Simultaneous Measurement of Film Surface Topography and Thickness Variation using Three-Wavelength Interferometry

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Abstract : In the optical interferometric surface profiling methods represented by the white-light interferometry, if the measurement target is covered with a transparent film, the backside reflected light becomes a disturbance and accurate measurement cannot be performed. In addition, the optical film thickness measurement methods such as spectroscopy are slow due to single-point measurement, and their spatial resolution is limited. We propose a simultaneous measurement algorithm for surface profile and film thickness distribution using the three-wavelength interferometry. A three-wavelength interferogram obtained from a three-wavelength illumination system and a color camera is waveform-separated to estimate the surface height, backside height and film thickness of each pixel. The proposed method is validated through computer simulations and experiments.

<Keywords> Interferometry, transparent film, surface profile, film thickness distribution, three wavelengths, waveform separation, model matching

1. Introduction

The optical interferometry represented by the white interferometry is widely used as a high-precision threedimensional profile measurement method on the order of nanometers. However, if the measurement target is covered with a transparent film, the reflected light from the back surface becomes a disturbance, and accurate profile measurement cannot be performed.

In order to solve the above problem, we have developed many transparent film measurement algorithms by optical interferometry [1-7], and some of them have been put into practical use. Most of these methods separate the interferogram (intensity waveform) of the white interferometry into a front reflection component and a back reflection component, and in the case of a thick film with an optical film thickness exceeding one μ m, peak waveforms do not overlap and can be separated relatively easily. However, in the case of a thin film with a film thickness of several hundred nm or less, waveforms are superimposed and separation is not easy. As other solutions to this problem, the Fourier transform method of the white-light interferometry [8] and the wavelength scanning method [9, 10] have been proposed, but the former has the disadvantage that the calculation is complicated, and the latter has the disadvantage that the optical system becomes complicated.

In addition, there are spectroscopic methods and ellipsometry as optical film thickness measurement methods for transparent films, but they are essentially single-point measurement methods, and there is a need for high-speed film thickness distribution measurement.



Fig. 1 System configuration for three-wavelength vertical scanning interferometry.

On the other hand, we developed a low-cost and compact three-wavelength color imaging system, and using this system, we first developed a single-shot surface profiling method by carrier fringe introduction [11, 12]; then, a single-shot surface profiling method [13, 14] and a film thickness profiling method [15, 16] both by interference color analysis.

In this paper, we propose a new simultaneous measurement method of front surface, back surface, and film thickness distribution using the three-wavelength interferometry. The validity of the proposed method was confirmed by computer simulations and experiments [17].

2. Measurement principle

A three-wavelength interference optical system is constructed based on a commercially available interference microscope, as shown in Fig. 1. By inserting a three-wavelength band-pass filter (center wavelength 470 nm, 560 nm, and 600 nm; bandwidth 10 nm) into the light source and capturing an image with a color camera, we can obtain three interferograms with different wavelengths simultaneously from the BGR signals of the camera [11]¹.

As in the case of the white-light interference method, the luminance signal waveforms (interferograms) of each pixel are obtained by scanning the objective lens vertically with a piezo actuator, and three sine waves with different wavelengths are obtained as shown in Figure $2(a)^2$.

This intensity signal is the sum of the surface reflected light component and the back surface reflected light component of the film, and can be expressed by the following equation (see Appendix 1 for the derivation of the equation).

$$g(i, j) = a(j) + b_1(j)\cos 4\pi \left(\frac{z(i) - z_1}{\lambda(j)}\right)$$
(1)
+ $b_2(j)\cos 4\pi \left(\frac{z(i) - z_2}{\lambda(j)}\right)$

where, *i* is the image number, *j* is the wavelength number (B, G, R), *a* is the DC component, b_1 is the front surface interference signal amplitude, b_2 is the back surface interference signal amplitude, λ is the wavelength, and *z* is the height position. Position z_1 is front surface height, and z_2 is optical back surface height³.

Consider finding unknown variables by least-squares fitting this model function to the observed intensity data (i.e. by minimizing the squared sum of error *SSE* of the following equation):

$$SSE = \sum_{j=1}^{3} \sum_{i=1}^{N} \left[g(i, j) - g_{i,j} \right]^{2}$$
(2)

where, g_{ij} is the observed intensity, and N is the number of observed images.

Let us consider the necessary conditions to obtain the unknown parameters. The total number of unknown parameters is eleven: a(j), $b_1(j)$, $b_2(j)$, z_1 , and z_2 . However, there are nine meaningful parameters among three interferograms, because a sinusoidal wave has three meaningful parameters: the bias, amplitude, and phase. Therefore, this least-square fitting problem cannot be solved.

To make it solvable, let us consider the reduction of unknown variables. Among the eleven unknown variables, a(j) depends on the amount of incident light and the sample, and cannot be known. The heights z_1 and z_2 are the parameters to be estimated. As for the remaining parameters $b_1(j)$ and $b_2(j)$, they depend on the amount of incident light and the sample, but let us note that their ratio α ($\equiv b_1/b_2$) is a parameter that does not depend on the amount of incident light and depends only on the sample. That is, if the multiple reflected light in the film is ignored, it is theoretically expressed as follows (see Appendix 2 for the derivation of the equation):

$$\alpha = \frac{(n-1)(n+1)}{4n} \sqrt{\frac{(n+n_B)^2 + \kappa_B^2}{(n-n_B)^2 + \kappa_B^2}}$$
(3)

¹ If camera crosstalk cannot be ignored, it will be corrected by software [18].

 $^{^2}$ Since the half width of the band filter is 10 nm, the coherence length is about 20 μ m, and the interference signal becomes almost a sine wave within the range of several μ m.

³ The height obtained by subtracting the optical film thickness from the front surface height is called the optical back surface height z_2 , and is distinguished from the physical back surface height z_b .

where, *n* is the refractive index of the film, and n_B and κ_B are the refractive index and extinction coefficient of the substrate, respectively.

In the three wavelength bands we use (i.e. 470, 560, and 600 nm), the wavelength dependence of the refractive index of many films and substrates used in industry is very small. Therefore, assuming that the front-back amplitude ratio α is the wavelength-independent constant (see Appendix 3), we obtain

$$b_1(j) = \alpha b_2(j) \tag{4}$$

Substituting Eq. (4) into Eq. (1), the model function becomes

$$g(i, j) = a(j) + \alpha b_2(j) \cos 4\pi \left(\frac{z(i) - z_1}{\lambda(j)}\right)$$

$$+ b_2(j) \cos 4\pi \left(\frac{z(i) - z_2}{\lambda(j)}\right)$$
(5)

The number of unknown parameters is reduced to nine, that is, a(j), $b_2(j)$, z_1 , z_2 , and α . Thus, the least-square fitting problem becomes solvable (see Appendix 5 for consideration of the necessary conditions).

From the obtained z_1 and z_2 and the refractive index n, the thickness t and the back surface physical height z_b can be calculated as follows:

$$t = (z_1 - z_2)/n \tag{6}$$

$$z_b = z_1 - t \tag{7}$$

3. Computer simulations

3.1 Simulation method

A set of theoretical interferograms were created under the following conditions:

- Wavelength: 470 nm, 560 nm, 600 nm
- Surface signal parameters: $a_1(B) = a_1(G) = a_1(R) =$
- $b_1(B) = b_1(G) = b_1(R) = 1$
- Back surface signal parameters: $a_2(B) = a_2(G) = a_2(R)$ = $b_2(B) = b_2(G) = b_2(R) = 0.5$
- Surface and back surface heights: $z_1 = 0$ nm, $z_2 = -200$ nm
- Observed data interval: 5 nm
- Observed data range: \pm 500 nm
- Added noise: uniform noise between [- 0.03, 0.03]

The added noise corresponds to $\pm 1\%$ of the signal range $(2b_1 + 2b_2 = 3)$, which is close to the normal camera noise level. The obtained waveform is shown in

Fig. 2 (a).

Least-squares fitting was done using Solver, an optimization tool in MS Excel. The initial values were $z_1 = 50$ nm, $z_2 = -250$ nm, $\alpha = 2.5$, a(j) = the intensity value average, and $b_2(j) =$ the intensity value range divided by $2(1 + \alpha)$.

3.2 Simulation results

The results are shown in Table 1. The estimation error of the nine unknown variables was small, and the error of the front surface height and the back surface height was one nm or less. In addition, Figs. 2 (b), (c), and (d) show the signal and fitted waveforms of the front and back surfaces. Note that, in the surface intensity waveform of Fig. 2 (b), z = 0 is the interference peak with zero optical path difference (hereinafter referred to as the 0th order fringe peak), and in the back surface intensity waveform of Fig. 2 (c), z = -200 is the 0th order fringe peak. In addition, the fitted intensity waveform in Fig. 2 (d) matches well with the observed intensity waveform in Fig. 2 (a).

Table 1Fitting results of simulations

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	Variables	True	Initial	Estimated	Error		
	<i>a</i> (B)	1.50	1.57	1.50	0.00		
	a (G)	1.50	1.42	1.50	0.00		
	a (R)	1.50	1.44	1.50	0.00		
	<i>b</i> ₂ (B)	0.50	0.39	0.49	-0.01		
	<i>b</i> ₂ (G)	0.50	0.30	0.48	-0.02		
	<i>b</i> ₂ (R)	0.50	0.25	0.48	-0.02		
	α	2.00	2.50	2.04	0.04		
	Z 1	0.0	50.0	0.6	0.6		
	Z 2	-200.0	-250.0	-200.7	-0.7		
	t	200.0	300.0	201.3	1.3		
-500 -300 -100 100 300 500 z-position (nm)							
(a) Synthesized data (b) Separated surface signals							
-500 -3	z2 300 -100 1 z-positio	00 300 0n (nm)	3 2 1 500 -50	0 -300 -100 z-p	0 100 300 500 position (nm)		
(c) Separated back-surface (d) Fitted signals							



4. Actual experiments

4.1 Experimental method

The film thickness step sample (SiO₂/Si; film

Intensity

refractive index n = 1.46; nominal film thickness 100 nm/300 nm) whose cross section is shown in Fig. 3 (a) was measured. A vertical scan image was taken with the optical system shown in Fig. 1. The color camera was a commercially available single-plate CMOS camera $(658 \times 492 \text{ pixels}; \text{BGR}; 8 \text{ bits each})$, which was connected to a PC via LAN interface. Since the imaging speed was set to 15 fps and the scanning speed of the piezo mechanism was set to 150 nm/s, images were acquired at a pitch of 10 nm on the z-axis. The scanning range was set to about 1 µm, and about 100 images were obtained. The pixel on the center line (white line) of the obtained image (Fig. 3 (b)) was used as the measurement target point, the interferogram was obtained, and the crosstalk correction was performed using the crosstalk coefficient obtained in advance.



Fig. 3 Test target in experiments

Furthermore, in order to balance the error evaluation among the three wavelengths, the intensity values were normalized by [(intensity value - mean value)/ $\{(maximum value - minimum value)/2\}] +1$, so that they are in the range of approximately [0, 2].

As the calculation software, MS Excel was used. The initial values were calculated from the interferogram and the expected film thickness value as follows:

- a(j) = average intensity $\simeq 1.0$
- $b_2(j) = (\text{intensity range})/2(1+\alpha) \approx 0.67$
- $\alpha = 0.5$, derived from Eq. (3).

• $z_2 = 0$ th-order fringe peak position of the interferogram. This position is detected as the maximum point of the sum of the BGR intensity values. Since the amplitude of the back surface is larger than that of the front surface, it is assumed that the back surface peak position is close to the observed peak position.

• $z_1 = z_2$ + (expected optical film thickness). Please note that the optical film thickness is the product of the physical film thickness and the refractive index.

4.2 Experimental results

First, Fig. 4, Fig. 5, and Table 2 show the measurement results at the measurement points L (thickness 300 nm) and measurement point C (thickness 100 nm) shown in the image of Fig. 3 (b).

Fig. 4 (a) shows the observed intensity waveform at point L (after crosstalk correction and normalization), and it was separated by the proposed method to the front side signal (Fig. 4 (b)) and back side signal (Fig. 4 (c)). Figure 4 (d) shows the sum signal of both, which fits well with the observed intensity waveform. Figures 5 (a), (b), (c), and (d) show similar results at point C.

Table 2 shows the measurement results of both points. The first nine lines of the variable are the parameters obtained by fitting, and from the results, the film thickness *t* and the back surface height z_b are obtained by Eqs. (6) and (7).





Fig. 5 Waveforms at point C (thickness: 100 nm)

The film thicknesses obtained were 295 nm and 101 nm, which are close to the manufacturer's nominal values. In addition, the heights of the back surfaces of both points are almost the same, and the surface step is measured to be 193 nm, which is a reasonable result.

Next, Fig. 6 shows the measurement results of the points on the center line in Fig. 3 (b). The front surface height z_1 , the back surface height z_b , and the film thickness *t* are stably measured, and the amplitude ratio α is also stable around 0.45. The squared sum of error *SSE* is small except for the edge part, indicating that the fit is stable.

Table 2 Experimental results at two points

Position	Le	ft(L)	Center(C)		
Variables	Initial	Estimated	Initial	Estimated	
a (B)	1.00	0.99	1.00	1.00	
a (G)	1.00	0.98	1.00	1.08	
a (R)	1.00	1.01	1.00	1.04	
<i>b</i> ₂ (B)	0.67	0.73	0.67	1.20	
<i>b</i> ₂ (G)	0.67	1.71	0.67	1.68	
<i>b</i> ₂ (R)	0.67	1.58	0.67	1.74	
a.	0.50	0.46	0.50	0.45	
Z 1	868	821	606	628	
Z 2	430	391	460	481	
t	300	295	100	101	
Z A	568	527	506	528	



Fig. 6 Measurement results of thin-film step sample

5. Implementation issues and solutions

5.1 Local minima problem

The least squares fit of this method has a large number of local solutions because the model includes a periodic function. Therefore, the correct solution may not be obtained depending on the initial value by the usual nonlinear optimization method. For example, Fig. 7 shows the estimation results when the initial value of the film thickness is changed in the simulation in Section 3. When the initial film thickness is between 125 and 350 nm, it converges to the correct film thickness (around 200 nm), but otherwise it falls into a local minimum near the initial value. This problem can be solved by the multi-start method used for global optimization problems having local minima. That is, fitting is performed using multiple initial values, and the global minimum is selected from the results. In the case of the proposed method, there may be little difference in the evaluation function value *SSE* as shown in Fig. 7. Therefore, the converged value of the unknown variable (for example, α) is also used for the selection.



Fig. 7 Effect of the initial value of thickness on the results of simulation

5.2 Calculation time

In the experiments in this report, Solver, an optimization tool for MS Excel, was used. The calculation time was about 1.6 s/point using a Windows PC (CPU: 3.4 GHz). In order to increase the speed, we are developing software for the actual equipment using the C ++ language. In the initial test results, a speed of about 3 ms/point was obtained. Further speedup such as parallel processing is an issue for the future.

6. Summary

We proposed a simultaneous measurement method for surface profile, back surface profile, and film thickness distribution by the three-wavelength interferometry. The interference signal model is fitted to the interferograms (intensity waveforms) of three wavelengths by the least squares, and the front surface peak position, back surface peak position, and waveform parameters are collectively obtained. This algorithm separates two superposed sinusoidal signals of the same frequency, which is an unsolvable problem in general, but it becomes possible by some assumptions. The proposed method is validated through computer simulations and experiments.

This method is highly practical because we can easily obtain the necessary hardware by inserting a threewavelength filter in the path of illumination and replacing the monochrome camera with a color camera in the conventional white-light interferometric profiler. In the future, we would like to improve the robustness of the algorithm and put it into practical use.

Appendix 1 Derivation of Eq. (1)

In the interferometer as shown in Fig. 1-1, assuming that the reflected light intensities from the reference surface, film surface, and film back surface are I_R , I_1 and I_2 , respectively, their combined intensity I is expressed by the following equation [19].

$$I = I_{1} + I_{2} + I_{R} + 2\sqrt{I_{1}I_{2}\cos(\varphi_{1} - \varphi_{2})} + 2\sqrt{I_{R}I_{1}}\cos(\varphi_{R} - \varphi_{1}) + 2\sqrt{I_{R}I_{2}}\cos(\varphi_{R} - \varphi_{2})$$
(1-1)

where, φ is the phase of each reflected light.

In the vertical scanning interferometry, the relative distance between the reference and the sample is changed. At this time, only the 5th to 6th terms on the right side change, and the 1st to 4th terms on the right side are constant. Therefore, by denoting

$$a = I_1 + I_2 + I_R + 2\sqrt{I_1 I_2} \cos(\varphi_1 - \varphi_2) \qquad (1-2)$$

$$b_1 = 2\sqrt{I_R I_1} \tag{1-3}$$

$$b_2 = 2\sqrt{I_R I_2} \tag{1-4}$$

we obtain

$$I = a + b_1 \cos(\varphi_R - \varphi_1) + b_2 \cos(\varphi_R - \varphi_2)$$
(1-5)

The phase differences between the reference surface, the film surface, and the film back surface depend on their relative distances, and assuming that the reference surface height is z,

$$\varphi_R - \varphi_1 = \frac{2\pi(z - z_1)}{\lambda/2} \tag{1-6}$$

$$\varphi_R - \varphi_2 = \frac{2\pi(z - z_2)}{\lambda/2} \tag{1-7}$$

Then, the following equation is obtained.

$$I = a + b_1 \cos\left(\frac{4\pi[z(i) - z_1]}{\lambda}\right) + b_2 \cos\left(\frac{4\pi[z(i) - z_2]}{\lambda}\right) \quad (1-8)$$



Fig. 1-1 Illustration of interference optical system

Appendix 2 Derivation of Eq. (3)

From Eqs. (1-3) and (1-4) of Appendix 1, the front-back amplitude ratio is

$$\begin{aligned} \alpha &= b_1 / b_2 \\ &= (2\sqrt{I_R I_1}) / (2\sqrt{I_R I_2}) \\ &= \sqrt{I_1 / I_2} \end{aligned}$$
(2-1)

Furthermore, assuming that the multiple reflected light is negligible (see Appendix 4), and the intensity reflectance of the front surface is R_1 and the intensity reflectance of the back surface is R_2 , using Eq. (4-1), we obtain

$$\alpha = \sqrt{\frac{R_1}{\left(1 - R_1\right)^2 R_2}}$$
(2-2)

On the other hand, the reflectance of light perpendicularly incident from air (refractive index = 1) onto a substrate (refractive index n_B , extinction coefficient κ) covered with a transparent film (refractive index n) is obtained as follows from the extension of Fresnel's formula:

$$R_1 = \frac{(n-1)^2}{(n+1)^2}$$
(2-3)

$$R_{2} = \frac{(n - n_{B})^{2} + \kappa_{B}^{2}}{(n + n_{B})^{2} + \kappa_{B}^{2}}$$
(2-4)

When this is introduced into Eq. (2-2), Eq. (3) is

obtained.

Appendix 3 Wavelength dependence of the amplitude ratios

Table 3-1 shows the wavelength dependence of the amplitude ratios for typical film structures. Generally, the refractive index dispersion of the film is small, the dispersion of the substrate is dominant, and its value of silicon (Si) is relatively large. However, α is in the range of \pm 5%.

Table 3-1 Wavelength dependence of amplitude ratio α

Film	λ	п	n_B	к	α
g:0	470	1.46	4.52	0.12	0.38
S1U2	560	1.46	4.05	0.04	0.41
/51	600	1.46	3.95	0.03	0.42
C.N	470	2.05	2.50	3.25	0.67
51N /Cm	560	2.03	3.20	3.30	0.68
/Cr	600	2.03	3.20	3.30	0.68

Appendix 4 Effect of multiple reflected light

The ratio of multiple reflected light (repeatedly reflected light on the upper and lower surfaces of the film) in a typical film structure is calculated, and it is shown that the multiple reflected light is negligible.

In Fig. 1-1, it is assumed that the amount of incident light is one, and the intensity reflectance of the front and back surfaces are R_1 and R_2 , respectively. Then the intensities of reflected waves are expressed by:

$$I_{1} = R_{1}$$

$$I_{2} = R_{2}(1 - R_{1})^{2}$$

$$I_{3} = R_{2}(1 - R_{1})^{2}(R_{1}R_{2})$$

$$I_{4} = R_{2}(1 - R_{1})^{2}(R_{1}R_{2})^{2}$$
: (4-1)

The sum after I_2 is

⁴⁾ Sum of two cosine waves is expressed by the following equations:

 $A\cos(\omega t + \alpha) + B\cos(\omega t + \beta) = C\cos(\omega t + \Phi)$

 $C = \sqrt{(A\cos\alpha + B\cos\beta)^2 + (A\sin\alpha + B\sin\beta)^2}$ $\Phi = \tan^{-1} [(A\sin\alpha + B\sin\beta)/(A\cos\alpha + B\cos\beta)]$

$$I_{2\infty} = R_2 (1 - R_1)^2 [1 + (R_1 R_2) + (R_1 R_2)^2 + (R_1 R_2)^3 + \cdots]$$

$$= \frac{R_2 (1 - R_1)^2}{1 - R_1 R_2}$$
(4-2)

The difference between ignoring and considering multiple reflected light is

$$\Delta I_{2} = I_{2} - I_{2\infty}$$

$$= -\frac{R_{1}R_{2}^{2}(1-R_{1})^{2}}{1-R_{1}R_{2}}$$
(4-3)

Its relative error ε is

$$\varepsilon \equiv \Delta I_2 / I_{2\infty}$$

$$= -R_1 R_2$$
(4-4)

Table 4-1 shows the errors in typical film structures. Even in the case of a chromium (Cr) substrate having a large backside reflectance of the film, the multiple reflection component is 4 % or less of the backside reflected light, and it can be seen that the multiple reflected light can generally be ignored.

Table 4-1 Ratio of multiple reflection (λ =560nm)

Film	п	nB	к	R_1	R_2	I_2	<i>E</i> (%)
SiO ₂ /Si	1.46	4.05	0.04	3.5	22.1	20.6	-0.8
SiN /Cr	2.03	3.20	3.30	11.6	32.0	25.0	-3.7
SiO2 /Cr	1.46	3.20	3.30	3.5	42.7	39.8	-1.5
SiO2 /BK7	1.46	1.52	0.00	3.5	0.0	0.0	-0.0

Appendix 5: Necessary conditions for solution

Consider the necessary conditions for solving the problem (a kind of inverse problem) of decomposing observed sum of two sine waves of the same frequency into two waves.⁴

Let us ignore the DC component for simplicity. Then, one sine wave has two parameters: amplitude and phase. When the number of observed sine waves is m, the number of the obtainable parameters (the number of observed data for the inverse problem) is 2m. On the other hand, the unknown variables are the amplitudes $b_1(j)$, $b_2(j)$ and the phases $\phi_1(j)$, $\phi_2(j)$ of the two sine waves. Therefore, the number of the unknows is 4m, and the problem is unsolvable. However, when the interference waveforms are observed simultaneously at m wavelengths as in the proposed method, the heights z_1 and z_2 that determine the phases of the two sine waves after decomposition are common regardless of the wavelength. Therefore, the number of unknown variables is reduced to 2m + 2.

Using the assumption that the amplitude ratio $\alpha \equiv b_1(j)/b_2(j)$ is constant for further reduction, the number of unknown variables becomes m+3. Therefore, the necessary condition to obtain a solution is:

$$2m \ge m+3 \tag{5-1}$$
$$\therefore m \ge 3$$

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