Sinusoidal wavelength-scanning interferometer using an acousto-optic tunable filter for measurement of thickness and surface profile of a thin film

Hisashi Akiyama[1], Osami Sasaki[2], and Takamasa Suzuki[2]

[1]*Graduate School of Science and Technology, Niigata University, Niigata-shi 950-2181, Japan*
[2]*Faculty of Engineering, Niigata University, Niigata-shi 950-2181, Japan*
osami@eng.niigata-u.ac.jp

Abstract: A sinusoidal wavelength-scanning interferometer for measuring thickness and surfaces profiles of a thin film has been proposed in which a superluminescent laser diode and an acousto-optic tunable filter are used. The interference signal contains an amplitude Z_b of a time-varying phase and a constant phase α. Two values of an optical path difference (OPD) obtained from Z_b and α, respectively, are combined to measure an OPD longer than a wavelength. The values of Z_b and α are estimated by minimizing the difference between the detected signals and theoretical ones. From the estimated values, thickness and surface of a silicon dioxide film coated on an IC wafer with different thicknesses of 1 μm and 4 μm are measured with an error less than 5 nm.

OCIS codes: (120.3180) Interferometry; (120.5060) Phase modulation; (240.0310) Thin films.

References and links

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1. Introduction

It is important to measure positions of the surfaces of a thin film in three dimensions with a high accuracy of a few nanometers. For example, it is required in the manufacturing process of liquid crystals displays and semiconductors that three-dimensional profiles of transparent conductive films of ITO (Indium Tin Oxide) and silicon dioxide films coated on an IC wafer are measured. Many instruments for measuring thickness of a film on one measuring point are available, but they can not measure the surface profiles and need a long time to obtain two-dimensional distribution of thickness of the film. To achieve the three-dimensional measurement of thickness and surface profiles of a thin film, white light interferometers and wavelength-scanning interferometers have been developed. In white light interferometers, the positions of the reflecting surfaces are determined by finding positions where the amplitude of the interference signal has a peak by scanning the optical path difference (OPD) [1]. In wavelength-scanning interferometers, spectral phase of the interference signal, which varies according to the scanning of the wavelength instead of the scanning of the OPD, is utilized for thickness measurement. In the case of linear wavelength-scanning, the positions of the reflecting surfaces are determined by the peaks of the frequency spectrum of the interference signal [2]. When thickness of a film is very thin, the distance between the two peaks of the amplitude of the interference signal in white light interferometers or the distance between the two peaks of the frequency spectrum of the interference signal in wavelength-scanning interferometers, which are caused by the two reflecting surfaces, become too short to distinguish the positions of the two peaks. Therefore, these conventional methods of finding the peaks are not suitable to measure the positions of the two reflecting surfaces in a very thin film. In reference [3], a spectral phase function of an interference signal was detected around a position where OPD is almost zero in a white light interferometer. An error function was defined by the difference between the detected spectral phase function and the theoretical one. By minimizing the error function, the surface profiles and the thickness of the film were estimated. In this case, the measurement accuracy strongly depends on the mechanical scanning of the OPD by use of a piezoelectric transducer. On the other hand, in references [4, 5] linear wavelength-scanning interferometers are proposed in which an acoustic-optic tunable filter (AOTF) was used to obtain the scanning width of about 100 nm. In this case also, an error function about the spectral phase function of the interference signal was minimized to estimate the surface profile and the thickness whose range was within a few microns.

In this paper we propose a different method using a sinusoidal wavelength-scanning interferometer compared with the methods in references [4,5]. Signal components caused by interference between the lights reflected from a film and a reference light are completely selected from a detected interference signal by the use of a sinusoidal phase modulation produced by a vibrating reference mirror. The double sinusoidal modulation of the wavelength and the phase leads to an error function for the signal estimation which is defined not for the spectral phase of the interference signal, but for the signals derived from the detected interference signal. This error function allows a good estimation of the positions of the two reflecting surfaces of a film even when the wavelength-scanning width is small. The detected interference signal contains a time-varying phase produced by sinusoidal wavelength-scanning and a constant phase α. The amplitude of the time-varying phase is called modulation amplitude Z_b which is proportional to the OPD and the wavelength scanning width. Since a rough value and a fine value of the OPD are obtained from Z_b and α respectively, the OPD longer than a wavelength can be measured with a high accuracy of few nanometers [6-8]. The important unknowns in the error function are the values of Z_b and α for the two reflecting surfaces, and initial values of Z_b are obtained with double sinusoidal phase-modulating interferometry [9]. Combination of the estimated values of Z_b and α provide the positions of the two reflecting surfaces of a film with a high accuracy of a few nanometers. In the experiment, a superluminescent laser diode (SLD) and an AOTF are used to achieve a wavelength-scanning width of 47 nm. The thickness distribution and surfaces profiles of a silicon dioxide film on an IC wafer with different thicknesses of 1 μm and 4 μm are measured with an error less than 5nm.

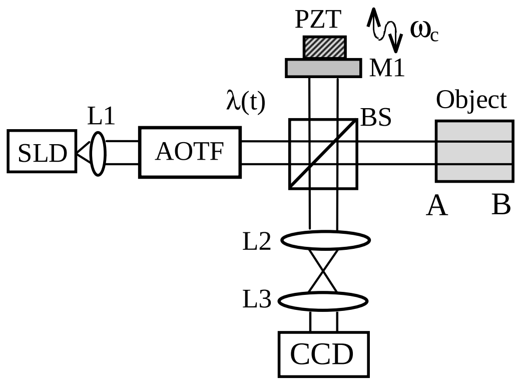

Fig. 1. Interferometer for measuring thickness and surface profiles of thin film.

2. Principle

Figure 1 shows an interferometer for measuring thickness and surface profiles of a thin film. The output light of the SLD is collimated by lens L1 and incident on the AOTF. The wavelength of the first-order diffracted light from the AOTF is proportional to the frequency of the applied signal. Modulating the frequency of the applied signal sinusoidally, the wavelength of the light from the AOTF is scanned as follows:

$$\lambda(t)=\lambda_0+b\cos(\omega_b t), \quad (1)$$

where λ_0 is the central wavelength. The intensity of the light source is also changed, and it is denoted by M(t). The light is divided into an object light and a reference light by a beam splitter (BS). The reference light is sinusoidally phase modulated with a vibrating mirror M1 whose movement is a waveform of $a\cos(\omega_c t+\theta)$.

The object is a silicon dioxide film coated on IC wafer as shown in Fig. 2, and the refractive index of air, silicon dioxide and IC wafer are denoted by n_1, n_2 and n_3, respectively. The film has two surfaces A and B, and multiple-reflection light from the two surfaces is defined by U_i (i=1, 2, 3, …). The amplitudes of the interference signals caused by reference light and object light U_i are denoted by a_i (i=1, 2, 3, …). The constant ratios of a_i to a_1 are defined by $K_i=a_i/a_1$ (i=1, 2, 3, …), and it is calculated with the refractive index of n_1, n_2 and n_3. Since $n_1=1.00$, $n_2=1.46$ and $n_3=3.70$, the constant ratio K_2, K_3 and K_4 are $K_2=2.24$, $K_3=0.18$ and $K_4=0.01$, respectively. Since the amplitude of $a_4<<a_1$, the interference signal caused by U_4 and higher reflection light can be neglected. Lights U_i (i=1, 2, 3, …) interfere with each other

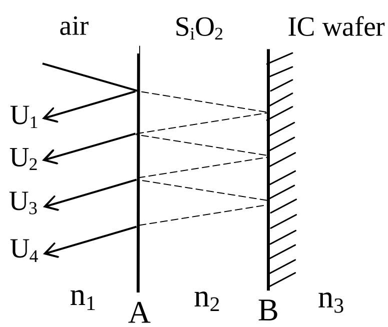

Fig. 2. Multiple reflections by a thin film.

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to cause an interference signal. Since the reference light is sinusoidally phase modulated, this interference signal and intensity components of each light can be filtered out through Fourier transform of the interference signals detected with the CCD [10]. The positions of two surfaces A and B are expressed by OPDs L_1 and L_2. Among the detected interference signals the interference signals caused by interference between U_i (i=1, 2, 3) and the reference light are expressed as

$$S(t) = M(t)\sum_i a_i \cos[Z_c \cos(\omega_c t + \theta) + Z_{bi} \cos(\omega_b t) + \alpha_i], \quad (i=1, 2, 3) \qquad (2)$$

where

$$Z_c = 4\pi a/\lambda_0,$$

$$Z_{bi} = 2\pi b L_i/\lambda_0^2, \quad (i=1, 2)$$

$$Z_{b3} = Z_{b1} + 2(Z_{b2} - Z_{b1}),$$

$$\alpha_i = 2\pi L_i/\lambda_0, \quad (i=1, 2)$$

$$\alpha_3 = \alpha_1 + 2(\alpha_2 - \alpha_1) + \pi. \qquad (3)$$

Putting $\Phi_i = Z_{bi}\cos(\omega_b t) + \alpha_i$, the interference signal S(t) is rewritten as

$$S(t) = M(t) A \cos[Z_c \cos(\omega_c t + \theta) + \Phi(t)], \qquad (4)$$

where,

$$A\exp[j\Phi(t)] = \sum_i a_i \exp(j\Phi_i) \qquad (i=1, 2, 3) \qquad (5)$$

The intensity modulation M(t) is obtained by detecting the intensity of the reference light. The Fourier transform of S(t)/M(t) is denoted by $F(\omega)$. If the following conditions are satisfied,

$$\Im[A\sin\Phi(t)] = 0,$$

$$\Im[A\cos\Phi(t)] = 0, \qquad |\omega| > \omega_c/2 \qquad (6)$$

where $\Im[y]$ is the Fourier transformation of y, the frequency components of $F(\omega)$ in the regions of $\omega_c/2 < \omega < 3\omega_c/2$ and $3\omega_c/2 < \omega < 5\omega_c/2$ are designated by $F_1(\omega)$ and $F_2(\omega)$, respectively. Then we have

$$F_1(\omega - \omega_c) = -J_1(Z_c)\exp(j\theta)\Im[A\sin\Phi(t)],$$

$$F_2(\omega - 2\omega_c) = -J_2(Z_c)\exp(j2\theta)\Im[A\cos\Phi(t)], \qquad (7)$$

where $J_n(Z_c)$ is the nth-order Bessel function [9]. The values of Z_c and θ are measured by sinusoidal phase-modulation interferometry beforehand. Taking the inverse Fourier transform of $-F_1(\omega-\omega_c)/J_1(Z_c)\exp(j\theta)$ and $-F_2(\omega-2\omega_c)/J_2(Z_c)\exp(j2\theta)$, we obtain

$$A_s(t) = A\sin\Phi(t) = \Sigma a_i \sin[Z_{bi}\cos(\omega_b t) + \alpha_i],$$

$$A_c(t) = A\cos\Phi(t) = \Sigma a_i \cos[Z_{bi}\cos(\omega_b t) + \alpha_i]. \qquad (i=1, 2, 3) \qquad (8)$$

When the absolute value of Z_{bi} increases, the frequency distributions of $F_1(\omega)$ and $F_2(\omega)$ have a wider band around ω_c and $2\omega_c$, respectively, due to the terms of $Z_{bi}\cos(\omega_b t)$. Since the conditions given by Eq. (6) must be satisfied, maximum detectable value of $|Z_{bi}|$ depends on the ratio of the ω_c/ω_b. In contrast, when the absolute value of Z_{bi} decrease, the magnitude of the spectra in $F_1(\omega)$ and $F_2(\omega)$ becomes so small that they can not be distinguished from noise. Therefore the absolute value of Z_{bi} must be between 1 rad and 12 rad at $\omega_c = 32\omega_b$.

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The detected values of $A_s(t_m)$ and $A_c(t_m)$ are obtained from the detected interference signals at intervals of Δt, where $t_m=m\Delta t$ and m is an integer. Using the detected values of $A_s(t_m)$, $A_c(t_m)$, and known values of K_i (i=2, 3), we define an error function

$$H = \sum_m \{[\hat{A}_s(t_m) - A_s(t_m)]^2 + [\hat{A}_c(t_m) - A_c(t_m)]^2\}, \tag{9}$$

where $\hat{A}_s(t_m)$ and $\hat{A}_c(t_m)$ are the estimated signals which contain unknowns of a_1, Z_{bi}, and α_i. The values of unknowns of a_1, Z_{bi}, and α_i are searched to minimize H by multidimensional nonlinear least-squares algorithm.

We obtain values of L_i from the values of Z_{bi} that is denoted by L_{zi}, and also obtain other values of L_i from the values of α_i that is denoted by $L_{\alpha i}$. Since the measurement range of $\alpha_i=2\pi L_{\alpha i}/\lambda_0$ is limited $-\pi$ to π, a value of $L_{\alpha i}$ is limited to the range from $-\lambda_0/2$ to $\lambda_0/2$. On the other hand, a value of $Z_{bi}=2\pi bL_{zi}/\lambda_0^2$ provides a rough value L_{zi} of L_i. To combine L_{zi} and $L_{\alpha i}$, the following equation is used:

$$m_{ci}=(L_{zi}-L_{\alpha i})/\lambda_0. \tag{10}$$

If the measurement error ε_{Lzi} in L_{zi} is smaller than $\lambda_0/2$, a fringe order m_i is obtained by rounding off m_{ci}. The suffixes of i=1 and 2 in the L_{zi}, $L_{\alpha i}$, m_{ci}, and m_i correspond to surface A and B, respectively. Then an OPD L_i longer than a wavelength is given by

$$L_i=m_i\lambda_0+L_{\alpha i}. \tag{11}$$

Since the measurement accuracy of $L_{\alpha i}$ is a few nanometers, an OPD over several ten micrometers can be measured with a high accuracy.

The positions P_1 and P_2 of the front and rear surfaces, respectively, are obtained from the estimated values as follows:

$$P_1=(m_1\lambda_0+L_{\alpha i})/2, \quad P_2=P_1+[m\lambda_0+(L_{\alpha 2}-L_{\alpha 1})]/2n_2, \tag{12}$$

where $m=m_2-m_1$. The thickness d is given by P_2-P_1. Thus we can measure the thickness and the two surface profiles of the object.

3. Determination of initial values

While searching for the real values of the unknowns, the existences of numerous local minima was recognized. The conditions of the initial values were examined by computer simulations. The initial values move to the real values almost certainly when differences between the initial values and the real values are within the following values: about 2rad for Z_{b1} and Z_{b2}, about 1.5rad for α_1 and α_2, and about 50% accuracy for a_1. However if one of these condition for the differences is not satisfied, the initial values do not always reach the global minimum. Good initial values are required to reach the global minimum in a short time.

First we consider how to determine a better initial value of a_1. We adjust the position of the object so that $L_1 \simeq 0$ or $Z_{b1} \simeq 0$. In this case Eqs. (8) is reduced to

$$A_s(t)=C_1+K_2a_1\sin[Z_{b2}\cos(\omega_b t)+\alpha_2]+K_3a_1\sin[Z_{b3}\cos(\omega_b t)+\alpha_3],$$
$$A_c(t)=C_2+K_2a_1\cos[Z_{b2}\cos(\omega_b t)+\alpha_2]+K_3a_1\cos[Z_{b3}\cos(\omega_b t)+\alpha_3], \tag{13}$$

where $C_1=a_1\sin\alpha_1$ and $C_2=a_1\cos\alpha_1$ are constant with time. The constant ratio $K_3=a_3/a_1$ is almost 10 times smaller than K_2. Therefore, these third terms of Eq. (13) can be neglected when rough values of a_1, Z_{b1} and Z_{b2} are sought as the initial values. The position of $L_1=0$ can be found by checking whether the signals of $A_s(t)$ and $A_c(t)$ are changing from K_2a_1 to $-K_2a_1$ with a constant amplitude of K_2a_1. Since K_2 is a known value, a value of a_1 is obtained from the amplitude of K_2a_1. Next we consider how to determine the initial values of Z_{b1} and Z_{b2}. Equation (13) is the same as the equations appeared in the double sinusoidal phase-

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modulating interferometry [9] since the first and third terms can be eliminated from Eq. (13). Using the signal processing of double sinusoidal phase modulating interferometry for Eq. (13), the value of Z_{b2} can be calculated. After that the value of Z_{b1} is changed from 0 rad to some value by moving the position of the object with a micrometer so that the absolute values of Z_{b1} and Z_{b2} are between 1rad and 12rad according to the condition described in Section 2. Then the initial values of Z_{b1} and Z_{b2} can be obtained knowing rough values of the thickness and the refractive index of the object. On the other hand the initial values of α_1 and α_2 can not be determined from the detected signals. Therefore the initial value of α_1 is given at intervals of 1.0 rad in the range from $-\pi$ to π rad for the initial value of $\alpha_2=0$. When a global minimum can not be obtained, the initial value of α_2 is changed by 1.0 rad and the search is repeated again. Considering all combinations of α_1 and α_2, the search becomes successful at most after 36 repetitions. The values estimated first at one measuring point are used as the initial values of the adjacent measuring points, because the difference in real values of α_1 and α_2 between the adjacent measuring points is within $\pi/2$ to detect the interference signal with a sufficient amplitude.

4. Experimental result

We constructed the interferometer shown in Fig. 1 and tried to measure the front and rear surface positions of a silicon dioxide film coated on an IC wafer whose configuration is shown in Fig. 3. The central wavelength and spectral bandwidth of the SLD was 830 nm and 46 nm, respectively. The central wavelength λ_0 of the first-order diffracted light from the AOTF was 837.1 nm, and its spectral bandwidth was about 4 nm. The wavelength scanning frequency of $\omega_b/2\pi$ was 15.8 Hz and the wavelength-scanning width 2b was 47.3 nm. The phase modulating frequency of $\omega_c/2\pi$ was $32(\omega_b/2\pi)$=506 Hz. A two-dimensional CCD image sensor was used to detect the interference signals. Lenses L2 and L3 formed an image of the object on the CCD image sensor with magnification of 2/3. Number of the measuring point was 60×30 in a region of 1.8 mm×0.9 mm on the object surfaces along the x and y axes, respectively. Positions of the pixels of the CCD image sensor are denoted by I_x and I_y, respectively. Intervals of the measuring points were Δx=30 μm and Δy=30 μm.

The object has two thicknesses of $d_L \simeq 1\,\mu$m and $d_R \simeq 4\,\mu$m as shown in Fig. 3. First, we estimated values of unknowns Z_{b1}, Z_{b2}, α_1 and α_2 at the two points of I_x=1, I_y=1 and I_x=60, I_y=1 by minimizing the error function given by Eq. (9). The estimated values at the point of I_x=1, I_y=1 were used as initial values of the adjacent measuring points in the region of 1μm thickness, and the estimated values at the point of I_x=60, I_y=1 were also used as initial values in the region of 4μm thickness. Values of Z_{b1}, Z_{b2}, α_1, and α_2 were estimated on all of the measuring points. Figure 4 shows the OPD L_{zi} (i=1, 2) calculated from Z_{bi} with Eq. (3). Figure 5 also shows the OPD $L_{\alpha i}$ (i=1, 2) calculated from α_i with Eq. (3). Exact measured values could not be obtained in the region of I_x=25-30 because light was strongly diffracted on the

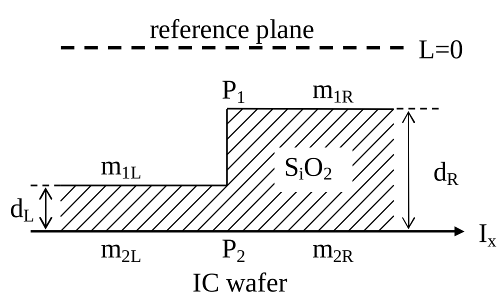

Fig. 3. Two dimensional shapes of the object along I_x.

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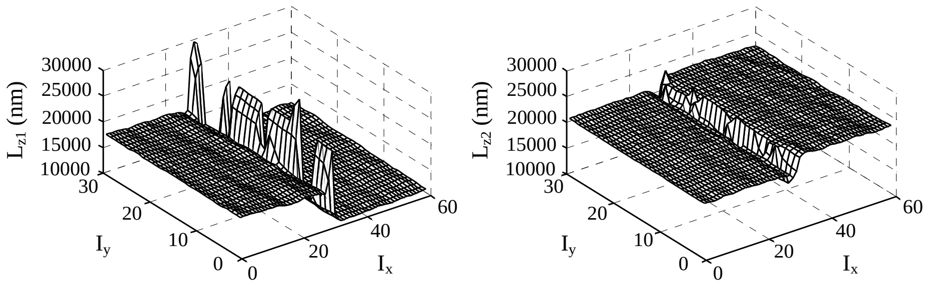
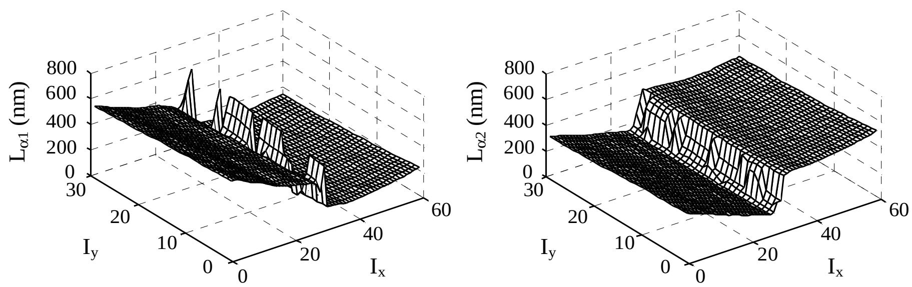


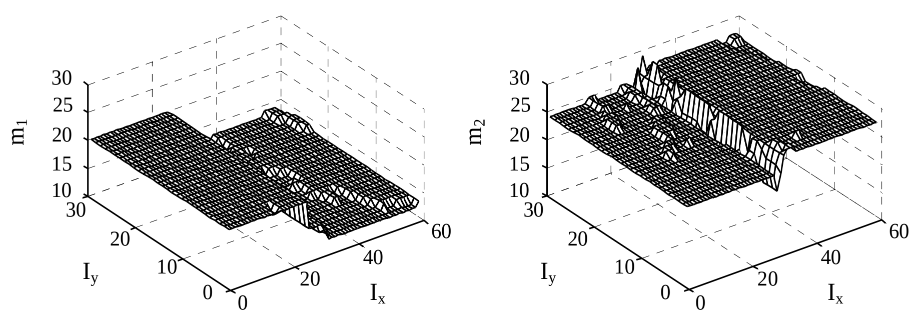
(a) (b)

Fig. 4. Measured OPD L_{zi} calculated from Z_{bi} of the (a) front surface and (b) rear surface.



(a) (b)

Fig. 5. Measured OPD $L_{\alpha i}$ calculated from α_i of the (a) front surface and (b) rear surface.



(a) (b)

Fig. 6. Distribution of the fringe order (a) m_1 and (b) m_2.

boundary of the two different thickness part of the object. By combining L_{zi} and $L_{\alpha i}$ with Eq. (10), the fringe order m_1 of the front surface and the fringe order m_2 of rear surface were obtained. Fringe order m_i in the region of I_x=1-24 is denoted by m_{iL}, and m_i in the region of I_x=31-60 is denoted by m_{iR}, as shown in Fig. 3. Figure 6(a) shows that fringe order m_{1L} was almost 20, while there were two different values for the fringe order m_{1R}. A value of m_{1R}=12

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appeared in 33% of the measuring points and m_{1R}=13 appeared in 63% of the measuring points. Figure 6(b) shows that fringe order m_{2L} and m_{2R} were almost 24 and 27, respectively. Considering that the estimated OPDs $L_{\alpha i}$ of the front and rear surface changed smoothly as shown in Fig. 5, it was clear that fringe order m_{iL} and m_{iR} were constant values on each of the measuring regions. It is certainly decided that fringe order m_{1L} m_{2L} and m_{2R} were 20, 24 and 27, respectively. Figure 7 shows the two different positions of P_2 calculated in the cases of m_{1R}=12 and m_{1R}=13 along I_x at I_y=15 with Eq. (12). Considering that position P_2 is the position of the IC wafer surface which does not contain a discontinuous part, fringe order m_{1R} can be determined to be 13. Figure 8 shows the measured positions P_1 and P_2 of the front and rear surfaces of the object with m_{1L}=20, m_{1R}=13, m_{2L}=24, and m_{2R}=27. Figure 9 shows the thickness distribution calculated from P_2-P_1. Table 1 shows the measured values of L_{zi}, $L_{\alpha i}$, m_{ci}, P_i and d along I_x at I_y = 15. In the region of d_L the average value of the thickness was 1071 nm, and in the region of d_R the average value of the thickness was 4114 nm. It was made clear by repeating the measurement three times that the measurement repeatability was less than 5 nm. The object was also measured with a commercially available white light interferometer to examine the measurement accuracy. The average values of d_L and d_R measured with the white light interferometer were 1074 nm and 4113 nm. This measurement result indicated that the measurement accuracy of the proposed interferometer was in the rage of a few nanometers.

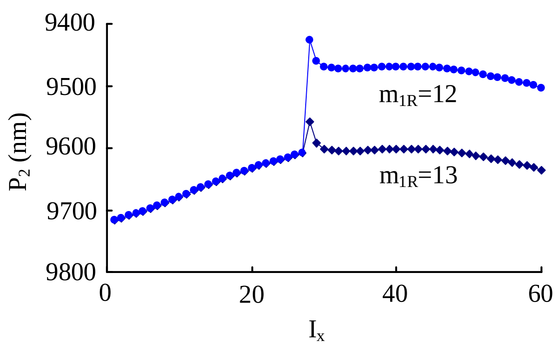

Fig. 7. Position P_2 of the object in the case of m_{1R}=12 and m_{1R}=13 along I_x at I_y=15 with m_{1L}=20, m_{2L}=24, m_{2R}=27.

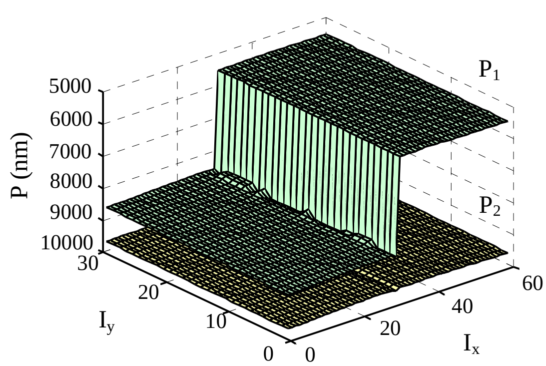

Fig. 8. Measured positions P_1 and P_2 of the surfaces.

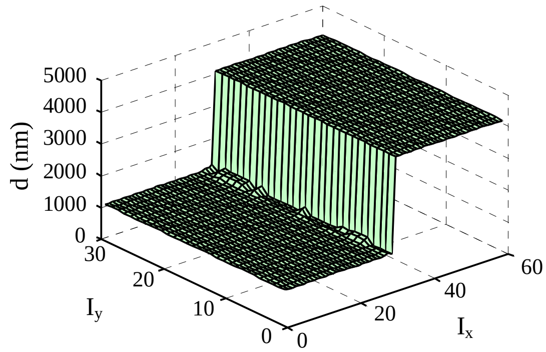

Fig. 9. Measured thickness of the object.

Table 1. Measured values along one line of I_x at I_y=15.

I_x	L_{z1} (nm)	L_{z2} (nm)	$L_{\alpha1}$ (nm)	$L_{\alpha2}$ (nm)	m_{c1}	m_{c2}	P_1 (nm)	P_2 (nm)	d (nm)
5	17200	20387	526	295	19.9	24.0	8634	9702	1068
15	17066	20727	418	207	19.9	24.5	8580	9654	1074
25	16933	20517	346	126	19.8	24.4	8544	9615	1071
35	10508	23098	101	391	12.4	27.1	5492	9604	4112
45	10765	23063	91	387	12.8	27.1	5487	9602	4115
55	11057	22727	128	427	13.1	26.6	5505	9621	4116

5. Conclusions

A sinusoidal wavelength-scanning interferometer for measuring thickness and surface profiles of a thin film has been proposed in which the SLD and the AOTF were used. The interference signal contains the amplitude of the phase modulation Z_b and the constant phase α related to the thickness and the surfaces profiles. Values of Z_b and α were estimated by reducing the difference between the detected signal and the estimated signal. By combining the two estimated values of Z_b and α, the positions of the front and rear surfaces of the silicon dioxide film coated on an IC wafer were measured with an error less than 5 nm.