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# Experimental study on the influence of surface roughness for photothermal imaging with various measurement conditions

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ABSTRACT

Imaging techniques for internal visualization of materials have become increasingly important in a wide range of industrial fields. Imaging techniques such as magnetic resonance imaging (MRI) and computed tomography (CT) employing X-rays have existed for quite some time. However, such classic techniques have physical limitations (for e.g., X-rays cannot penetrate high-density materials such as metals) because they were developed as medical applications. Therefore, alternative techniques for industrial fields should be explored. Photothermal imaging was explored from the perspective of visualization of the interior of metals as photothermal effects depend on the thermal properties of the materials. To establish photothermal imaging as a reliable technique, it is important to analyze the physical limitations and noise in the measurement. Therefore, in this study, the conditions leading to a minimum level of noise were explored using aluminum 6061 specimens of five surface roughness values under conditions of different pump beam frequencies and radii. In this work, surface roughness and pump beam frequency and radius were considered important parameters affecting photothermal imaging. Finally, comprehensive criteria to reduce signal noise in photothermal imaging were proposed.

## 1. Introduction

Large-scale production of semiconductors is necessary in various industries. Semiconductors are an important component in the production of electronic parts such as transistors and integrated circuits. In such industries, accuracy and high yield rate are essential in manufacturing processes such as the growth or deposition of semiconductors and electrode materials for integrated circuits [1]. In addition, these products should be well packaged for protection [2]. However, at the end of the packaging process, diagnosing and evaluating whether the internal circuit is built as intended is a challenge. To solve these problems, visualization methods such as magnetic resonance imaging (MRI), computed tomography (CT), X-ray imaging, and ultrasonic wave imaging are necessary. However, these methods are not suitable for visualizing the interiors of products such as packaged semiconductors or metallic circuits because they can be applied to objects that are transparent to X-rays, for e.g., the human body [3].

An imaging technique using photothermal effects was studied recently as an alternative imaging method [4]. The use of photothermal imaging for finding hidden subsurface patterns has been explored since it was proposed by Murphy [5]. McDonald et al. investigated the visualization feasibility for a 6.3-mm slit inside a metal (aluminum) [6]. Wetsel and McDonald, conducted various studies on detecting subsurface structure [7].

A few researchers who studied imaging methods based on photothermal effects reported that unknown subsurface defects could be detected in their experiments [5–9]. However, the method was not systematically researched. Moreover, even though McDonald et al. and Murphy et al. concluded that signal noise was caused by irregularities of the surface during the measurement [7,9], no quantitative analysis and research were performed.

Fig. 1 illustrates the photothermal effect [4,11] and probe beam deflection when pump beam irradiates the surface of materials. The temperature distribution occur in material through the absorption of photothermal energy, which consequently induces the gradient of refraction index in air layer on the surface of material. The temperature distribution on the surface of the test section mainly depends on the thermal diffusivity of the material distribution [11–14]. However, if an unexpected parameter such as an irregularity (roughness) of the surface, other than the material distribution, exists, it may influence the temperature distribution; hence, useful information cannot be obtained from the probe beam signal. Such unexpected parameters can be

*Abbreviations:* STD, standard deviation; TDL, thermal diffusion length; EDS, energy density per single-shot

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**Nomenclature**

| | |
|---|---|
| $A_{pump}$ | Area of the pump beam ($m^2$) |
| $Cp$ | Specific heat (J/kgK) |
| $f$ | Radius of the pump beam (m) |
| $k$ | Thermal conductivity (W/mK) |
| $L$ | Thickness of the sample (m) |
| $L_d$ | Thermal diffusion length (m) |
| $L_h$ | Z-position of probe beam(m) |
| $n$ | Refractive index |
| $P$ | Power of the pump beam (W) |
| $Q$ | Heat source ($W/m^3$) |
| $q$ | Heat flux($W/m^2$) |
| $q_x$ | Integral variable in complex form |
| $q_y$ | Integral variable in complex form |
| $R_a$ | Mean roughness of sample surface (nm) |
| $R_b$ | Radius of the pump beam (m) |
| $R_\Omega$ | Reflectance of sample surface (%) |
| $S$ | Probe beam path |
| $T$ | Temperature (K) |
| $t$ | Time (s) |
| $x_0$ | Relative position (m) |
| $x_c$ | X coordinate of the center of the pump beam (m) |
| $y_c$ | Y coordinate of the center of the pump beam (m) |

*Greek symbols*

| | |
|---|---|
| $\alpha$ | Thermal diffusivity ($m^2/s$) |
| $\lambda$ | Optical absorption coefficient ($m^{-1}$) |
| $\omega$ | Angular frequency (1/s) |
| $\varphi$ | Deflection angle (°) |
| $\psi$ | Phase delay (°) |

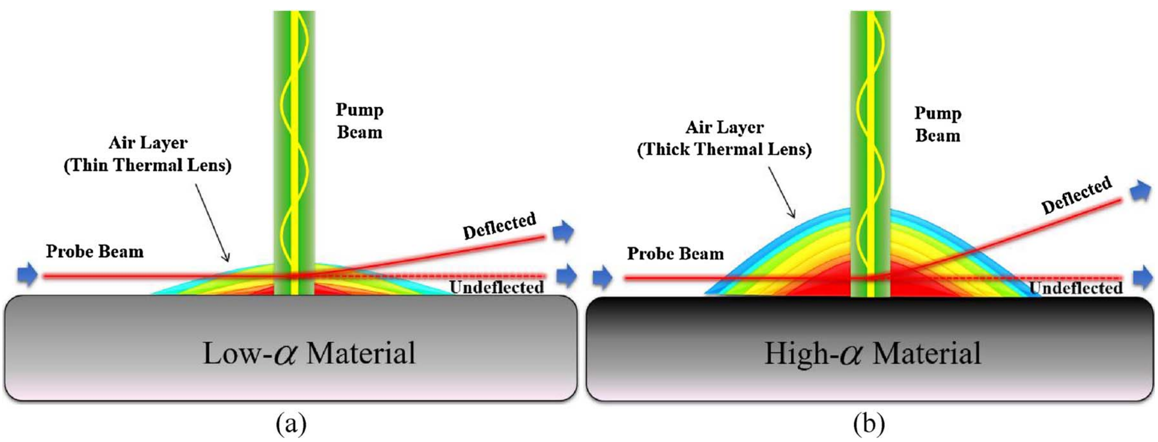


**Fig. 1.** Temperature distribution of air layers and probe beam deflection with photothermal effect for materials with (a) low and (b) high thermal diffusivity.

considered to be noise and should be removed or manipulated for accurate measurements.

Generally, the presence of noise indicates the existence of signals other than the one to be observed. Noises can be decreased by overlapping signals in other imaging methods [15]; however, the overlapping method is not suitable for photothermal imaging because more time is required for scanning in this technique than in other imaging methods. In this study, the noise in photothermal effect signals caused by surface irregularities was analyzed, and other parameters that may affect the noise were considered.

Thus, the noise level and its tendency under various conditions of surface roughness, modulated frequencies of pump beam, and pump beam radius were examined.

## 2. Concept of photothermal imaging

As shown in Fig. 1, when a modulated pump beam irradiates the test samples, the samples absorb energy by the photothermal effect, and their temperature increases [4,10–14]. Since the absorption coefficient of air is very small, the amount of energy absorbed by the air layer can be neglected [10–14]. The absorbed energy diffuses in all directions by thermal diffusion, which changes the temperature of the test samples and forms unique temperature distribution fields depending on the frequency of the modulated pump beam and distribution of the test sample's thermal diffusion coefficient. A unique propagation depth of the thermal energy is found for each material. The length of thermal energy propagation is called thermal diffusion length (TDL, $L_d$) [16].

$$L_d = \sqrt{\frac{\alpha}{\pi f}} \tag{1}$$

Eq. (1) shows the correlation of the frequency of the modulated pump beam and the thermal diffusion coefficient, expressing TDL. As the frequency of the modulated pump beam increases, TDL decreases. Further, the TDL also decreases with a decrease in the thermal diffusion coefficient of the sample. Therefore, the modulation frequency should be selected properly to achieve sufficient TDL to detect subsurface patterns, which are located deep inside the measurement samples.

The temperature distribution of the air adjacent to the surfaces of the test samples follows that of the surfaces of the test samples; thus, it depends solely on the thermal diffusion coefficient of the test sample when the power and frequency of the modulated pump beam are fixed. The temperature distribution of this air causes variation in the refractive index; as a result, the probe beam is deflected as it propagates along the surfaces. The probe beam oscillates because the pump beam is modulated as a harmonic function. The probe beam has a smaller deflection angle for materials with small thermal diffusion coefficients [Fig. 1(a)] than for materials with large thermal diffusion coefficients [Fig. 1(b)].

As shown in Fig. 2(a), the phase delay between the modulated pump beam and the probe beam arises because of the time required for heat energy to diffuse. In the photothermal imaging method, this phase delay is employed for the measurement. The phase delay is selected for this purpose instead of the deflection angle because the deflection angle is usually so small in reality that it is very difficult to measure. As shown in Fig. 2(b), scanning must be obtain 2-dimension entire material distribution to detect patterns of high α materials.