Abstract—During the last few decades, photothermal radiometry (PTR) has been greatly developed and widely applied in the field of nondestructive testing. However, the traditional PTR system employs an expensive lock-in amplifier to detect the weak photothermal signal, which leads to high cost and long test time. In this paper, a fast transmission PTR system based on sampling by using an internal computer sound card was developed to lower the system cost and shorten the test time. A piece of amorphous silicon (a:Si) thin film solar cells with artificial defects was prepared and tested by the system. The results show that the sharpened defects can be identified easily and quickly according to the significant peaks of the original infrared signal sampled by the internal computer sound card. Furthermore, more detailed defects can be investigated by processing the infrared signal. These validate the effectiveness of the proposed transmission PTR system as a low cost and efficient non-destructive test technique.

Index Terms—Amorphous silicon thin film solar cells, internal computer sound card, nondestructive testing, transmission photothermal radiometry.

1. Introduction

In 1979, photothermal radiometry (PTR), based on “photoacoustic effect”, was first introduced by Nordal and Kanstad who are two of the most famous scientists in the field of photoacoustic and photothermal phenomenon\(^1\). During the last few decades, the PTR technique has been greatly developed and extensively studied worldwide drawn by its high sensitivity, high security, and high resolution. The PTR technique has been widely applied in the field of nondestructive testing, including surface cracks imaging\(^2\), deep subsurface defects detection\(^3\), hairline crack detection\(^4\), quantitative evaluation of the kinetics of human enamel simulated caries\(^5\), industrial steel hardness inspection\(^6\), thermal diffusivity determination of polymerized dental resins\(^7\), properties characterization of semiconductor materials\(^8\),\(^9\), and thermal conductivity measurement of thin films\(^{10}\) and surface roughness investigation\(^{11}\). However, an expensive lock-in amplifier was adopted in the traditional PTR system to detect the weak photothermal signal\(^{2}\)\(^−\)\(^{11}\), which resulted in high system cost and long test time. To lower the system cost and shorten the test time, a fast transmission PTR system based on sampling by an internal computer sound card (also known as an audio card) is introduced in this paper. The signals, whose frequency range is 10 Hz to 20 kHz and amplitude is lower than 1.5 V, can be sampled by the internal computer sound card. The sample rate of the internal computer sound card can be up to 96 kHz and the sample resolution is 16 bits or 20 bits, or even 24 bits for some advanced sound cards. It was reported that an internal computer sound card was applied in signal processing in a photoacoustic system\(^{12}\). Thus the internal computer sound card is also qualified enough for photothermal signal detection in a PTR system, which means that there is no need to use an extra expensive lock-in amplifier.

2. Theoretical Consideration

A 3-dimensional (3D) simplified transmission PTR model is shown in Fig. 1. A single layer sample of optically opaque material, with the thickness of \(l\), is surrounded by air. A laser beam with the intensity \(I_0\) and angular modulation frequency \(\omega = 2 \pi f\) is impinged on the front surface of the sample, which absorbs light on its surface. Because the sample studied here is a piece of amorphous silicon thin film solar cells, there will be both radiative recombination and non-radiative recombination when the sample absorbs the laser. Photo-carrier radiometry
(PCR)\(^{[13]-[16]}\) studies the photons induced by the radiative recombination, while PTR studies the infrared photons induced by the non-radiative recombination. The behavior of the infrared photons can be described by the typical heat transfer theory. The corresponding thermal conduction equation is given by

\[
\nabla^2 T(r, z, t) = \frac{1}{D} \frac{\partial T(r, z, t)}{\partial t} - \frac{\beta P \eta (1 - R)}{\pi \kappa W^2} e^{-(r/w)^2 - \beta z} e^{i \omega t}, (0 \leq z \leq l) \tag{1}
\]

where \(r, z, t, D, \kappa, \beta, P, \eta, R, \) and \(W\) are the radial axis of the sample, the axial axis of the sample, time, thermal diffusivity, thermal conductivity, optical absorption coefficient, laser power, non-radiative conversion efficiency, reflectivity of the front surface of the sample, and laser spot radius, respectively.

Assuming that \(T(r, z, t) = T(r, z)e^{i \omega t}\), then (1) can be transformed as

\[
\nabla^2 T(r, z) - \frac{j w}{D} T(r, z) = - \frac{\beta P \eta (1 - R)}{\pi \kappa W^2} e^{-(r/w)^2 - \beta z}. \tag{2}
\]

Assuming that \(T(q, z) = H_0(T(r, z))\) is the Hankel transform of zero-order of function \(T(r, z)\), thus (2) can be transformed as

\[
\frac{d^2 T(q, z)}{dz^2} - \xi^2 T(q, z) = -H(q)e^{-\beta z} \tag{3}
\]

where \(q\) is the scaling factor along the \(r\)-axis, \(\xi^2 = q^2 + \frac{j w}{D}\), and \(H(q) = \left(\beta P \eta (1 - R) / 2 \pi \kappa \right) e^{-(q/w)^2}\).

Considering \(z\) as the only variable, (3) is a typical second-order homogeneous linear differential equation. With boundary conditions:

\[
-\kappa \frac{dT(q, z)}{dz} \bigg|_{z=0} = 0 \quad \text{and} \quad -\kappa \frac{dT(q, z)}{dz} \bigg|_{z=l} = 0.
\]

The general solution for (3) is given by

\[
T(q, z) = \frac{H(q)\beta e^{-(\beta + \xi)^2 (q/w)^2}}{(\xi^2 - \beta^2)(e^{(\beta - \xi)^2 (q/w)^2} - 1)} e^{\xi z} + \frac{H(q)\beta (e^{-(\beta + \xi)^2 (q/w)^2})}{(\xi^2 - \beta^2)(e^{(\beta - \xi)^2 (q/w)^2} - 1)} e^{-\xi z} + \frac{H(q)}{\xi^2 - \beta^2} e^{-\beta z}. \tag{4}
\]

The solution to (1) is the inverse Hankel transform of \(T(q, z)\):

\[
T(r, z) = \int_0^\infty T(q, z)J_0(qr)dq \tag{5}
\]

where \(J_0(qr)\) is the Bessel function of the first kind of order zero.

The output of the infrared detector, which detects the infrared radiation from the rear surface of the sample, is given as

\[
Q = 2\pi \int_0^\infty 4\sigma_0 T(r, l) A d^2 r (d^2 r + r^2) \tag{6}
\]

where \(\sigma = 5.67 \times 10^{-12} \text{ W/cm}^2\text{K}^4\), \(T_0, R_0, A, d\) are the Stefan-Boltzmann constant, ambient temperature, radius of the active radiation area of the rear surface of the sample, the active area of the infrared detector, and the distance between the rear surface of the sample and the infrared detector, respectively. \(Q\) is related to \(f, \omega, D, \kappa, \beta, P, \eta, R, W, A, d, R_0, \) and \(l\).

For investigating a piece of amorphous silicon thin film solar cells with mechanical defects on the rear surface by scanning, the value of \(Q\) has to be normalized. Then the normalized \(Q\) would be only sensitive to the changes of the thickness of the sample \(l\), which is the dominative affection made by the mechanical defects. Thus, if the internal computer sound card is qualified enough to record the weak changes of the pre-amplified output of the infrared detector, the defects can be detected by the fast transmission PTR system theoretically.

Furthermore, the infrared signal is processed to display the element whose frequency is in accord with that of the reference signal. In a traditional PTR system, since the amplitude of the photothermal infrared signal is much smaller than that of the noise in most time in the practical experiment, a lock-in amplifier is employed to increase the signal to noise ratio (SNR) by locking the photothermal infrared signal with the modulation frequency \(f\). For the proposed fast transmission PTR system, the scan line is equally divided into small enough sections, in which the properties of the sample are homogeneous, so each section could be assumed as a point. Thus, the data sampled by the internal computer sound card while doing a line scan are equally divided into small sections, too. Then each section of data are processed by the fast Fourier transformation (FFT) to gain the signal whose frequency is the same as that of the reference signal. Such a process will increase the system’s SNR and show much more detailed defects.
3. Experimental Setup

The schematic diagram of the fast transmission PTR system is shown in Fig. 2, which is similar to the tradition transmission PTR system\cite{17} except that the lock-in amplifier is replaced by an internal computer sound card. A semiconductor laser beam (the wavelength is 830 nm and the power is about 200 mW) is modulated by a chopper and then focused onto the front surface of the sample. The heat emission on the opposite surface is monitored via an infrared radiometric detection by an HgCdZnTe detector (Vigo, PVM-10.6) whose active area is 1 mm×1 mm. In front of the detector, a long wave pass filter is used to block the excitation laser beam and the radiative recombination induced photons, which insures that only the infrared photons induced by non-radiative recombination will be detected by the infrared detector. The output from the detector is pre-amplified and sampled by an internal computer sound card (Realtek ALC662, whose sample resolution is 16 bits and sample rate is up to 96 KHz). Meanwhile, the reference signal, which is also the modulation signal for the semiconductor laser, is adjusted by an adjustment circuit and sampled by the internal computer sound card as well. Both the reference signal and infrared signal sampled by the internal computer sound card are processed and analyzed by the PC.

4. Experimental Results

A piece of amorphous silicon thin film solar cells with mechanical defects on the rear surface was tested by the fast transmission PTR system, in which the modulation frequency is 4 kHz and the sample rate is 40 kHz. As shown in Fig. 3, both the reference signal and infrared signal are sampled by the internal computer sound card. It only takes 2.8 s to scan a 7.7 mm line of the sample. It is faster than traditional lock-in thermography systems\cite{18-20}, which takes more than 1000 s to achieve a test. According to (6), the thinner the sample is, the stronger the infrared signal will be. Thus, the mechanical defects which affect the thickness of the sample can be easily identified by the two significant peaks of the infrared signal. The higher peak appears at about 1.8 s. Then the two significant defects can be easily located at $x_1=(7.7 \text{ mm}/2.8 \text{ s}) \times 1.4 \text{ s}=3.85 \text{ mm}$ and $x_2=(7.7 \text{ mm}/2.8 \text{ s}) \times 1.8 \text{ s}=4.95 \text{ mm}$ because that the line-scan is a uniform motion in a straight line.

![Fig. 3. Reference signal and infrared signal sampled by the internal computer sound card.](image1)

Normally, the reference signal sampled by the internal computer sound card should have one frequency of 4 kHz and the three multiple frequency of 12 kHz. However, as shown in Fig. 4, the frequency spectrum of the reference signal shows that there are some low frequency signals. There must be some noise in the fast transmission PTR system. Considering the very low non-radiative conversion efficiency $\eta$, the photothermal infrared signal is much smaller than the noise. As shown in Fig. 5 (a), the amplitude of the photothermal infrared signal with the frequency $f=4 \text{ kHz}$ is only 0.33 mV, while the amplitude of the photothermal infrared signals in the frequency range of 0 to 200 Hz is up to 2 mV, even 13.12 mV for $f=0$ as shown in Fig. 5 (b). Thus, the original infrared signal shown in Fig. 3 contains a lot of noise that is much larger than the photothermal infrared signal, which means that many detailed defects can not be revealed.

![Fig. 4. Frequency spectrum of the reference signal sampled by the internal computer sound card.](image2)

![Fig. 5. Frequency spectrum of the infrared signal sampled by the internal computer sound card: (a) frequency range from 0.2 kHz to 20 kHz and (b) frequency range from 0 to 20 kHz.](image3)
The traditional PTR system\cite{2,11,17} employs a lock-in amplifier to detect the weak photothermal infrared signal among the large noise via locking the photothermal infrared signal with the modulation frequency \( f \). To realize the similar function of the lock-in amplifier in the fast transmission PTR system, the infrared signal data are equally divided into small sets. Then each set of data are processed by FFT. Hence, for each section, the signals whose frequency is the same as that of the reference signal will be obtained and plotted in Fig. 6 which shows a lot of more detailed defects which could not be identified in Fig. 3. Comparing Fig. 3 and Fig. 6, only two sharpened defects can be identified by the two significant peaks in Fig. 3, while the significant ones and the smaller ones can be all revealed in Fig. 6. There are defects all along the scan line except the range between 1 mm to 3 mm. Specifically, the defects at 0 to 1 mm are as deep as the sharpened defect at \( x=4.95 \) mm, but much wider. Thus the infrared signal does not change much at 0 to 1 mm because only the changes of the infrared radiation could be detected by the infrared detector. That is why the original infrared signal in Fig. 3 can only reveal the sharpened defects.

![Image](image_url)

Fig. 6. Element of the infrared signal with the same frequency \( f=4 \) KHz as that of the reference signal.

5. Conclusions

A fast transmission PTR system based on sampling by the internal computer sound card is proposed, which can not only detect the defects effectively, but also lower the system cost and shorten the test time.

a) By analyzing the 3D transmission PTR model, the transmission PTR system can detect the defects which affect the thickness of the sample.

b) In the proposed system, the expensive lock-in amplifier can be replaced by an internal computer sound card to detect the weak photothermal infrared signal, which lowers the cost of the fast transmission PTR system.

c) The internal computer sound card can sample signals continuously while doing a line scan on the sample. It is much faster than the traditional lock-in thermography systems in which the lock-in amplifier has to detect the signal point by point.

d) The original infrared signal sampled by the computer sound card can reveal the sharpened defects, but not the defect which are homogeneous and continuously distributed.

e) The infrared signal processing is turned out essential and useful. It helps the fast transmission PTR system to realize the lock-in amplifier function, which increases the SNR and reveals more detailed defects.

The theoretical analysis and experiment results validate the proposed fast transmission PTR system is a low-cost, efficient, and effective non-destructive test technique.

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References


