Multi-layer Transparent Film Thickness Measurement by Interference Color Analysis

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Previously, we reported a novel areal film thickness measurement method to estimate the transparent thin film thickness distribution from an interference color image captured by a color camera and three-wavelength light source. In this paper we propose an improved algorithm to measure the multi-layer transparent film thickness. The validity of the proposed method is proved by computer simulations.

1. Introduction

By expanding the Global Model Fitting (GMF) algorithm [1-2] developed for the three-wavelength single-shot interferometry, we developed a new film thickness distribution measurement method, called GMFT (Global Model Fitting for Thickness) [3-6]. The film thickness is estimated from the interference color image obtained by the color camera. As a result, the film thickness distribution on the semiconductor wafer and the film thickness change of the soap film flowing down can be measured at high speed and with high accuracy.

By the way, in the industry, there is a strong need for measuring the thickness of multi-layer transparent films. In this paper, we propose a new algorithm that expands the GMFT method to support multi-layer films and report the results of computer experiments.

2. Measurement principle

2.1 Relationship between interference color and film thickness in multi-layer transparent film

The interference of the multi-layer film as shown in Fig. 1 is multi-beam interference, and assuming the normal incidence and ignoring the multiple reflection, the reflected light intensity of wavelength λ is expressed by the following equation [1]:

$$I = \sum_{j=1}^{N+1} I_j + 2\sum_{i=1}^{N}\sum_{j=i+1}^{N+1}\sqrt{I_i I_j}\cos\left[(4\pi/\lambda)\sum_{k=i}^{j-1} n_k t_k\right] \quad (1)$$

It is transformed to

$$I = I_0\left\{a + 2\sum_{i=1}^{N}\sum_{j=i+1}^{N+1} b_{ij}\cos\left[(4\pi/\lambda)\sum_{k=i}^{j-1} n_k t_k\right]\right\} \quad (2)$$

where I_0 is the incident intensity, a is DC component, b_{ij} is the interference amplitude, expressed respectively by

$$a = \frac{\sum_{j=1}^{N+1} I_j}{I_0} \quad (3)$$

$$b_{ij} = \frac{\sqrt{I_i I_j}}{I_0} \quad (4)$$

On the other hand, since the reflectance and transmittance of each interface can be expressed by the refractive index using the Fresnel's formula, the right side of Eqs. (3) and (4) can be expressed by the refractive index. Therefore, when each refractive index n_k is known, a and b_{ij} are known variables, and the only unknown variables on the right side of Eq. (2) are I_0 and t_k.

Below, we consider the case of N = 2 (two-layer film). We assume that the illuminating light is monochromatic with three wavelengths (B, G, R), those wavelengths are λ_B = 470 nm, λ_G = 560 nm, λ_R = 600 nm, the incident light intensity is I_0 = 500, the refractive indexes are n_1 = 1.5, n_2 = 2 and n_3 = 4 and do not depend on the wavelength. The film thickness profiles (hereinafter, the film thickness is in nm) are expressed as $t_1 = 0.5x + 100$ and $t_2 = -0.125x + 50$, where x (x = 0, ⋯, 200) is the horizontal position (pixel) as shown in Fig. 2(a),

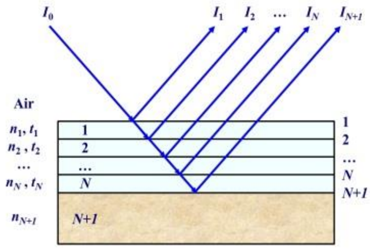

Fig. 1 Interference of multi-layer film

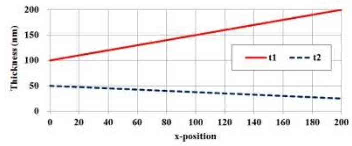

Fig. 2(a) Assumed thickness profiles

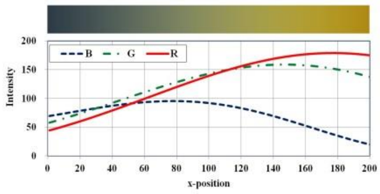

Fig. 2(b) Interference color (up) and BGR intensities of the assumed film (down)

Then the reflection intensity at each wavelength is obtained by Eq. (2) and is as shown in the graph in Fig. 2(b). The color chart in the upper part of Fig. 2(b) is synthesized from the obtained RGB intensity values and shows the interference color of the assumed film thickness profile.

The intensities of the three wavelengths to be measured can be obtained by the three-wavelength color imaging system shown in Fig. 3 [3-6]. In this imaging system, a three-wavelength bandpass filter is inserted in the light source or the imaging system, and the

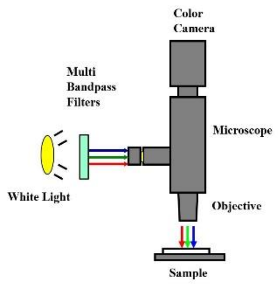

Fig. 3 Optics of three wavelength color imaging system

1) Here, $n_1 < n_2 < \cdots < n_B$ is assumed. If the signs are opposite, the phase is inverted during reflection, so the sign of each term becomes negative.

interference color image of the sample is captured by a normal color camera.

2.2 Measurement algorithm (first step)

By transforming Eq. (2), the intensity $g(i, j)$ of the interference fringe model at the wavelength λ_j (j = 1, 2,…, L) at the observation point x_i (i = 1, 2, …, M) is expressed by the following equation:

$$g(i,j) = I_0(j)\begin{bmatrix} a(j) + b_1(j)\cos[4\pi n_1 t_1(i)/\lambda_j] \\ +b_2(j)\cos[4\pi n_2 t_2(i)/\lambda_j] \\ +b_3(j)\cos[4\pi\{n_1 t_1(i) + n_2 t_2(i)\}/\lambda_j] \end{bmatrix} \quad (5)$$

where it is assumed that the incident intensity $I_0(j)$ does not depend on the observation point and is constant. If the illumination is uniform, this is a general assumption.

The unknown variables $I_0(j)$, $t_1(i)$ and $t_2(i)$ are obtained by the least-squares fitting between the model and the observed intensity values of multiple points:

$$J[I_0(j), t_1(i), t_2(i)] = \sum_{i=1}^{M}\sum_{j=1}^{L}\left[g(i,j) - g_{ij}\right]^2, \quad (6)$$

where $g(i, j)$ is the model intensity value shown in Eq. (5) and g_{ij} is the observed intensity value.

Next, let us consider the conditions under which the above unknown parameters are obtained. When the number of wavelengths is L and the number of points is M, the number of unknown parameters is L+2M. Since the number of intensity values obtained from M points is LM, the necessary condition is:

$$M \geq L/(L-2) \quad (7)$$

In case of three wavelengths (L= 3), it is $M \geq 3$.

Since the least-squares fitting of this algorithm includes the cos function which is a periodic function, there are many local minimums. Therefore, it is important to set the initial value appropriately.

The method of estimating the initial value of $I_0(j)$ from the observed intensity values is described below. From the intensity values of the observation points, its DC component g_c is calculated by the following formula.

$$g_c = (max + min)/2 \quad (8)$$

where max is the maximum value of intensity values and min is the minimum value. Since $g_c(j) = I_0(j)a(j)$ can be approximated from Eq. (5), the initial value of $I_0(j)$ is calculated by the following equation:

$$I_0(j) = g_c(j)/a(j) \quad (9)$$

2.3 Measurement algorithm (second step)

The above least-squares fitting 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 other points are obtained by the following method (called the intensity coincidence method [7]) using the parameters obtained by fitting.

The intensity value of each wavelength is expressed by the following equation by modifying Eq. (5).

$$g(j) = I_0(j)\begin{bmatrix} a(j) + b_1(j)\cos[4\pi n_1 t_1/\lambda_j] \\ +b_2(j)\cos[4\pi n_2 t_2/\lambda_j] \\ +b_3(j)\cos[4\pi(n_1 t_1 + n_2 t_2)/\lambda_j] \end{bmatrix} \quad (10)$$

The film thickness is determined by this model formula and the least-squares fit of the observed values:

$$J(I_0, t_1, t_2) = \sum_{j=1}^{m}\left[g(j) - g_j\right]^2, \quad (11)$$

where $g(j)$ is the model intensity value shown in Eq. (10), and g_j is the observed intensity value.

By the way, since the intensity value used here is a periodic function of film thickness, the above least squares method has a periodic local solution. Therefore, the general nonlinear programming solution may converge to a local solution near the initial value and is not guaranteed to obtain a correct solution.

The multi-start method is used to solve this problem. That is, in the expected film thickness range, the solutions of the least squares method are obtained by starting from the multiple initial values of the set step interval, and the solution with the smallest sum of squared error is selected as the global solution.

3. Computer experiment

3.1 Experimental method

The color chart (201 pixels in the horizontal direction) shown in Fig. 2(b) was used as the measurement target image. The Solver of MS Excel was used for least-squares fitting. For GMFT fitting, six points (x coordinate = 21, 41, ..., 121) at regular intervals were used. Furthermore, using the obtained recipe, the line profile of 201 points in the horizontal direction of the target image was calculated by the intensity coincidence method.

3.2 Experimental results and discussion

(1) GMFT fitting

Table 1 shows the observed intensity values used for the fitting and the fitted intensity values of the six points. The initial values of all unknown variables were set to 110% of the true values. As a result of fitting, both parameters and film thicknesses were in agreement with the true values (Tables 1 and 2).

Table 1 Observed and fitted intensities

Point No.	x	Observed			Fitted		
		B	G	R	B	G	R
1	21	84	89	77	84	89	77
2	41	87	104	94	87	104	94
3	61	86	118	111	86	118	111
4	81	83	130	127	83	130	127
5	101	76	139	141	76	139	141
6	121	67	145	153	67	145	153

Table 2 Fitting results

Parameters		True	Initial	Estimated	Error(%)
I_0	B	500	550	500.0	0.00
	G	500	550	500.0	0.00
	R	500	550	500.0	0.00
t_1	$t_1(1)$	110.0	121	110.0	0.00
	$t_1(2)$	120.0	132	120.0	0.00
	$t_1(3)$	130.0	143	130.0	0.00
	$t_1(4)$	140.0	154	140.0	0.00
	$t_1(5)$	150.0	165	150.0	0.00
	$t_1(6)$	160.0	176	160.0	0.00
t_2	$t_2(1)$	47.5	52	47.5	0.00
	$t_2(2)$	45.0	50	45.0	0.00
	$t_2(3)$	42.5	47	42.5	0.00
	$t_2(4)$	40.0	44	40.0	0.00
	$t_2(5)$	37.5	41	37.5	0.00
	$t_2(6)$	35.0	39	35.0	0.00

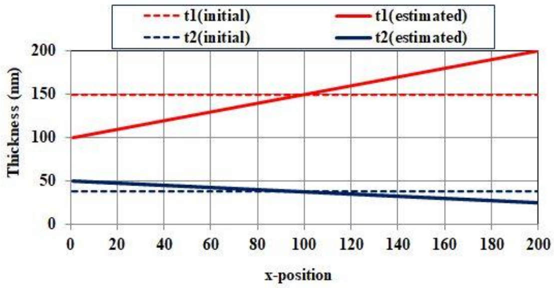

Fig. 4 Estimated thickness profile by intensity coincidence method

(2) Intensity coincidence method

The initial values were t_1 = 150 nm and t_2 = 37.5 nm. Figure 4 shows the obtained film thickness profile. All points were in agreement with the true values, and it was proved that the correct estimation is possible.

4. Summary

Previously, we have developed a technique for estimating the film thickness of each pixel from a thin film interference color image of a transparent film obtained by a three-wavelength illumination system and a color camera. We extended this algorithm to a multi-layer transparent film. The validity was confirmed by computer experiments. It has the features of high horizontal resolution, high speed, and no calibration required.

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