Semi-transparent Film Thickness Measurement by Interference Color Analysis

Independent Consultant Katsuichi KITAGAWA, Toray Engineering Co., Ltd. Masafumi Otsuki

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 semi-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 one-shot interferometry, we developed a new film thickness distribution measurement method, 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 semi-transparent films such as color filters and color resists. In this paper, we report a new algorithm that expands the GMFT method to support semi-transparent films and the results of computer experiments.

2. Measurement principle

2.1 Relationship between interference color and film thickness in semi-transparent film

Consider the interference between the light reflected from the front surface and the light reflected from the back surface of the semitransparent film. Ignoring multiple reflections, the sum of reflected light is expressed by the following equation.

$$I(\lambda) = I_1(\lambda) + I_2(\lambda) + 2\sqrt{I_1(\lambda) I_2(\lambda)} \cos\{\delta(\lambda)\}, \quad (1)$$

where, I_1 and I_2 are the intensities of both reflected lights, λ is the wavelength, and δ is the phase difference. Assuming that the physical film thickness is t, the film refractive index is $n(\lambda)$, and vertical incidence is assumed, the optical path difference (OPD) of both reflected lights is $2n(\lambda)t$. Therefore, the phase difference is $\delta(\lambda) = 4\pi n(\lambda)t/\lambda$. Substituting this equation into Eq. (1) and assuming that the refractive index has no wavelength dependence, the following equation is obtained.

$$I(\lambda) = I_1(\lambda) + I_2(\lambda) + 2\sqrt{I_1(\lambda) I_2(\lambda)} \cos(4\pi n t/\lambda), \quad (2)$$

where the intensity I_2 of the back-reflected light in the semitransparent film is expressed by the following equation according to the Lambert-Beer law, where the film absorption coefficient is k.

$$I_2(\lambda) = I_{20}(\lambda) e^{-2k(\lambda)t}, \quad (3)$$

where I_{20} is the amount of light reflected from the back surface when there is no absorption.

From Eqs. (2)(3), we obtain

$$I(\lambda) = I_1(\lambda) + I_{20}(\lambda) e^{-2k(\lambda)t} + 2\sqrt{I_1(\lambda) I_{20}(\lambda)} e^{-k(\lambda)t} \cos(4\pi n t/\lambda). \quad (4)$$

Using this equation, we obtained the relationship between the reflected light intensities and the film thickness assuming 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 intensities of reflected lights are I_1 = 20 and I_2 = 80 , the film refractive index n = 1.4 and the absorption coefficients are k(B)=0.0004 (/nm), k(G)=0.0003 (/nm) and k(R)=0.0002 (/nm). The results are shown in Fig. 1. The color chart in the upper part of this figure was synthesized from the obtained BGR intensity values and shows the relationship between film thickness and interference color.

The three-wavelength intensity signal can be obtained by the three-wavelength color imaging system [3-6] shown in Fig. 2. Insert a three-wavelength bandpass filter in the light source or the imaging system, and capture the interference color image with a normal color camera.

2.2 Measurement algorithm (first step)

By transforming Eq. (4), the intensity $g(i, j)$ of the interference fringe model with the wavelength number j (j=1,2,…,m) at the observation point i (i = 1, 2, …, N) is given by:

$$g(i,j) = I_1(j) + I_{20}(j) e^{-2k(j)t(i)} + 2\sqrt{I_1(j) I_{20}(j)} e^{-k(j)t(i)} \cos\{4\pi n t(i)/\lambda(j)\} \quad (5)$$

where it is assumed that the amount of front-reflected light $I_1(j)$, the amount of back-reflected light $I_{20}(j)$ when the film does not absorb, and the absorption coefficient $k(j)$ do not depend on the observation point and are constants. The unknown variables $I_1(j)$, $I_{20}(j)$, $k(j)$ and $t(i)$ are obtained by fitting the observed intensity values of multiple points to this model by least squares. That is, the parameters that minimizes the sum of squared error in the following equation is found.

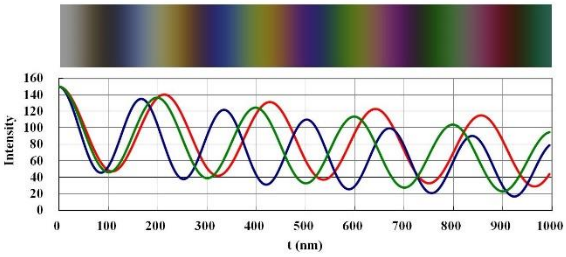

Fig. 1 Relationship between film thickness and interference color (up) and RGB intensities (down)

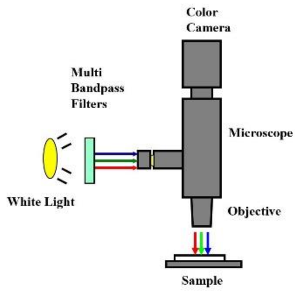

Fig. 2 Optics of three wavelength color imaging system

$$J = \sum_{i=1}^{N} \sum_{j=1}^{m} \left[g(i,j) - g_{ij} \right]^2 . \tag{6}$$

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 m and the number of points is N, the number of unknown parameters is $3m+N$. Since the number of intensity values obtained from N points is mN, the necessary condition is:

$$N \geq \frac{3m}{m-1} \tag{7}$$

In case of three wavelengths, it is $N \geqq 5$.

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.

2.3 Measurement algorithm (second step)

The method of estimating the film thickness at points other than the fitting point using the waveform parameters obtained in the first step (called the intensity coincidence method) is described below.

By modifying Eq. (5), the relationship between the intensity value at each wavelength and the film thickness is expressed by the following equation.

$$g(j) = I_1(j) + I_{20}(j)\, e^{-2k(j)t} + 2\sqrt{I_1(j) I_{20}(j)}\, e^{-k(j)t} \cos\{4\pi n t / \lambda(j)\} \tag{8}$$

The film thickness that best fits this model is found by the least squares method. That is, the film thickness that minimizes the sum of squared errors in the following equation is obtained.

$$J = \sum_{j=1}^{m} \left[g(j) - g_j \right]^2 , \tag{9}$$

where $g(j)$ is the model intensity shown in Eq. (8), 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 the correct solution.

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

3. Computer experiment

3.1 Experimental method

The color chart in Fig. 1 was used as the target image (200 pixels in the horizontal direction). The wavelengths are 470, 560, and 600 nm, and the interference signal parameters are I_1 = 20, I_2 = 80, and the refractive index of the film is 1.4 for each wavelength. The absorption coefficients are k(B)=0.0004 , k(G)=0.0003, k(R)=0.0002. The Solver of MS Excel was used for least-squares fitting.

For GMFT fitting, six points (x coordinate = 21, 41, ..., 120) at constant intervals in the image were used. Using the obtained recipe, the line profile of 200 points in the horizontal direction of the target image was calculated by the intensity coincidence method. Since the film thickness range is 1000 nm, we adopted the multi-start method with an initial value range of 0-1000 nm and increments of 100 nm.

Table 1 Observed and fitted intensities

Point No.	x	Observed			Fitted		
		B	G	R	B	G	R
1	21	47	26	30	47	26	30
2	41	97	163	186	97	163	186
3	61	130	22	29	130	22	29
4	81	13	133	175	13	133	175
5	101	119	23	31	119	23	31
6	121	57	105	163	57	105	163

Table 2 Fitting results

Parameters		True	Initial	Estimated	Error(%)
t	$t(1)$	100.0	90.0	100.0	0.00
	$t(2)$	200.0	180.0	200.0	0.00
	$t(3)$	300.0	270.0	300.0	0.00
	$t(4)$	400.0	360.0	400.0	0.00
	$t(5)$	500.0	450.0	500.0	0.00
	$t(6)$	600.0	540.0	600.0	0.00
I_1	B	20.0	18.0	20.0	0.00
	G	20.0	18.0	20.0	0.00
	R	20.0	18.0	20.0	0.00
I_{20}	B	80.0	72.0	80.0	0.00
	G	80.0	72.0	80.0	0.00
	R	80.0	72.0	80.0	0.00
k	B	0.00040	0.00036	0.00040	0.00
	G	0.00030	0.00027	0.00030	0.00
	R	0.00020	0.00018	0.00020	0.00

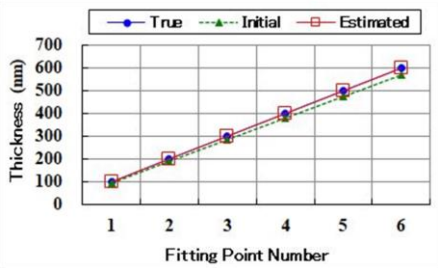

Fig. 3 Estimated thicknesses by GMFT six points fitting

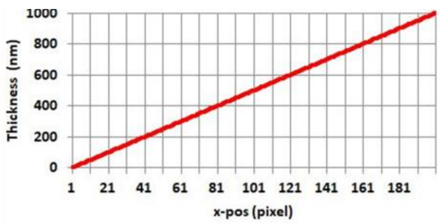

Fig. 4 Estimated thickness profile

3.2 Experimental results and discussion

(1) GMFT fitting

Table 1 shows the observed intensity values of the six wavelengths used for fitting together with the fitted intensity value. As a result of fitting with the initial values of all unknown variables set to 90% of the true values, both parameters and film thickness were in agreement with the true values (Table 2, Fig. 3).

(2) Intensity coincidence method

Next, using the waveform parameters (recipe) obtained above, the film thicknesses at 200 points on the horizontal line were estimated by the intensity coincidence method. The intensity value profile is shown in Fig. 1. Figure 4 shows the obtained film thickness profile. All points were in agreement with the true values, and it is 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 semi-transparent film. The interference intensities, absorption coefficients, and film thicknesses are collectively estimated by the least-squares fit between the model assuming that the film absorption follows Lambert-Beer's law. The validity was confirmed by computer experiments.

References

[1] K. Kitagawa: "Multi-Wavelength Single-Shot Interferometry by Global Model Fitting", Proc. of JSPE Autumn Meeting, 777-778 (Nagoya, Sept. 2010) (in Japanese).

[2] K. Kitagawa: "Single-shot surface profiling by multi-wavelength interferometry without carrier fringe introduction", Journal of Electronic Imaging, **21**, 021107 (2012).

[3] K. Kitagawa: "Transparent film thickness measurement by three-wavelength interference method -An extended application of Global Model Fitting Algorithm-", Proc. of JSPE Spring Meeting, 1037-1038 (Tokyo, March 2012) (in Japanese).

[4] K. Kitagawa and M. Otsuki: "Development of Transparent Film Thickness Measurement System by Three-wavelength Interference Method -Extension of Global Model Fitting Algorithm-", Proc. of JSPE Autumn Meeting, 621-622 (Kitakyushu, Sept. 2012) (in Japanese).

[5] K. Kitagawa: "Thin-film thickness profile measurement by three wavelength interference color analysis", Applied Optics, **52**, 1998-2007 (2013).

[6] K. Kitagawa and M. Otsuki: "Wide-view Transparent Film Thickness Measurement System by Interference Color Analysis", J. Jpn. Soc. Precis. Eng., **79** (11), 1078-1082 (2013) (in Japanese).

This is an English translation of the paper:
Katsuichi Kitagawa and Masafumi Otsuki: "Semi-transparent Film Thickness Measurement by Interference Color Analysis", Proc. of JSPE Autumn Meeting, 769-770 (Sendai, Sept. 2015)
(original in Japanese; translated by the author in Sept. 2020)