Profile measurement of thin films by linear wavenumber-scanning interferometry

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ABSTRACT

Conventional methods to measure the positions of the front and rear surfaces of thin films with multiple-wavelength interferometers are reviewed to make it clear how the method proposed here is novel and simple. Characteristics of the linear wavenumber-scanning interferometry used in the proposed method are analyzed in detail to make the measurement accuracy clearly. The positions of the front and rear surfaces of a silicon dioxide film with 4μm thickness is measured by utilizing the phases of the sinusoidal waves forms corresponding to each of the optical path differences contained in the interference signal. The experiments and the theoretical analysis show that the measurement error is about 15 nm.

Keywords: multiple wavelengths, linear wavenumber-scanning, interferometer, profile measurement

1. INTRODUCTION

Laser interferometers with single-wavelength light source have a limitation that they can measure an optical path length (OPD) shorter than a wavelength. Multiple wavelengths are required to measure an OPD longer than a wavelength with interferometers. For this measurement, white light interferometers have been used in which the positions of the reflecting surfaces are determined usually by finding peak positions of the envelope of the interference signal through a mechanical scanning of the OPD. To eliminate this mechanical scanning wavelength-scanning interferometers have been developed in which a phase change of the interference signal due to the wavelength scanning is utilized. The wavelength scanning is done in two different domains: time domain by using a wavelength tunable light source and spatial domain by using a white light source and a diffraction grating. In the time-domain scanning, there are two kinds of the scanning: linear scanning and sinusoidal scanning. When an object has one refl ecting surface, all of the scanning methods provide relatively easy measurements of the OPD corresponding to the position of the refl ecting surface. In construct, when an object has two reflecting surface such as a silicon dioxide film coated on an IC wafer, the measurement becomes difficult to need some complicated methods. Theses methods are reviewed in the next section to show clearly how a method proposed in this paper is novel and simple.

In this paper the novel method utilizing phase information provided by the linear wavenumber scanning is proposed to measure simply and exactly the positions of the front and rear surfaces of a silicon dioxide film with 4μm thickness. Since the wavenumber of the light source is scanned linearly with a large wavelength-scanning width, the interferometric technique for the profile measurement is called linear wavenumber-scanning interferometry.

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2. REVIEW OF PROFILE MEASUREMENTS OF THIN FILMS

Table 1 shows a review of profile measurements of thin films using multiple wavenumbers of a light source. A white light interferometer by mechanical scanning of the OPD was employed to obtain a phase distribution along the multiple wavenumbers[2]. The phase distribution can be obtained from Fourier transform of the interference signal, which means that the mechanical OPD scanning is equivalent to wavenumber scanning of the white light source. The obtained phase distribution is fitted to the theoretical one to estimate the positions of the two reflecting surfaces of the film with iterative computation such as nonlinear least-squares algorithm. This fitting method was proposed first in Ref. 1, and was used in the other references until the two-step method was proposed in Ref.6. The multiple wavenumbers was generated in spatial domain by using a white light and a diffraction grating in Ref.1, and the phase distribution was calculated with the phase shifting method where the five adjacent samples of the interference signal were used. This phase shifting method was adopted into an interferometer with the time-domain wavenumber scanning in Ref.4. The term "discontinuous" in the second column means that the wavenumber changes at intervals with step scanning waveform. The interference signal changing according to the wavenumber scanning was detected and its Fourier transform was calculated to get the phase distribution in Ref.3. The continuous wavenumber scanning of sinusoidal waveform was used and a continuous signal derived from the interference signal was fitted to the theoretical one. Since the signal fitting method needs a long computation time, a new method called two-step method was proposed in Ref.6. At step1 the thickness d is measured from an interference signal caused between the two waves reflected by the front surface F and the rear surface R without using a reference wave,

Table 1 Methods for profile measurement of thin films with multiple wavelengths.

Scanning domain	**Scanned wavenumbers**	**Processing of interference signal**	**Information extracted from interference signal**	**Profile determination method**	**References**
White light OPD mechanical scanning	Discontinuous Step	Fourier transform	Phase	Fitting phase values	2 (1999)
Wavenumber scanning in spatial domain by a grating	Continuous Linear	Phase shifting method	Phase	Fitting phase values	1 (1996)
		Simultaneous two-step method Step 1 Fourier transform Step 2. Fourier transform	Step 1 Frequency Step 2 Frequency	OPD computation	6 (2006)
Wavenumber scanning in time domain	Discontinuous Step	Fourier transform	Phase	Fitting phase values	3 (2002)
		Phase shifting method	Phase		4 (2004)
	Continuous Sinusoidal	Double sinusoidal phase-modulating interferometry	Signals containing phase	Fitting signal values	5 (2008)
	Discontinuous Step	Two-step method Step 1 Signal itself Step 2 Phase shifting method	Step 1 Period Step 2 Phase	OPD computation	7 (2008)
		Simultaneous two-step method Step 1 Signal itself Step 2 Phase shifting method			8 (2009)
	Continuous Linear	Two-step method Step 1 Fourier transform Step 2 Fourier transform	Step 1 Phase of frequency Step 2 Phase of frequency	OPD computation	Present

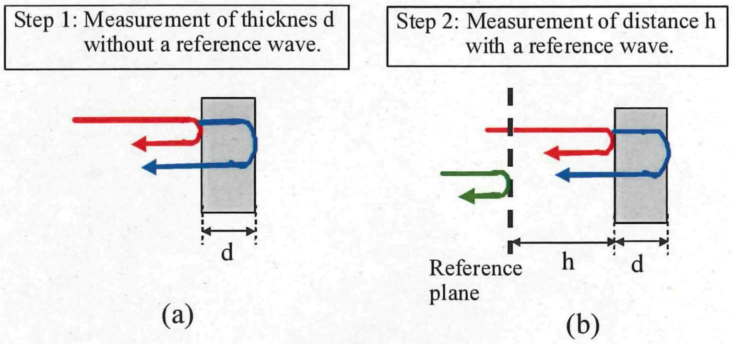

Fig.1 Two-step method.

as shown in Fig.1 (a). At step 2 an interference signal caused by a reference wave and the waves reflected from the film surfaces is detected to obtain the distance between the reference plane and the front surface, as shown in Fig.1 (b). Linear wavenumber-scanning produces an interference signal consisting of sinusoidal waveforms whose frequencies are proportional to OPDs. Since the frequencies obtained by the Fourier transform of the interference signal are used to determine the distances of d and h in Ref.6, the measurement accuracy is not so high. The first step in Refs.7 and 8 is the same as that in Ref.6, and the second step is the same as the phase detection method in Ref.4. The phase distribution detected at the second step provides the distance of h with a simple computation because the thickness is obtained at the first step. The two steps were carried out simultaneously by utilizing the polarization of the light wave in Refs.6 and 8.

In this paper a novel method utilizing characteristics of the linear wavenumber scanning is proposed where the phase of the sinusoidal waveform in the interference signal is used to determine exactly the positions of the front and rear surfaces of a thin film. The measurement resolution of the positions can be improved to the order of nanometer by using the phase information of the signal. This method is also categorized into the two-step method. At step1 the scanning width of the wavenumber is adjusted to obtain an interference signal whose length is an integer multiple of the period of the sinusoidal waves signal. At step 2 the position of the reference mirror is adjusted exactly to distinguish the two sinusoidal wave signals corresponding to the two surfaces of the film. This method is most similar to that proposed in Ref.6, but the utilization of the phase information and the two-dimensional measurement are different compared to the method of Ref.6.

3. MEASUREMENT OF ONE OPD

A measurement method of thin-film profile by a linear wavenumber-scanning interferometer is explained with an experimental setup shown in Fig.2. The light source is a Hg lamp, and a wavenumber of the light source is selected by an acoustic optical tunable filter (AOTF) according to a voltage feed to its driver.

First a blocking plate blocks a beam incident onto a mirror (M) and two beams reflected by the front surface F and the rear surface R of a thin film interfere with each other. The OPD between the two beams is denoted by L at a measurement point of P as shown in Fig.3. When a wavenumber of the light source is scanned as $\sigma(t)$ with time t, ac component of the interference signal is expressed as

$$S(t)=\cos[2\pi\sigma(t)L] . \qquad (1)$$

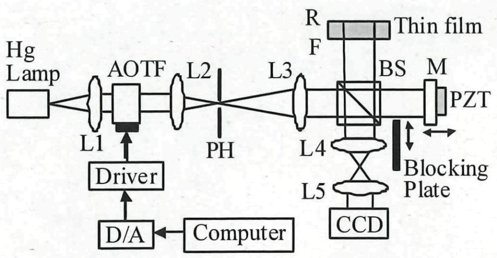

Fig.2 Setup of a wavenumber-scanning interferometer.

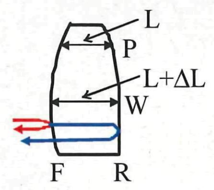

Fig.3 OPD between the two surfaces.

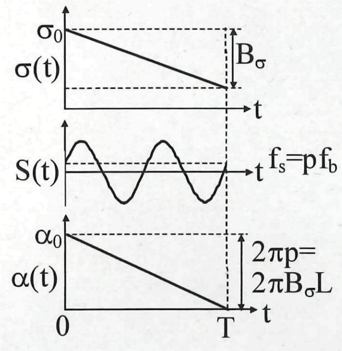

Fig.4 Wavenumber scanning $\sigma(t)$, interference signal $S(t)$, and phase $\alpha(t)$ of $S(t)$ detected at point P.

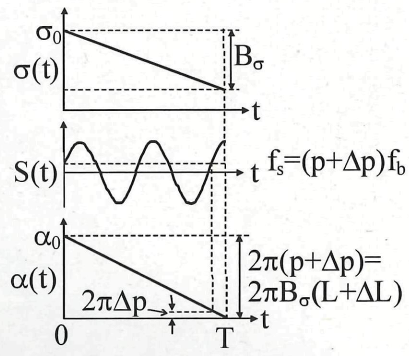

Fig.5 Wavenumber scanning $\sigma(t)$, interference signal $S(t)$, and phase $\alpha(t)$ of $S(t)$ detected at point W.

When the scanning $\sigma(t)$ is a linear function of time as shown in Fig.4, the interference signal becomes a sinusoidal waveform which is given by

$$S(t)=\cos[2\pi p f_b t+\alpha_0]\ , \qquad (2)$$

where p is an integer, and one period of the frequency f_b is the length T of the interference signal to be processed. In Fig.4 the interference signal of p=2 is depicted. Then since the phase of the interference signal changes by $2\pi p$ with the wavenumber-scanning width of B_σ during the length T, the following relation is satisfied:

$$2\pi B_\sigma L=2\pi p\ . \qquad (3)$$

When the wavenumber at t=0 is σ_0, the phase α_0 is given by

$$\alpha_0=2\pi\sigma_0 L\ . \qquad (4)$$

If it is assumed that the OPD of L_b produces the frequency f_b in the interference signal with the relation of $B_\sigma L_b=1$, the OPD between the light waves reflected by the front and rear surfaces of the thin film is equal to pL_b. In other words the OPD of L_b produces one circle of a sinusoidal waveform in the interference signal during the interval of T. The frequency f_b and the OPD L_b are called a basic frequency and a basic OPD, respectively. The phase α_0 is obtained from the phase of the frequency component of pf_b in Fourier transform of the signal S(t). Since the values of p, B_σ, σ_0, and α_0 are known, two measured values of the OPD L are obtained from Eqs.(3) and (4), respectively, as follows:

$$L_\sigma=p/B_\sigma=pL_b\ , \qquad (5)$$

$$L_\alpha=\alpha_0/2\pi\sigma_0\ . \qquad (6)$$

Considering the initial wavelength of $\lambda_0=1/\sigma_0$ the following equation holds:

$$L=m\lambda_0+L_\alpha\ , \qquad (7)$$

where m is zero or a positive integer. To determine the value of m the OPD L_σ is used as L in Eq.(7) and the following equation is obtained:

$$m_c=(L_\sigma- L_\alpha)/\lambda_0\ . \qquad (8)$$

Although the measured value of L_σ is not equal to the real value of L, the value of m is determined exactly by rounding off m_c in the condition that the absolute value of the difference between L_σ and L is smaller than $\lambda_0/2$. The measurement accuracy of L is equal to that of L_α in Eq.(7).

Equation (3) is satisfied only on one measurement point of P where the length of the interference signal is adjusted at T. This measurement point is called the primary measuring point. When an OPD on another measurement point such as point W is different from that on the primary measurement point by ΔL as shown in Fig.3, the phase change of the interference signal during the length T becomes $2\pi p+\Delta\Phi$ and the frequency of the interference signal is expressed as $(p+\Delta p)f_b$ as shown in Fig.5. Among these expressions the following equation is satisfied:

$$\Delta p=\Delta L/L_b=\Delta\Phi/2\pi\ . \qquad (9)$$

Fast Fourier transform (FFT) is used to obtain a frequency distribution F(f) of the interference signal S(t). The components of harmonic frequencies of f_b are obtained with FFT because the signal length to be processed is $T=1/f_b$. When the interference signal is given by

$$S(t)=\cos[2\pi(p+\Delta p)f_bt+\alpha_0]\ , \qquad (10)$$

the frequency component is expressed as

$$F(pf_b+nf_b)=T(-1)^n[\sin(\Delta p\pi)/(\Delta p-n)\pi]\ \exp[j(\Delta p-n)\pi+\alpha_0]\ , \qquad (11)$$

where n is an integer. Equation (11) means that the phase of the frequency component of pf_b in Fourier transform of the signal S(t) is $\alpha_0+\Delta p\pi$. Since the phase of $\alpha_0+\Delta p\pi$ is used as α_0 in Eq.(6), the measurement error of L_α becomes $(\Delta p/2)\lambda_0$ at the measurement point W. Although the OPD to be measured is $L=(p+\Delta p)L_b$, it is still satisfied in experiments that the absolute value of the difference ΔpL_b between L_σ and L is smaller than $\lambda_0/2$ to obtain an exact value of m.

4. MEASUREMENT OF TWO OPDs

A reference wave reflected from the mirror M is used to measure the positions of the front and rear surfaces of the thin-film. Due to the multiple reflections in the film there are multiple objective waves reflected from the two surfaces such as U_1, U_2, and U_3 as shown in Fig.6. Although the propagation direction of the three object waves is not normal to the front surface of the film in Fig.6, actually the propagation direction is normal to the

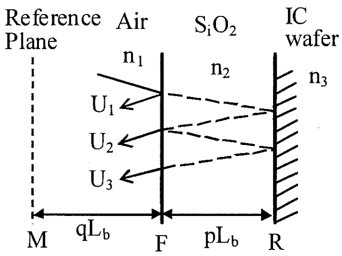

Fig.6 Multiple reflections by a film and position of the reference plane.

front surface in the interferometer of Fig.1. The position of the mirror M corresponds to the position of the reference plane shown in Fig.6. The position of the mirror M is adjusted by a piezoelectric transducer (PZT) so that the OPD between the object wave of U_1 and the reference wave is equal to qL_b on the primary measurement point P as shown in Fig.6, where q is a positive integer. The OPD between the object waves of U_1 and U_2 is known to be pL_b beforehand from the measurement described in Sec.3. In the adjusted position of the reference mirror M the interference signal contains multiple sinusoidal waveforms of different frequencies of qf_b, $(p+q)f_b$, and pf_b when the object wave U_3 is neglected. The frequencies of qf_b and $(p+q)f_b$ are produced by the interference between the object waves and the reference wave, and the frequency of pf_b is produced by the interference between the two object waves. These three components are distinguished by FFT of the interference signal to obtain the two values of α_0 corresponding to the front and rear surfaces of the film. Therefore the two values of the OPDs representing the positions of the two surfaces are calculated on the primary measurement point P in the same way as in Sec.3. At the other measurement points corresponding to the point W measurement errors are caused by the situation that the values of p and q change by Δp and Δq, respectively.

5. EXPERIMENTS

The linear wavenumber-scanning light source was constructed as shown in Fig.2. The wavelength of the output light from the AOTF was detected with an optical spectrum analyzer to determine the voltage fed to the driver to the AOTF. The voltage signal was generated with a D/A converter and a computer. The wavenumber was scanned linearly between 1.342×10^{-3} nm^{-1} and 1.718×10^{-3} nm^{-1}. The object was a silicon dioxide film coated on an IC wafer with thickness of 4 μm. A two-dimensional CCD image sensor was used to detect the interference signals. Lenses L4 and L5 formed an image of the object on the CCD image sensor with magnification of 1/3. Number of the measuring points was 60 × 30 and intervals of the measuring points were $\Delta x=\Delta y=59.4$ μm along the x and y axes in a region of 3.56 mm×1.78 mm on the object surface. Positions of the pixels of the CCD image sensor were denoted by I_x and I_y, respectively.

First the reference wave was blocked with the blocking plate, and the interference signal produced by the two object waves of U_1 and U_2 was detected. The signal detected on a primary measurement point P of $I_x=I_y=0$ is shown in Fig.7 (a). The horizontal axis denotes the sampling points of the signal whose interval was about 0.24 ms. The number N_s of the sampling points was determined to be 126 so that amplitude distributions of frequency components calculated with FFT has a sharp peak at frequency of pf_b as shown in Fig.7 (b). To carry out FFT of the signals the values on the sampling points of 128 were interpolated from the original values of the signals. The vertical axis denotes the ratio A_R of the amplitude to that of frequency $4f_b$. At the first sampling point the wavenumber σ_0 was 1.698×10^{-3} nm^{-1} and the scanning width B_σ of the wavenumber was 0.326×10^{-3} nm^{-1}. The wavelength changed from λ_0=589 nm to 729 nm. Therefore the basic OPD of $L_b=1/B_\sigma$ was 3067 nm at N_s=126 to measure one OPD corresponding to the thickness of the film. For the thickness distribution measurement the value of L_σ was $4L_b$=12268 nm. The phase α_0 of frequency $4f_b$ was -0.77 rad in Fig.7, which leads to L_α =-72 nm, m_c=20.95, m=21, and L=12297 nm on the primary measurement point P of $I_x=I_y=0$.

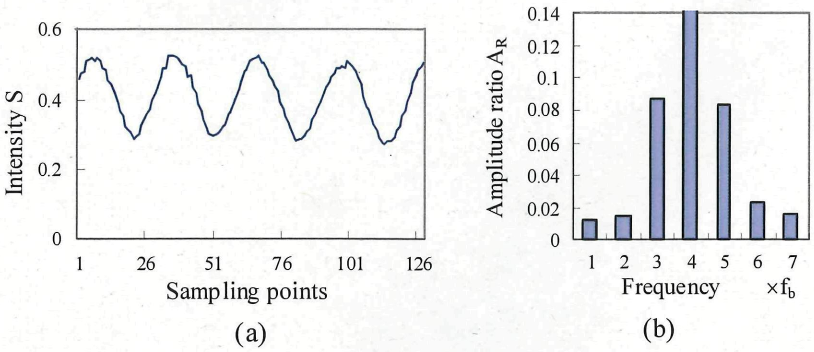

Fig.7 (a) Interference signal intensity S(t), and (b) amplitude distributions of frequency components of S(t) calculated with FFT.

Next the profile measurement of the film was tried using L_b=3067 nm as described in Sec.4. The position of the reference mirror M was adjusted at the OPD=0 (q=0) so that a waveform of the interference signal became almost the same as that of Fig.7 (a). In this situation the position of reference plane was coincident with that of the front surface of the film. After that the reference mirror M was displaced by about L_b measuring the displacement amount with a laser displacement meter, and a fine adjustment of the position was made with the PZT. The frequency components of $2f_b$ and $6f_b$ were produced by the interference between the reference wave and the two object waves of U_1 and U_2, respectively as shown in Fig.8. To measure the positions of the front and rear surfaces the phases of the frequency components of $2f_b$ and $6f_b$ were obtained with FFT and the calculations to obtain one OPD were carried out for the front surface of $L_\sigma=2L_b$ and the rear surface of $L_\sigma=6L_b$. The measured position distributions or surface profiles of the front and rear surfaces

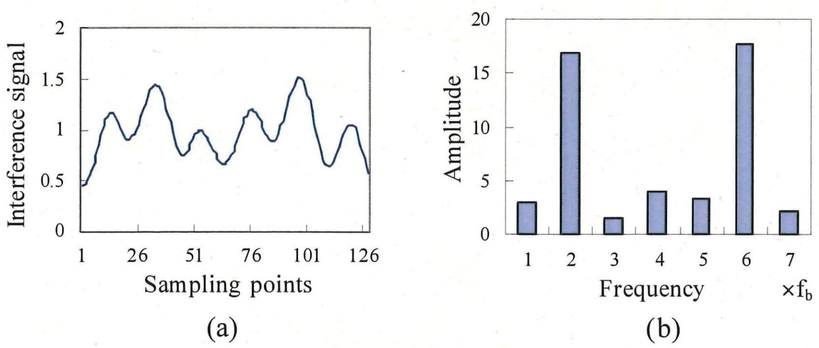

Fig.8 (a) Interference signal intensity, and (b) amplitude distributions of frequency components of (a) calculated with FFT.

represented by OPD are shown in Fig.9. Since the difference between the measured value and the L_σ is less than 140 nm, the value of Δp given by Eq.(9) is less than 0.05. This means that the condition to obtain an exact value of m is satisfied and the measurement error of the phase α_0 is less than 15nm.

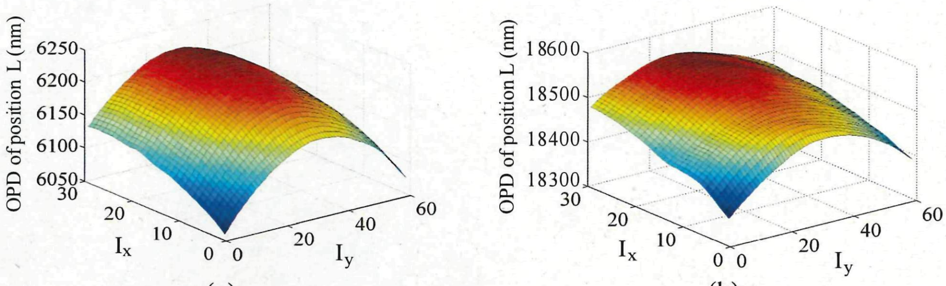

Fig.9 (a) Position of the front surface, and (b) Position of the rear surface of the film.

6. CONCLUSIONS

Conventional methods to measure the positions of the front and rear surfaces of thin films with multiple-wavelength interferometers were reviewed to make it clear how the method propose here is novel and simple. The principle of the linear wavenumber-scanning interferometry used in the proposed method was described in detail to analyze the measurement accuracy clearly. The positions of the front and rear surfaces of a silicon dioxide film with 4μm thickness was measured by utilizing the phases of the sinusoidal waves signals corresponding to each of the OPDs with the linear wavenumber-scanning interferometer. The measurement error was estimated to be about 15 nm as expected from the theoretical analysis.

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