

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1. Introduction

Temperature control is one of the most important technologies in the modern light-emitting industry.[1−3] Thermal property of light-emitting diode (LED) packaging material determines the heat dissipations of the phosphor and the chip surface, accordingly having an influence on the efficiency and the life-span of the light-emitting device.[4,5] Recently polyvinyl alcohol (PVA) was regarded as a new LED packaging material and has many advantages over silicon dioxide which is the traditional packaging material.[6,7] Whether PVA can replace silicon dioxide as a better LED packaging material still has much room for experimental researches. In terms of heat dissipation, some corresponding comparative studies need carrying out.

Photoacoustic piezoelectric (PAPE) technique has proved to be an effective method to determine the thermal diffusivity of various materials.[8−15] Based on Blonskij's simplified thermoelastic theory,[8] many metals[8,9] and composite materials[10−15] have been studied. Nevertheless, the present PAPE technique can only investigate the hard materials because the influence of piezoelectric transducer (PZT) on the vibration of the sample is neglected in the single-layer model. To some relatively soft materials, e.g. PVA and silicon dioxide, the single-layer theory is invalid.

In the present paper in order to develop the PAPE technique to study the thermal diffusivity of soft materials, an advanced theory is developed for the two-layer model (soft material with hard substrate). The two-layer theory is employed successfully to investigate soft material, and the thermal diffusivity of PVA, and silicon dioxide are measured and analysed.

2. Theory

The principle of the PAPE technique is as follows: a periodic heat source caused by the intensity modulated laser generates thermal waves; the thermal

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waves propagate in the sample and induce thermoelastic strains; the periodic thermoelastic strains are detected by the piezoelectric transducer attached to the back side of the sample.

The two-layer model is shown in Fig. 1. The sample is a thin circular plate consisting of two layers with thickness of l and H, respectively. The PZT is situated on the back side of the sample. Since we choose the hard and thick material to be the substrate, the influence of PZT on the strains in the sample is negligible.

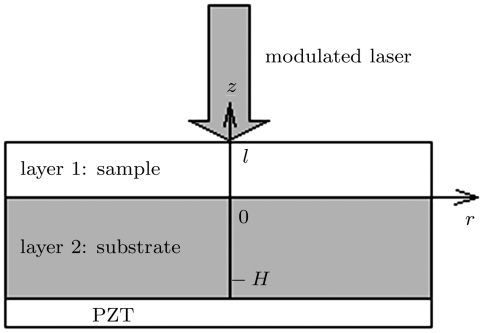


Fig. 1. Theoretical model under investigation.

Temperature distribution in the sample can be obtained from the heat conduction equation

$$\frac{\mathrm{d}^2 T_j}{\mathrm{d}z^2} - \sigma_j^2 T_j = -\frac{I\beta}{k_j}\,\mathrm{e}^{-\beta(l-z)}, \tag{1}$$

where T is the temperature, $j = 1, 2$ are the numbers of the upper and the lower layers, respectively; $\sigma^2 = \mathrm{i}\omega/D$, with ω being the modulation frequency and $D = k/(\rho C)$ the thermal diffusivity (k is the thermal conductivity, ρ is the density and C is the specific heat); I is the intensity of the incident laser; β is the optical absorption coefficient. Four boundary conditions are found from the adiabatic surfaces of the model and the continuities of the temperature and the heat flow at the interface between the two layers.

We consider the case of strong optical absorption, thus the solution of the temperature distribution has the form[16]

$$\begin{aligned} T_1 &= \frac{I}{k_1\sigma_1 Z}[\cosh(\sigma_2 H)\cosh(\sigma_1 z) \\ &\quad + q\sinh(\sigma_2 H)\sinh(\sigma_1 z)], \\ T_2 &= \frac{I}{k_1\sigma_1 Z}\cosh[\sigma_2(H+z)] \quad \text{continuity}, \end{aligned} \tag{2}$$

where $Z = \cosh(\sigma_2 H)\sinh(\sigma_1 l) + q\sinh(\sigma_2 H) \times \cosh(\sigma_1 l)$, and $q = (k_2\rho_2 C_2)^{1/2}/(k_1\rho_1 C_1)^{1/2}$.

Thermoelastic stresses and strains can be found from equations[16]

$$\frac{\partial^2 \sigma_{xx}}{\partial z^2} + \alpha_j F_j \frac{\partial^2 T_j}{\partial z^2} = 0, \tag{3}$$

where σ_{xx} is the stress in the x direction, α is the linear thermal expansion coefficient, and F is a biaxial modulus which is related to the Young's modulus E and Poisson's ratio ν by $F = E/(1-\nu)$. The boundary condition at the interface requires the continuity of the strains. Using the stress free boundary conditions for $z = l, -H$, we can obtain the thermoelastic stresses and strains in the two layers.

Piezoelectric equation takes the form[16]

$$V = \frac{eL}{\varepsilon S}(\varepsilon_{xx} + \varepsilon_{yy})_{z=-H}, \tag{4}$$

where e is the piezomodulus, L is the thickness of the transducer, ε is a dielectric constant, S is the surface area of the transducer, and ε_{ii} is the strain in the i direction.

The output voltage of PZT has the form[16]

$$\begin{aligned} V = \frac{eL}{\varepsilon S}\frac{2I}{k_1\sigma_1 Z}\Bigg\{ & \alpha_2 F_2 m\frac{\sinh(\sigma_2 H)}{\sigma_2} + \alpha_1 F_1 m\frac{Z - q\sinh(\sigma_2 H)}{\sigma_1} + \alpha_2 F_2 n\frac{1-\cosh(\sigma_2 H)}{\sigma_2^2} \\ & + \alpha_1 F_1 n\frac{[Z\sigma_1 l - \cosh(\sigma_1 l)\cosh(\sigma_2 H) - q\sinh(\sigma_1 l)\sinh(\sigma_2 H) + \cosh(\sigma_2 H)]}{\sigma_1^2}\Bigg\}, \end{aligned} \tag{5}$$

where

$$m = \frac{C - HA}{CB - A^2}, \quad n = \frac{A - HB}{CB - A^2},$$
$$B = F_1 l + F_2 H, \quad A = \frac{1}{2}(F_2 H^2 - F_1 l^2),$$

and

$$C = \frac{1}{3}(F_1 l^3 + F_2 H^3).$$

Some simplifications need considering. Thermal waves have great damping in the process of propagation, and the penetration depth is determined by the thermal diffusion length $l_\mathrm{t} = (2D/\omega)^{1/2}$. When the modulation frequency is higher than a certain value, the thermal diffusion length will satisfy $l_\mathrm{t} < l$, which means that the upper layer is thermally thick

and the thermal properties of lower layer make little contribution to the output signal. In this condition, thermoelastic effect will not be arisen in the lower layer and it acts only as acoustic-propagating media. In this approximation, we can obtain $q = 1$ and $Z = \sinh[\sigma_1(l + H)]$. So the thermal two-layer problem is simplified and we can concentrate on the elastically two-layer model.

Here we introduce a parameter $p = F_1/F_2$, which represents the ratio of elastic parameters between the two layers. By simple transform of Eq. (5) we obtain the expression of the phase of the PA signal

$$\begin{aligned}\tan\varphi = {} & (2U\sin[a(H+l)]\cosh[a(H+l)] + 2V\cos[a(H+l)]\sinh[a(H+l)] + 4apA'\{\cos^2[a(H+l)] \\ & - \cosh^2[a(H+l)]\} - 3pB'\{\sin[2a(H+l)] - \sinh[2a(H+l)]\})/(2V\sin[a(H+l)]\cosh[a(H+l)] \\ & - 2U\cos[a(H+l)]\sinh[a(H+l)] + 3pB'\{\sin[2a(H+l)] + \sinh[2a(H+l)]\}),\end{aligned} \tag{6}$$

where $a = (\omega/2D)^{1/2}$ and

$$\begin{aligned}&A' = H^3 + 3H^2l + 3Hl^2p + l^3p, \quad B' = H^2 + 2Hlp + l^2p, \quad C' = H^3 - 3Hl^2p - 2l^3p,\\ &U = 3B'\{1 - (1-p)[\cos(aH)\cosh(aH) - \sin(aH)\sinh(aH)]\} - 2aC'(1-p)\sin(aH)\cosh(aH),\\ &V = -3B'\{1 - (1-p)[\cos(aH)\cosh(aH) + \sin(aH)\sinh(aH)]\} - 2aC'(1-p)\cos(aH)\sinh(aH).\end{aligned}$$

Two particular cases are worth noting.

(1) $H = 0$. In this case we have

$$\tan\varphi = \frac{2al(\cos(al) + \cosh(al)) - 3(\sin(al) + \sinh(al))}{3(\sin(al) - \sinh(al))}. \tag{7}$$

This result satisfies the single-layer theory in Blonskij's work.[8]

(2) $p = 1$. In this case we have

$$\tan\varphi = \frac{2a(H+l)[\cos(a(H+l)) + \cosh(a(H+l))] - 3[\sin(a(H+l)) + \sinh(a(H+l))]}{3[\sin(a(H+l)) - \sinh(a(H+l))]}. \tag{8}$$

This result also satisfies Blonskij's theory because the elastical two-layer model is identical to the single-layered model when the materials of the two layers have the same elastic properties.

The theoretical analysis shows that it is possible to determine the thermal diffusivity from the phase-to-frequency or amplitude-to-frequency characteristics. The thermal diffusivity of the upper layer D and the ratio p are the only two parameters determining the phase-to-frequency characteristic (under the known thicknesses of both layers). The phase-to-frequency characteristic has proved to be a better way to study the thermal diffusivity of the sample.[8–15]

Some theoretical predictions for the materials of known properties are shown in Fig. 2. The Al/brass theoretical model has $l = 1$ mm, $H = 1$ mm, $D = 82$ mm^2/s, and $p = 0.63$. The brass/Al theoretical model has $l = 1$ mm, $H = 1$ mm, $D = 34$ mm^2/s, and $p = 1.59$. The rubber/glass theoretical model has $l = 0.5$ mm, $H = 1$ mm, $D = 1$ mm^2/s, and $p = 0.08$. One can observe that the curve of rubber/glass is more complicated than others because p is a very small value, namely the difference in elastic property between rubber and glass is great. The non-monotonic phase-to-frequency characteristic never appears in the single-layer theory.

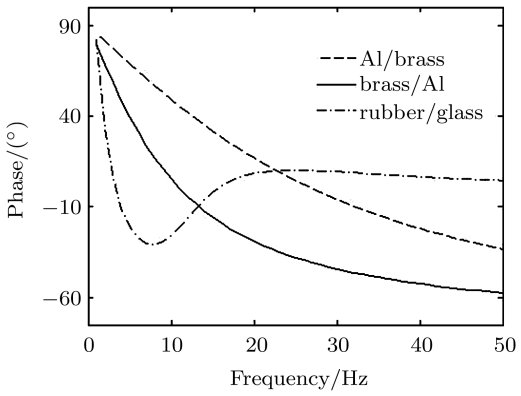


Fig. 2. Theoretical curves for some materials.

3. Experiment and discussion

The experimental setup is shown in Fig. 3. The laser produced by an argon-ion laser equipment (wavelength 514 nm, power 130 mW) is modulated by an acousto-optic modulator driven by a function generator; the modulated laser beam induced on the surface of the sample changes the temperature distribution of the sample; vibrations of the sample, caused by the periodic heating, are detected by a piezoelectric transducer attached on the back side of the sample; lock-in amplifier deals with the output signal. PZT is made into the form of disk with a thickness of 0.2 mm and diameter of 18.2 mm.

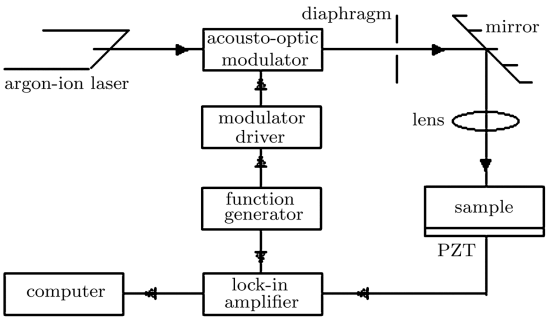


Fig. 3. Schematic diagram of experimental setup.

In order to verify the theory and adjust the experimental system, we carry out the measurement of reference sample. It is difficult to find the soft material which has a certain reference value of thermal diffusivity, so we choose brass which is relatively soft as a reference sample with aluminum alloy being the substrate. The optical absorption of metal sample is strong and we can treat it as surface absorption. In Fig. 4 the experimental data and the best fitting curve of the brass/Al sample are shown (D and p are determined as the two fitting parameters). The experimental value, the reference value and the relative error are shown in Table 1. The accuracy analysis shows that the relative error is less than 5% and the experimental system is available to measure the thermal diffusivity of PVA and silicon dioxide.

Table 1. Thermal diffusivity of brass/Al sample.

sample	experimental value /(mm^2/s)	reference value /(mm^2/s)	error/(%)
brass/Al	33.15	34[17]	2.5

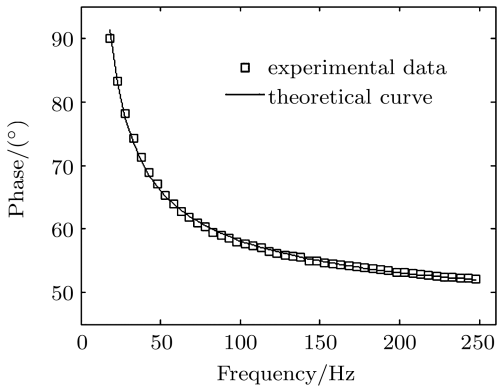


Fig. 4. Data and curve of brass/Al.

The samples of PVA and silicon dioxide both in the presence of phosphor are made into the form of disk with Yttrium Aluminum Garnet (YAG) being the substrate. Ammonium dichromate (ADC) has been used as photosensitive adhesive to solidify the PVA solution. PZT is attached on the back side of YAG. The sample surface is plated on a very thin carbon layer to enhance the optical absorption. The experimental data, the best fitting curve, and the value of thermal diffusivity are shown in Figs. 5 and 6.

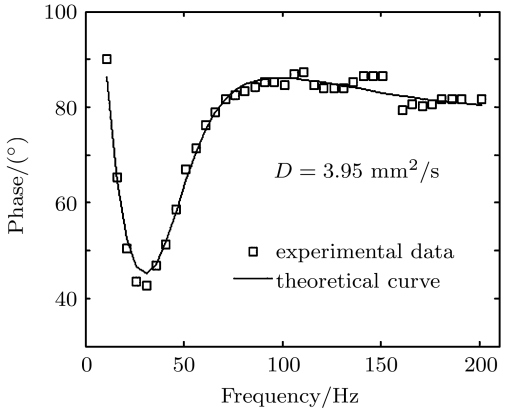


Fig. 5. Data and curve of PVA.

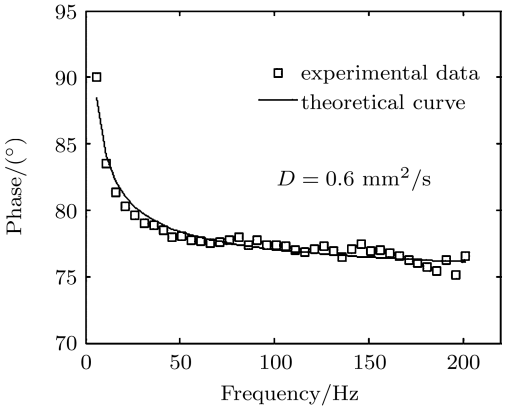


Fig. 6. Data and curve of silicon dioxide.

The thermal diffusivities of PVA and silicon dioxide are calculated to be 3.95 mm^2/s and 0.6 mm^2/s, respectively. The reference value of silicon dioxide, according to the handbook,[18] is in a range from 0.27 to 0.64 mm^2/s, which shows the rationality of the experimental results. However, the reference value of PVA is still unknown. Since the experimental conditions of the two measurements are the same, one may believe that the experimental result of PVA is also reliable as that of silicon dioxide.

It is obviously that the experimental data accord well with the theoretical curve in low modulation frequencies. When the frequencies go up from 150 Hz to 200 Hz, the discrepancy between the theory and the experiment appears. With the frequency increasing, the PAPE signal and its signal noise ratio (SNR) decrease, leading to the instability of the phase.

The non-monotonic phenomenon which accords very well with the theoretical prediction appears in Fig. 5. The parameter p is calculated to be 0.04, which implies the great difference in elastic property between PVA and YAG. The traditional theory cannot fit this set of data because the difference in elastic property between the two layers was not taken into account. Explaining the non-monotonic phenomenon demands further investigation.

Several factors which restrict the accuracy of the experimental results should be noted. Firstly, the interaction between the substrate and PZT is neglected. Though YAG is hard and thick compared with PZT in our experiment, the expansion of YAG is still influenced. Secondly, the carbon layer plated on the sample surface brings error even if it is thin and compliant. Its influence on the sample vibration is negligible; nevertheless, it could have an influence on the temperature distribution in the sample. Thirdly, the contribution of the thermoelastic effect in the substrate to the output signal is not taken into account. The modulation frequencies in our experiment are larger than 11 Hz so as to satisfy the thermally thick condition of the upper layer material, however, there is still a little amount of heat propagating to the substrate and causing the thermoelastic effect in low modulation frequency.

Even if there are several factors restricting the accuracy of the experimental results, the two-layer PAPE technique has overcome the limitation to the conventional one which cannot be applicable to the study of the thermal diffusivity of soft material. PAPE technique will have a wide range of applications to the determination of the thermal diffusivities of various materials.

4. Conclusions

The two-layer PAPE theory has been developed and employed successfully to investigate the thermal diffusivities of soft materials. By introducing the ratio between elastic parameters of the two layers, the analytical expression of the phase versus modulation frequency has been obtained. The experimental system has proved to be accurate to measure the thermal diffusivity of two-layer material. PVA has a higher thermal diffusivity than silicon dioxide and is a better packaging material in the sense of thermal diffusivity in white LED.

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