음향파의 위상 추정을 이용한 실리콘 웨이퍼의 온도 측정

論 文
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Temperature Measurement of Silicon Wafers Using Phase Estimation of Acoustic Wave

姜 俊 赫* · 李 錫 垣**
(Joonhyuk Kang · Seokwon Lee)

Abstract – Accurate temperature measurement is a key factor to implement the rapid thermal processing(RTP). A temperature estimation method using acoustic wave has been proposed to overcome the inaccuracy and contamination problem of the previous methods. The proposed method, however, may suffer from the offset and low resolution problem since it is implemented in the time domain. This paper presents a temperature estimation method using the phase detection of acoustic wave. Based on the frequency domain approach, the proposed technique increases the resolution of the measured temperature and reduces the effect of noise. We investigate the performance of the proposed method via experiments.

Key Words : temperature measurement, RTP, phase estimation, acoustic wave, frequency domain

1. Introduction

Rapid Thermal Processing(RTP) is known to be a promising technology in semiconductor manufacturing especially for the devices with minimum feature size less than 0.5[μm]. RTP is based on the feedback control of the temperature of a silicon wafer. To implement the feedback control system, the measurement of system output, the temperature, is indispensable. The measurement using thermocouples and pyrometers have been attempted, which, however, are proved to be inappropriate since thermocouples contaminate the wafer and pyrometers may result in inaccurate output.

An acoustic approach to measure the temperature was proposed, which is based on the fact that the velocity of acoustic wave in the silicon wafer is a function of temperature[1]. A pulse of acoustic signal is triggered and the temperature is acquired by measuring the delay time between the echo of the pulse and the received signal of other transducers. Since this method uses the zero crossing of time domain signal, it results in wrong measurement when the abrupt noise is added to the zero crossing point. Furthermore, since the resolution of the measurement is dependent upon the speed of the sampling frequency(or the counter clock), the increment of resolution may require the modification of hardware and can be limited by the response of the hardware.

In this paper, we propose a novel approach to measure the delay time of the acoustic wave. Instead of sending a pulse, we send several cycles of high frequency sinusoidal wave and then estimate the phase difference of the signal and received signals. We use the phase difference to calculate the delay time of the acoustic wave. The performance of the proposed method will be investigated via experiments using RTP test-bed we built in [2].

2. Review of previous work

The set-up of the acoustic temperature sensor is shown in Fig. 1. Acoustic transducers are mounted at the bottom of the quartz support pins. The transducers use piezoelectric effect which generate acoustic wave according to the voltage applied and generate voltage according to the acoustic wave received. When the pulse of the acoustic wave is transmitted from one of the pin, the electronic measurement system detect the zero crossing point of the echo signal and then trigger the counter to start. The other transducers receive the signal and then stop the counter at the zero crossing point of the signal. The counted time interval can be regarded as the time of flight. The average travel velocity of the wave is easily calculated by the following equation.

* 正 會 員 : 韓國情報通信大學校 工學部 助敎授 · 工博
** 正 會 員 : 又松大 디지털情報通信學科 專任講師 · 工博
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$$v_i = \frac{l_i}{k_i \times \varDelta T} \tag{1}$$

where i is the receiver index, l_i is the length between transmitter and i-th receiver, k_i is the i-th counter value, $\varDelta T$ is the period of the input clock.

The next step to get the temperature is to use the relationship between the velocity and the temperature. The relationship is given by the experiment and is expressed as the following polynomial model.

$$T_i = a_0 + a_1 v_i + a_2 v_i^2 + a_3 v_i^3 + a_4 v_i^4 \tag{2}$$

The coefficients, $a_0, \ldots, a_4$, are determined by the least square method to minimize the mean square error between the experimental data and the polynomial. When the T_i's, which are the average temperature along their path, are calculated, the temperature profile of whole wafer can be obtained by tomographic technique as in [1][3].

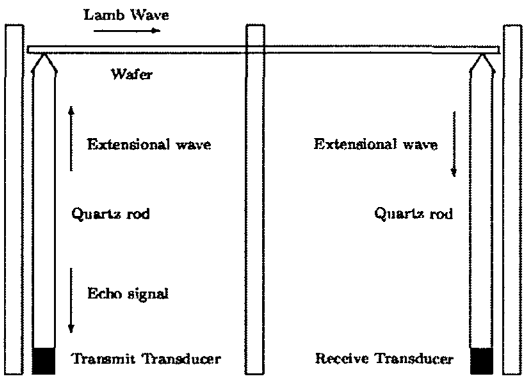

Fig. 1 Set-up of the acoustic temperature sensor

3. Phase estimation of acoustic wave

Here, we propose a method which estimates the phase of acoustic signal to get more stable temperature data with higher resolution. The proposed method transmits the sinusoidal wave with the frequency: $f_c = 333kHz$, instead of the pulse.

$$s(t) = A sin(2\pi f_c t) \tag{3}$$

Then, the received signals will also be sinusoidal wave as presented in Fig. 2. We use the Analog to Digital converter to process the received data. If we regard the zero input period as a constant time delay and estimate the phase of the same frequency component of the received signal, we can get the time of flight by adding them. To estimate the phase of the signal, we use the first 2 cycles of it to minimize the effect of multi-path.

$$\hat{t_f} = t_{const} + \frac{\hat{\phi}}{2\pi f_c} \tag{4}$$

The rest of the process to get the temperature is the same as the previous method.

The estimation of the phase is done by projecting the received signal to the orthogonal cosine and sine axis. This framework is equivalent to getting the phase from the Discrete Fourier Transformation of the received signal.

$$\hat{\phi} = \frac{\int_0^T r_w(t)\sin(2\pi f_c t)dt}{\int_0^T r_w(t)\cos(2\pi f_c t)dt} \tag{5}$$

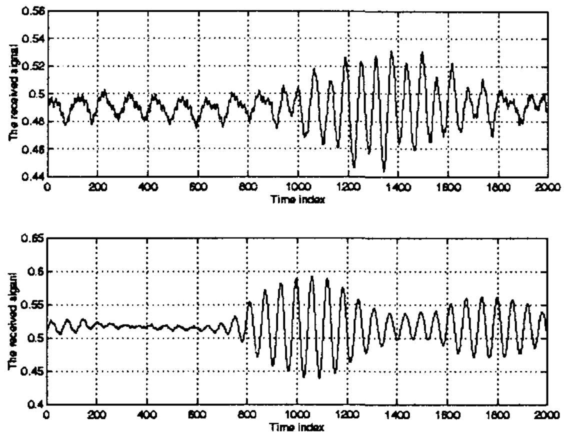

Fig. 2 The received signals(Experimental Data)

The algorithm to calculate the phase is depicted in Fig. 3. Since our method is based on the frequency domain approach, the resolution of estimated phase is independent of the sampling time of the Analog to Digital converter. Thus, higher resolution data can be achieved. Furthermore, the effect of noise is reduced by the projection which acts as a band-pass filter with very narrow pass-band. Especially, if the noise is spike type, the proposed method can efficiently reject it.

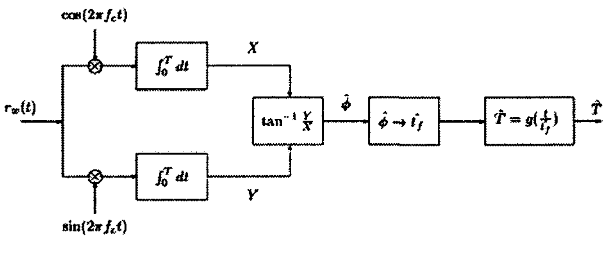

Fig. 3 The proposed phase estimation scheme

4. Experimental results

We conducted experiments to present the superior performance of the proposed method. We built a test bed with 4 quartz rods, 1 for transmitter and the rest for receiver. Each quartz rod is designed to be functioned as both transmitter and receiver. By alternating the role of transmitter, the system obtains average temperature for every possible path.

The experimental results are shown in Fig. 4 and Fig. 5. Figure 4 shows that the temperature measured by thermocouples and the temperature estimated using the proposed method along the long path. Figure 5 shows those along the short path. In both cases, the temperature data acquired by the proposed method are well matched to those from thermocouples. As long as steady state, transient tracking response is shown to be as good as that of thermocouples.

To show high resolution of our scheme, we set the temperature at the rather low range from room temperature up to 210 ° *C*. Considering that the maximum resolution the time domain method can reach is about 16 ° C, the transient response of the proposed method yields smooth curve with very high resolution.

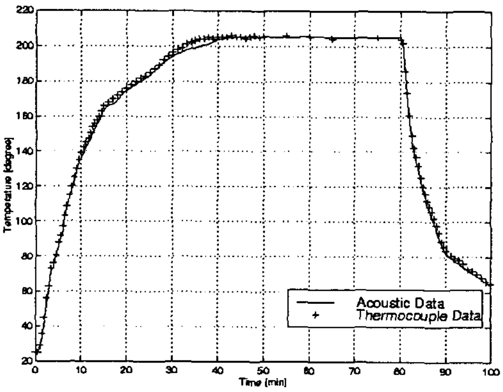

Fig. 4 The temperature profile for the long path

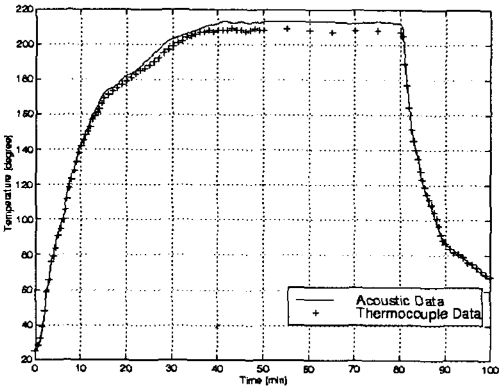

Fig. 5 The temperature profile for the short path

5. Conclusion

We proposed a temperature estimation method in the frequency domain. Compared with time domain method, the proposed method yields the estimation performance close to that of thermocouples. Throughout the experiments, it is proved that the proposed method has ability to estimate the temperature of silicon wafers precisely. Therefore, it can be concluded that the propose estimation method can be an efficient alternative to contact-type measurement by thermocouples.

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저 자 소 개

강 준 혁(姜 俊 赫)

1968년 5월 24일생. 1991년 서울대 제어계측공학과 졸업. 2002년 Univ. of Texas at Austin. Telecommunication and Information System Eng.(Ph. D.). 2003년~현재 한국정보통신대학교 공학부 조교수

Tel : 042-866-6709

E-mail : jhkang@icu.ac.kr

이 석 원(李 錫 垣)

1968년 7월 30일생. 1991년 서울대 제어계측공학과 졸업. 1998년 동 대학원 전기공학부 졸업(공박). 2001년~현재 우송대 디지털정보통신학과 전임강사

Tel : 042-630-9703

E-mail : lswss@lion.woosong.ac.kr