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UNCERTAINTY IMPROVEMENT OF GEOMETRICAL THICKNESS MEASUREMENT OF A SILICON WAFER USING A FEMTOSECOND PULSE LASER

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Abstract: We describe a method to simultaneously measure geometrical thickness and refractive index of a silicon wafer using a femtosecond pulse laser having 100 nm spectral bandwidth. The improved phase measurement algorithm is applied to increase insensitivity to environmental disturbances and interferometer noise. The measurement results show that the geometrical thickness and refractive index of a silicon wafer were measured to be 320.699 μm and 3.621 respectively, which are the improved results by about one order of magnitude in comparison with previous research. By considering the dispersion effect caused by 100 nm bandwidth source, the conclusion can be reached that there is no dispersion effect on measurement of geometrical thickness.

Keywords: Interferometry, Pulsed laser, Infrared, Spectrometer, Silicon wafer

1. INTRODUCTION

Silicon wafer is a fundamental material, which has long been used in manufacturing process of semiconductor integrated circuits. Recently, the field of semiconductor packaging technology based on vertically stacked wafers with narrower thickness is being emerged, which helps enhancement of the degree of integration of integrated circuits. In this case, the geometrical thickness measurement accuracy of a silicon wafer corresponding to each layer become very important.

Generally, one of the widely used measurement method of geometrical thickness of a silicon wafer is the capacitance gauging method which uses two capacitive sensors to measure the thickness from difference between front and back sides [1,2]. But, the optical measurement methods are strongly required to achieve much higher measurement accuracy. For example, both geometrical thickness and refractive index of silicon wafer can be determined simultaneously by measuring the optical path differences according to the rotation angle of the sample [3-6]. Also, a low-coherence source with broad band such as white-light was used to detect the shift of peak position of visibility envelope by inserting a sample into one arm [7]. Besides, using white-light based interference spectrum obtained from an optical spectrum analyzer, both geometrical thickness and refractive index were extracted by fitting into theoretical equation of interference signal [8-10]. This kind of method can make the measurement speed faster by eliminating phase shifting process such as mechanical movement or wavelength scanning, and minimize the effects of environmental disturbances like external vibration and air fluctuation during data acquisition. In 2010, KRISS developed thickness and refractive index measurement system of a silicon wafer based on optical comb of mode-locked laser with 10 nm spectral bandwidth, which measured the geometrical thickness of a silicon wafer at measurement uncertainty of about 1 μm [11]. According to analysis of measurement uncertainty, most important factor in uncertainty evaluation turned out to be the terms related to spectrum analysis based on Fourier transform, which is theoretically determined by spectral bandwidth of light source being used.

In this paper, on the basis of previous system developed in KRISS, we described a improved measurement system which can measure both geometrical thickness and refractive index simultaneously with much lower measurement uncertainty. To reduce the uncertainty terms related to FFT analysis, a femtosecond pulse laser with 10 times larger bandwidth was adopted. Also, we applied the phase measurement algorithm which is insensitive to environmental disturbances and interferometer noise. To consider the dispersion effect of silicon material which become a prominent error source by using much broader bandwidth, numerical simulation was performed. As a result, the measurement uncertainty of geometrical thickness can be reduced by one order of magnitude over previous system.

2. BASIC THEORY AND METHODOLOGY

The intensity of interference signal in spectral domain can be expressed as eq. (1) in terms of an optical path difference, L [11].

$$I(f,L) = I_0(f)\cdot\left(1+\cos\left(\frac{2\pi}{c}L\cdot f\right)\right) = I_0(f)\cdot\left(1+\cos\varphi(f,L)\right) \tag{1}$$

where f is the optical frequency, $I_0(f)$ is the spectrum of light source, c is the speed of light, and $\varphi(f,L)$ is the phase.

The obtained spectrum like eq. (1) is Fourier-transformed to determine the period of the interference spectrum corresponding to a specific *L* in time domain, which can be found at the position of *L*/*c*. After selection of an only positive peak which contains the optical path difference information, the inverse Fourier-transform about the selected peak term is performed. Finally, by taking the imaginary part of the logarithmic function result of the inverse Fourier-transformed term, the phase term $\varphi(f,L)$ can be extracted as shown in eq. (2).

$$\varphi(f,L) = \mathrm{Im}\left\{\ln\left(I'(f,L)\right)\right\} \tag{2}$$

Using this result, the optical path difference *L* can be determined by eq. (3).

$$L = \frac{c}{2\pi}\cdot\frac{d\varphi}{df} = \frac{d\varphi}{dk} \tag{3}$$

The phase measurement uncertainty depends on both uncertainties about *L* and *f*. Since wavelength accuracy of optical spectrum analyzer being used is expected to be about 10^{-6} level, most dominant factor in phase measurement uncertainty must be the uncertainty of *L*. By numerical simulation about measurement algorithm of optical path difference in ideal case, the *L* uncertainty at the level of 10^{-4} was obtained.

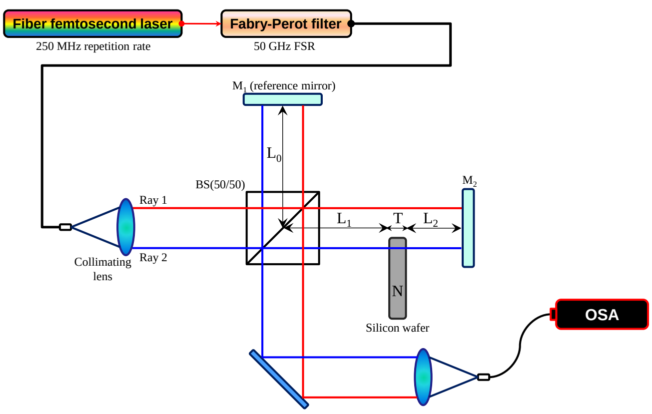


Fig. 1 Optical layout of the measurement system. (BS: beam splitter, OSA: optical spectrum analyzer)

Figure 1 shows the optical layout of the proposed measurement system. Two different interference signals can be measured through the OSA, which are Ray 1 and Ray 2. In Ray 1, only a single optical path difference exists as L_1 + T + L_2 - L_0 (≡*A*). But, in Ray 2, several first-order optical path differences can be contained, which are L_1 - L_0 (≡*B*), L_1 + N·T - L_0 (≡*C*), and L_1 + N·T + L_2 - L_0 (≡*D*). The other higher-order terms can be ignored due to relatively low intensity. Using all four optical path differences(*A*, *B*, *C*, *D*), the geometrical thickness T and refractive index N can be determined as follows:

$$T = (C-B) - (D-A)$$
$$N = \frac{C-B}{T} \tag{4}$$

Assuming a high degree of tilt stability, the Ray 1 measurement (*A*) does not depend on the wafer and does not have to be repeated when more than one wafer is measured. Also, unlike the previous research, instead of two separate measurements about optical path difference *B* and *C*, a single measurement in which the wafer is the interferometer cavity was performed, because it gives a same result with insensitivity to the environmental disturbances.

3. EXPERIMENTAL RESULTS & ANALYSIS

Figure 2 (a) shows the spectrum of the femtosecond pulse laser with about 100 nm spectral bandwidth. The repetition rate 250 MHz, which is stabilized to a rubidium reference clock, was extended to 50 GHz through a Fabry-Perot filter as shown in Figure 1, because the 250 GHz mode spacing is too narrow to be detected.

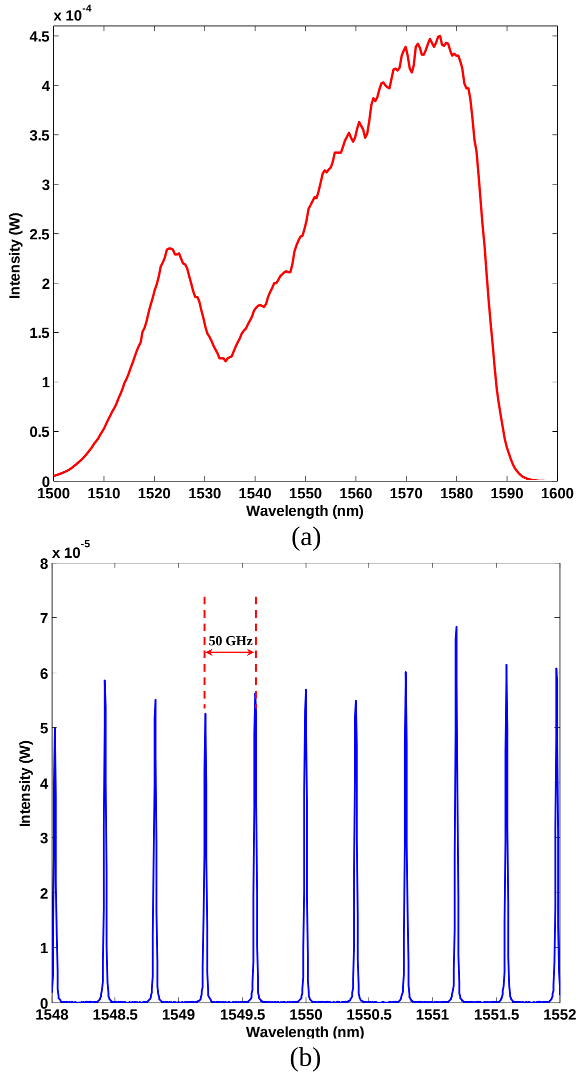
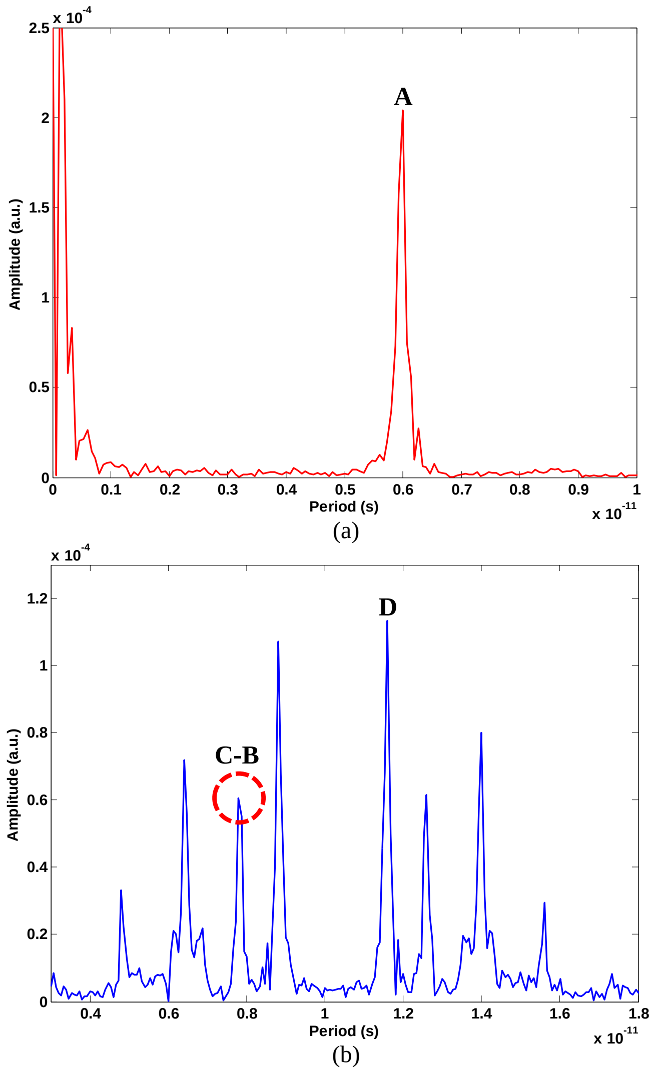


Fig. 2 (a) full spectrum envelope of the femtosecond pulse laser, (b) the optical comb of the femtosecond pulse laser with repetition rate of 50 GHz

Figure 3 shows the Fourier transformed results of two interference spectrum data acquired with 32768 sampling points and 0.02 nm sampling resolution from OSA. In Fig. 3

(a), a single peak which contains the information about optical path difference *A* was clearly detected at the position of about 6.0 ps. Also, in Fig. 3 (b), both peaks, which are related to optical path difference *C-B* and *D* can be identified at the position of about 7.8 ps and 11.6 ps respectively. To distinguish two peaks of optical path difference *C-B* and *D* from other peaks, an additional experiment was performed by blocking the beams reflected from two mirrors. For example, the only peak about optical path difference C-B can survive when both beams reflected from two mirrors are blocked. For three peaks selected from Figure 3, the phase measurement algorithm explained in the previous section was applied to calculate the three optical path differences, *A*, *C-B*, *D*. The three graphs depicted in Figure 4 represent the phase $\varphi(f,L)$ according to wave vector k in Eq. (3) for each optical path difference. The magnitude of slope of $\varphi(f,L)$ is proportional to on an optical path difference L. Finally, using Eq. (4), both geometrical thickness T and refractive index N can be calculated using three optical path differences, *A*, *C-B*, and *D* which were determined by using Eq. (3).



(a)

(b)

Fig. 3 Fourier transformed results of two interference spectrum signal, Ray 1 and Ray 2: (a) Ray 1 result, (b) Ray 2 result

Table 1 shows 10 times consecutive measurement results about a silicon wafer. The optical path difference *A* was measured to be 888.840 μm. As shown in Table 1, the averaged geometrical thickness *T* and refractive index *N* of a silicon wafer were 320.699 μm and 3.621 respectively. The measured geometrical thickness agrees well with the manufacturing specification for the silicon wafer thickness of 320 ± 10 μm. Also, the standard deviation of the geometrical thickness and refractive index of the silicon wafer were calculated to be 26.7 nm and 2.0 x 10^{-4} respectively, which show the enhanced uncertainty by about one order of magnitude in comparison with previous research.

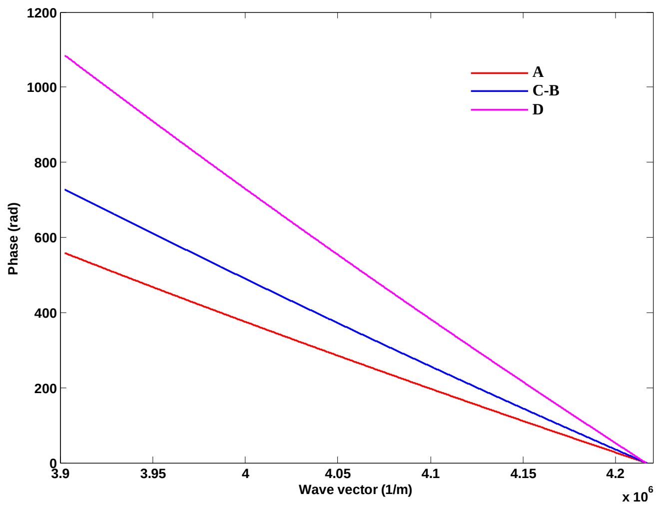


Fig. 4 Phase versus wave vector graph for three optical path differences, A, C-B, and D

Table. 1 Measurement results of a silicon wafer

	C-B (μm)	*D* (μm)	*T* (μm)	*N* (μm)
1	1161.2738	1729.3846	320.7296	3.6207
2	1161.1887	1729.3108	320.7182	3.6206
3	1161.2252	1729.3807	320.6848	3.6211
4	1161.2058	1729.3374	320.7087	3.6207
5	1161.1422	1729.2793	320.7033	3.6206
6	1161.2065	1729.3307	320.7161	3.6207
7	1161.2033	1729.3346	320.7091	3.6207
8	1161.1172	1729.2978	320.6597	3.6210
9	1161.1109	1729.3033	320.6480	3.6211
10	1161.1669	1729.2917	320.7156	3.6206
mean	1161.1841	1729.3251	**320.6993**	3.6208
Standard deviation	0.0505	0.0358	**0.0267**	0.0002

To consider the dispersion effect of silicon material on geometrical thickness measurement in 100 nm spectral bandwidth, a numerical simulation was performed. The simulated interference spectra for the no dispersion case were generated with T of 320.7 μm and N of the silicon wafer being a constant value at the center wavelength. In the case of dispersion, the N of the silicon wafer was determined by an empirical study [12]. The spectral bandwidth and sampling resolution were chosen as the same values used in the experiments. According to the simulation results, the dispersion effect caused the shift of peaks for OPD C-B and OPD D in Fourier domain as shown in Fig. 5.

The peaks for OPD C-B and OPD D were shifted the same amount, about 2.8×10^{-13} s, which corresponds to 42 μm in the optical path. It was too large to ignore in general cases. However, the dispersion of a silicon material affects only optical path differences *C*, and *D* which contain the equal amount of portion transmitted through the silicon wafer unlike *A* and *B*. So, according to Eq. (4), the dispersion effect on the geometrical thickness *T* must be cancelled, which was verified through the numerical simulation about peak shift of the Fourier transformed result.

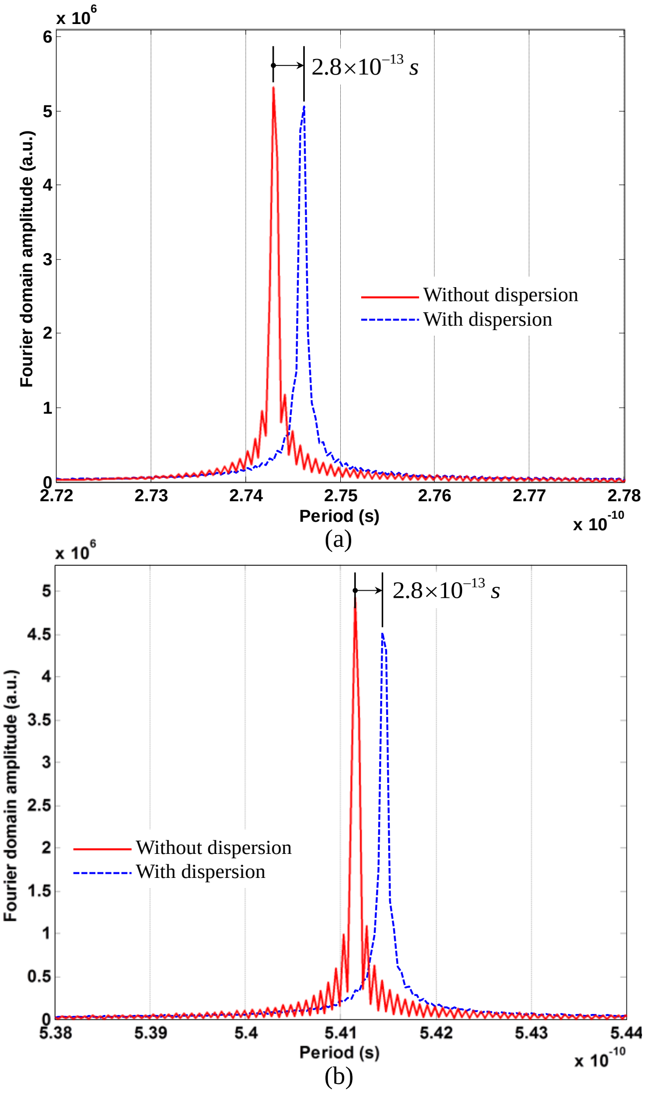


Fig. 5. Simulation results about peak shift caused by dispersion effect: (a) peak shift of OPD C-B, (b) peak shift of OPD D

To verify the measurement accuracy of geometrical thickness of a silicon wafer based on the proposed method, an comparative experiment about the same wafer was performed using a contact probe instrument. Figure 6 shows the optical layout of the contact probe instrument used for the comparative experiment. In this device, the geometrical thickness information can be measured from the difference between two readings of top and bottom probes in the moment of simultaneous contact with top and bottom surfaces of a silicon wafer.

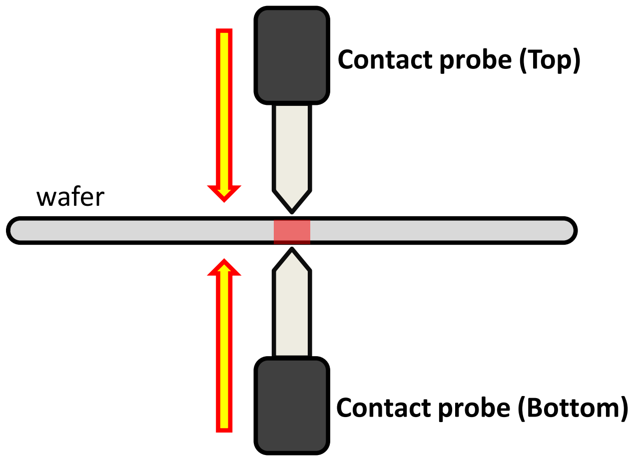


Fig. 6. Optical layout of contact probe for thickness measurement

The interferometric measurement proposed in this work was performed at a fixed center position for 10 times consecutive measurement. To match the measurement area as far as possible, the contact probe measurement was performed 100 times at the random position inside 3 mm by 3 mm area around the center point. Table 2 shows the comparative measurement results.

Table. 2. Comparative measurement results

	Mean (μm)	Standard deviation (μm)
Contact probe method	477.906	0.041
Interferometer method	477.980	0.016

The measurement uncertainty of the contact probe device is known as about 0.1 μm. As shown in Table 2, the thickness measurement result of interferometric method is well agreed with the contact probe results within the measurement uncertainty of contact probe method.

4. CONCLUSION

A improved measurement system of the geometrical thickness and refractive index of a silicon wafer was demonstrated. The method uses a femtosecond pulse laser having 100 nm spectral bandwidth. Also, we applied the phase measurement algorithm which is insensitive to environmental disturbances and interferometer noise. Therefore, the measurement accuracy of geometrical thickness and refractive index was improved by about one order of magnitude. By considering the dispersion effect caused by 100 nm bandwidth source, the conclusion can be reached that there is no dispersion effect on measurement of geometrical thickness. Also, it was verified that the thickness measurement result is well agreed with the contact probe result within 0.1 μm uncertainty.

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