Sensitivity Analysis of Transparent Film Thickness Measurement by Three-wavelength Interference Color Analysis Method

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We have developed a novel film thickness measurement algorithm (GMFT), which estimates the film thickness distribution from a color image captured by a color camera and three-wavelength light source. In this paper, we present some results of sensitivity analysis, propose an algorithm to reduce the measurement error, and discuss the measurement possibility of ultra-thin films.

1. Introduction

The conventional typical methods for measuring the thickness of transparent films are spectroscopy and ellipsometry, but there are problems that the measurement speed is slow and the size of the measurement spot is large.

In order to solve the above problems, we have developed an algorithm (GMFT) that estimates the film thickness of each pixel from the interference color image of the film obtained by a three-wavelength illumination system and a color camera, and have commercialized a film thickness profiler which has the features of a high horizontal resolution, high speed, and no need to calibrate [1-3].

In this report, we report the sensitivity analysis of this measurement method, the improved algorithm, and the examination result of the measurement possibility of ultra-thin films of several tens of nanometers or less.

2. Measurement principle and problems

2.1 Measurement algorithm

The film thickness is estimated from one color interference image taken by the three-wavelength imaging system shown in Fig. 1.



Fig. 1 Three wavelengths color imaging system

(1) GMFT method

The intensity g(i,j) of the interference fringe model with wavelength number j (j=1,2,...,m) at observation point i (i=1,2,...,n) in the image is given by the following equation.

$$g(i, j) = a(j)[1 + b(j)\cos\{\phi(i, j)\}]$$
(1)

$$g(i, j) = a(j)[1 + b(j)\cos\{4\pi t(i)/\lambda(j)\}]$$
(2)

where, a(j) and b(j) are the average intensity and the modulation of wavelength number j, $\phi(i,j)$ is the phase, and t(i) is the optical film thickness (hereinafter simply referred to as film thickness) at point i, λ_i is the wavelength of wavelength number j.

It is also assumed that the film refractive index is smaller than the substrate refractive index, the average luminance a(j) and the modulation b(j) are constant within the image, and it depends only on the wavelength.

The observed intensity values at multiple points are fitted to this model by least squares. That is, the variables a(j), b(j) and t(i) that minimize the sum of squared errors in the following equation are obtained.

$$J[a(j),b(j),t(i)] = \sum_{i=1}^{n} \sum_{j=1}^{m} \left[g(i,j) - g_{ij} \right]^{2}$$
(3)

where g(i,j) is the model intensity shown in Eq. (1) and g_{ij} is the observed intensity.

Given that the number of wavelengths is *m* and the number of points is *n*, the condition for finding unknown parameters by fitting is $mn \ge 2m + n$. Therefore, the necessary number of points *n* is:

$$n \ge 2m/(m-1) \tag{4}$$

In case of m=3, it becomes $n \ge 3$.

That is, in the case of 3 wavelengths and n points, n points film thicknesses and 6 waveform parameters are estimated using 3n observed values.

(2) ACOS method

The above least-squares fit increases the computational cost as the number of parameters increases. Therefore, the number of points used for fitting is limited to several to several tens, and the film thicknesses of other points are calculated by the following method (called ACOS method) using the parameters obtained by fitting.

First, the phase is calculated from the intensity by the following equation obtained by modifying Eq. (1).

$$\phi(i,j) = \cos^{-1}[\{g_{ij}/a(j) - 1\}/b(j)]$$
⁽⁵⁾

where $\cos^{-1}[$] is the inverse cosine function, and its range is $[0, \pi]$. If the argument is outside the domain [-1, 1], the solution is approximated by 0 or π .

Then, from the obtained phase, the film thickness candidate t(i,j) of wavelength *j* at point *i* is calculated by the following equation:

$$t(i,j) = \{\pm \phi(i,j)/2\pi + N(i,j)\}(\lambda_j/2)$$
(6)

where N(i,j) is the fringe order (integer).

From the obtained film thickness candidates, the order N(i,j) and the positive/negative of the phase are determined by the coincidence method, and t(i) is obtained by the following equation:

$$t(i) = (1/3)\sum_{i=1}^{n} t(i, j)$$
(7)

2.2 Problems

Figure 2 shows an example of measuring the film thickness of water droplets by this method. Noise that is synchronized with the interference fringes is observed. This is seemingly caused by the film thickness estimation error in the ACOS method, and the elucidation of the cause must be made to find its countermeasures.

(a) Fringe image (b) Measured thickness

Fig. 2 Measurement of water droplet

3. Sensitivity analysis

3.1 Effect of intensity noise for one wavelength

Consider the effect of intensity noise in the ACOS method. Since the film thickness can be obtained from Eqs. (5) and (6), by rewriting except for the order part, the following formula is obtained for one wavelength.

$$t(g) = \pm (\lambda/4\pi) [\cos^{-1}[(g-a)/ab].$$
 (8)

Therefore, the dependence of the film thickness on the intensity value, that is, the sensitivity coefficient c is written as follows [4].

$$c = \left| \partial t(g) / \partial g \right|$$

= $\left| \lambda / 4\pi a b \sqrt{1 - \{(g - a) / ab\}^2} \right|$ (9)

 $= |\lambda / 4\pi ab\sin(4\pi t / \lambda)|$

Since this formula includes division by zero, it is approximated with the following equation, considering the fact that the actual intensity value is an integer.

$$c = |t(g+1) - t(g)|, \text{ or } |t(g) - t(g-1)|$$
(10)

Figure 3 shows the intensity, phase, and sensitivity coefficient for the film thickness range 0-1000 nm in case of a=100, b=0.5, $\lambda =600$ nm. Figures 3(a)(b)(c) are for the intensity error of +1, and Fig. 3(d) are for the intensity error of ± 1 . It is clear that, in the vicinity of the multiple of 1/4 of the wavelength, the sensitivity is high, that is, the measurement is easily affected by the intensity noise.



Fig. 3 Sensitivity coefficient for one wavelength

3.2 Error of three wavelength coincidence method

In the case of 3 wavelengths, it is necessary to consider the occurrence of order error.

(1) When order error does not occur:

From Eq. (7), the film thickness error is the average of the errors at each wavelength.

(2) When order error occurs:

When an error occurs in order estimation, the film thickness changes by a multiple of half the average value of the three wavelengths (that is, about 270 nm). The analysis of this problem will be given in the next report.

3.3 Computer experiment

(1) Experimental method

The theoretical intensity value for the film thickness gradient of 0 to 1000 nm was generated and used as the target of the ACOS method simulation. The generation condition is a=100 and b=0.5 in Eq. (2), and the uniformly distributed random number [-1,1] is added to the intensity values as noise. This noise level corresponds to 2% of the interference amplitude ± 50 , which is close to the level in an actual

data. Waveform parameters a and b were set to the true values, and the simulation was made using MS Excel.

(2) Experimental results

Figures 4(a)(b)(c) show the estimated intensity values, phase, and film thickness and the errors. The phase error increases with a cycle of 1/4 of each wavelength, and the film thickness error increases accordingly, but it is not so clear as with the case of one wavelength due to the averaging effect in the case of three wavelengths.



Fig. 4 Error analysis of thickness estimation

Improved algorithm and test results

4.1 Improved algorithm

4.

From the above consideration and experiment, it was clarified that the error of the estimated film thickness depends on the film thickness. Therefore, we propose the following algorithm that introduces weighting into the film thickness estimation.

$$t(i) = \sum_{j} w(j)t(i,j) / \sum_{j} w(j)$$
⁽¹¹⁾

where, the weight w(j) is the square of the reciprocal of the sensitivity coefficient expressed by Eq. (9), and is calculated by the following equation:

$$w(j) = \left| \{ a(j)b(j) \}^2 - \{ g(j) - a(j) \}^2 \right| / \{ \lambda(j) \}^2$$
(12)

4.2 Test results

Computer experiments were conducted under the same conditions as in Section 3.3. The results are shown in Fig. 4(d). The standard deviation of the error is 0.66 nm, which is significantly smaller than the 1.02 nm of the conventional method (Fig. 4(c)).

5. Lower limit of film thickness measurement

There is a need in industry to measure the thickness of ultra-thin films of several tens of nm or less. We discuss the possibility of measuring such ultra-thin films.

Figure 5 shows the results of computer experiments for film thicknesses of 0-100 nm. Figure 5(a) is the intensity, and Fig. 5(b) is the estimated film thickness and the error. The error is ± 1 nm or less when the film thickness is 20 nm or more, and the lower limit of measurement is considered to be about 20 nm.



Fig. 5 Intensity and estimated thickness error for thin film under 100 nm

6. Summary

The sensitivity of the film thickness measurement method (GMFT method) that estimates the film thickness of each pixel from the interference color image of the transparent film obtained by the three-wavelength illumination system and the color camera was analyzed, and the following conclusions were obtained.

(1) It was confirmed by theoretical analysis and computer experiments that the film thickness estimation error due to intensity noise depends on the film thickness and increases near a multiple of 1/4 of the wavelength.

(2) We proposed a weighted film thickness averaging method that takes advantage of this property, and confirmed by computer experiments that the error is significantly reduced.

(3) The lower limit of the film thickness measurement range is estimated to be about 20 nm.

In the future, we will analyze the order estimation error problem and study its countermeasures.

References

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