Thickness Profile Estimation from Three Wavelength Interference Color Image using Model Fitting Method

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Conventional transparent film thickness measurement methods such as spectroscopy are basically capable of measuring a single point at a time, and the spatial resolution is limited. We propose a novel areal film thickness measurement method by extending the Global Model Fitting algorithm developed for three-wavelength interferometric surface profiling. It estimates the film thickness distribution from a color image captured by a color camera with three-wavelength illumination. The validity of the proposed method is demonstrated by computer simulations and actual experiments.

1. Introduction

The typical conventional transparent film thickness measurement methods are spectroscopy and ellipsometry. They are basically capable of measuring a single point at a time, and it takes a long time to obtain the thickness distribution. Furthermore, the spatial resolution is limited because of the measurement spot size.

A possible solution to this problem is to capture the interference color with a color camera and estimate the film thickness by color analysis.

The interference color of thin films exists in nature as the iridescent color of soap bubbles and oil films, and the relationship with film thickness has been studied for a long time since Newton's Color Scale. For example, Fig. 1 is a locus diagram of thin film interference colors measured in the 1950s [1]. As a method for quantitatively obtaining the film thickness from this color information, there is a spectroscopic method, which is widely used in industry, but the spectroscopic method is point measurement (unless an expensive spectroscopic imaging camera is used).

The use of a color camera without relying on spectroscopy has been studied [2-5], and there are many proposals for limited applications because the observed values are only RGB brightness. Using the calibration data (for example, the relationship between hue and film thickness) obtained in advance, the semiconductor film thickness [2], the magnetic disk head flying height (Fig. 2) [3], and the bearing gap and lubricating oil film thickness [4] [5] are measured from the color image of white light interference. There is a proposal to obtain the surface height from color information in the same way [6-8].

However, there are some problems in using these proposed methods as a general-purpose and practical film thickness measurement method. Figure 3 shows the relationship among film thickness, interference color, and hue obtained by simulation under a certain lighting condition. As can be seen from this figure and Fig. 1, the coordinate values (e.g. hue) in the color space change periodically corresponding to the interference order. Therefore, unless the film thickness range is narrow enough, it is difficult to uniquely determine the film thickness from the color information. Furthermore, frequent calibration is required because the interference color depends on the illumination system, optical system, and imaging system as well as the optical properties of the target surface.

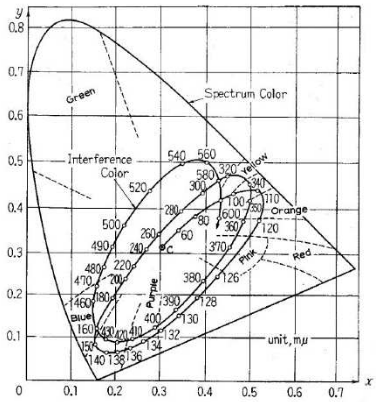


Fig. 1 Locus diagram of thin film interference colors [1]

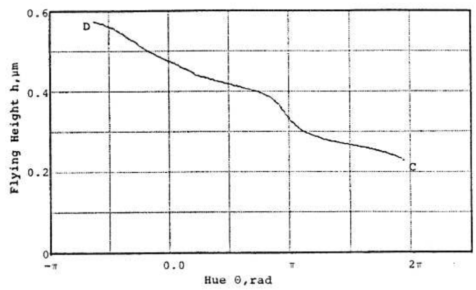


Fig. 2 Hue and disk head flying height [3]

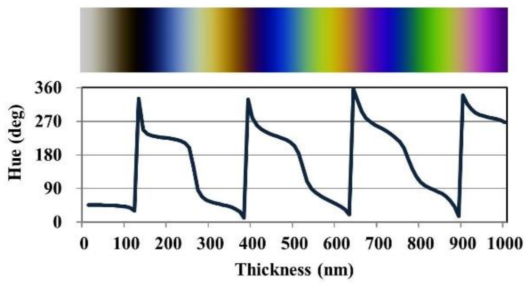


Fig. 3 Interference color and hue vs thickness (0-1000nm)

In order to solve the above problems, we applied a global model fitting (GMF) algorithm [9-12] for three-wavelength single-shot interferometry to develop a new film thickness profile measurement method [13]. The film thickness is estimated from the interference color image obtained by the three-wavelength illumination system and the color camera. We proved the validity of the proposed method by computer simulations and actual experiments.

2. Measurement principle

The film thickness is estimated from single color interference image taken by the three-wavelength imaging system shown in Fig. 4. Note that this imaging system is similar to the configuration of the previously reported three-wavelength single-shot interferometry [14].

The overall algorithm is shown in the flowchart in Fig. 5. The recipe is created in the first step, and the film thickness distribution is estimated in the second step.

2.1 Algorithm (1st step: GMF method)

The intensity $g(i, j)$ of the interference fringe model with wavelength number j ($j = 1, 2, \ldots, m$) at the observation point i ($i = 1, 2, \ldots, n$) is expressed by the following equation:

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

or

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

where $a(j)$ and $b(j)$ are the average intensity and amplitude, respectively, of the j-the wavelength, $\phi(i, j)$ is the phase, $t(i)$ is the optical thickness (hereafter called thickness) of i-th point, λ_j is the j-th wavelength. Furthermore, it is assumed that the film refractive index is smaller than the substrate refractive index, the average intensity $a(j)$ and the modulation $b(j)$ are constant within the image, and depend 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 error sum of squares in the following equation are obtained.

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

where $g(i,j)$ is the model intensity defined by Eq. (2) and g_{ij} is the observed intensity.

If the number of wavelengths is m and the number of points is n, the condition for finding unknown parameters is $mn \geq 2m + n$. Therefore, the necessary number of points is

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

In case of $m = 3$, the condition is $n \geqq 3$. If $n > 3$, then the problem becomes a non-linear least-square problem. To find the true solution, since the error function has a lot of local minimum, it is essential to make good initial estimates.

In this paper, $a(j)$ is set to be the average of the observed values, and $b(j)$ is set to be the range of observed values divided by $2a(j)$. The thickness is a rough estimate which is given usually by a priori knowledge of the target sample.

The above algorithm can be illustrated as shown in Fig. 6. That is, in the case of three wavelengths and n points of fitting, $3n$ observation values are used to estimate n film thicknesses and six waveform parameters.

2.2 Algorithm (2nd step: ACOS method)

The computational cost of the non-linear least-square problem is very high, so the method becomes impractical when the number of points is large. Therefore, we use the GMF algorithm as the first step with several or a few tens of points, and then the thicknesses of the other points are calculated as the second step by the following method, named the "arccosine (ACOS)" method, which uses the estimated waveform parameters (called recipe) obtained in the first step.

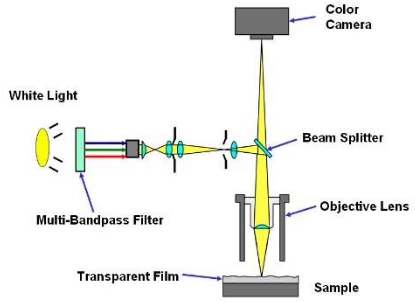


Fig. 4 Optics of three-wavelength interference color imaging

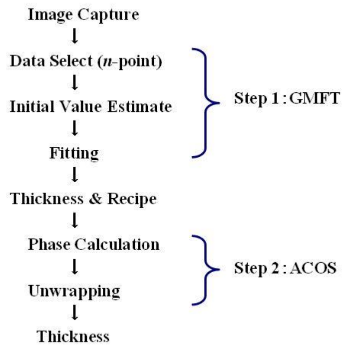


Fig. 5 Measurement flow-chart

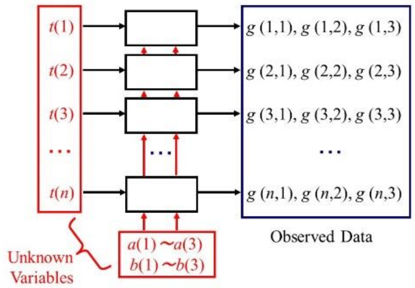


Fig. 6 Illustrated principle of the proposed algorithm (in case of three wavelengths and n-points fitting)

Substitute the observed value into Eq. (1) and obtain the phase by the following equation:

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

where $\cos^{-1}$ is the arccosine function and its value range is $[0, \pi]$.

From the phase data, the thickness, $t(i, j)$, is obtained by

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

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

From the film thickness candidates obtained above, the order $N(i, j)$ is determined by the coincidence method [15], the film thickness candidates $t(i, j)$ at each wavelength are determined, and the average value of them is the thickness $t(i)$.

3. Computer experiment

3.1 Test method

A three-wavelength interference color image was synthesized with the following conditions: (a) image size = 50×50 pixels; (b) pixel size = 1 μm; (c) wavelength = 470, 560, 600 nm; (d) target surface = sphere with 1-mm radius, with a small square protrusion of thickness 50 nm and size 4×4 pixels; (e) waveform parameters of a = 100 and b = 1. The target film thickness is shown in Fig. 7(a), and the synthesized interference color image is shown in Fig. 7(b). Solver of Excel was used for the solution of the least squares problem of GMF method. We performed two experiments. The first one used three points for fitting, and the second one used 50 points.

3.2 Experimental results

(a) Three points fitting of GMF method

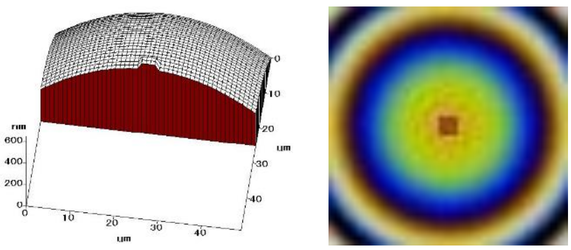
Figure 8 shows the BGR images and three points used for fitting. The coordinates of the three points are (5, 25), (15, 25), (25, 25). The intensity at each point is shown in Fig. 9(a). The initial film thickness was 95% of the true value. Table 1 shows the fitting results. The true values, initial values, and estimated values of the film thickness are shown in Fig. 9(b). Both the parameters and the film thicknesses agree with the true values.

(b) 50 points fitting of GMF method

Figure 10 shows the height obtained by setting the fitting points to 50 points with coordinates (1, 25) to (50, 25), and setting the initial height values to -50 nm of the true values. All points agree with the true values.

(c) ACOS method

The film thickness was estimated from the intensity values at 50 points on the y = 25 line (Fig. 11) using the parameters $a(j)$ and $b(j)$ of the interference fringe model obtained by the above three-point fitting. The results are in agreement with the true values as shown in Fig. 12.



(a) Target thickness (b) Interference color image

Fig. 7 Interference color image for computer experiments

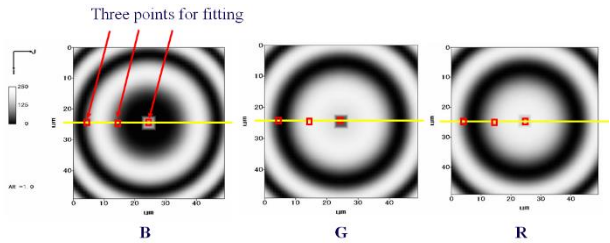
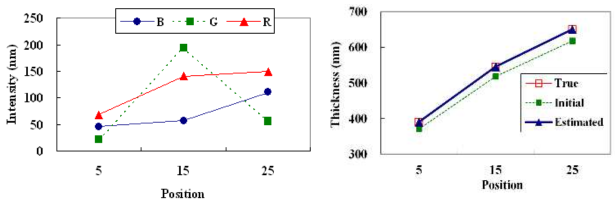


Fig. 8 BGR images and three fitting points



(a) Intensities (b) Estimated thicknesses

Fig. 9 Intensities and thickness estimation results in three points fitting

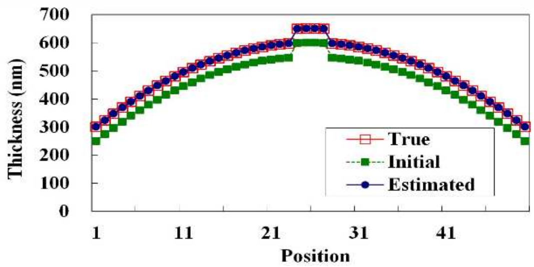


Fig. 10 Thickness estimation of 50 points fitting

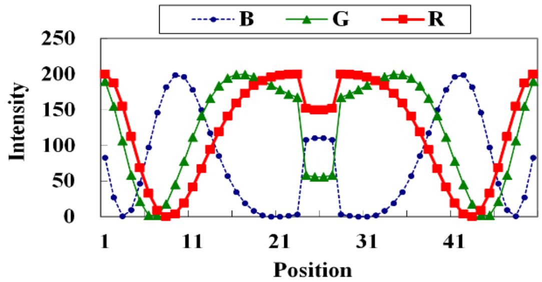


Fig. 11 Intensities of 50 points

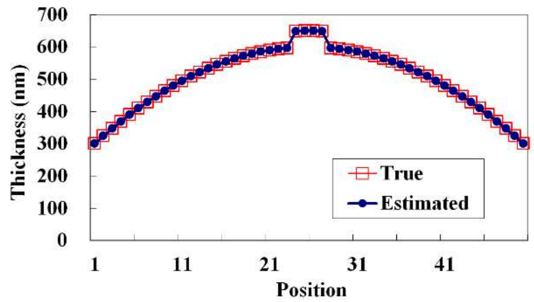


Fig. 12 Estimated thickness profile of 50 points by ACOS method

4. Actual experiments

4.1 Experimental equipment

Figure 13 shows a view of the experimental equipment. The illumination system is composed of a halogen lamp and a multi-bandpass filter [16][17]. As shown in Fig. 14, the transmission wavelength band of the filter is centered at 470 nm, 530 nm, and 627 nm, and the half-width is 10 nm. The camera is a 3-CCD color camera (Hitachi Kokusai Electric, HV-F22CL, 1360 x 1024 pixels). Figure 15 shows the spectral sensitivity characteristics of the camera and the three wavelengths used.

We implemented the proposed algorithm on a Windows PC using C language. The Davidon-Fletcher-Powell method [18] was used to solve the nonlinear least-squares problem.

Table 1 Estimation results by three points fitting

VARIABLES		TRUE	INITIAL	ESTIMATED	ERROR(%)
t	$t(1)$	390	371	390	0.00
	$t(2)$	545	518	545	0.00
	$t(3)$	650	618	650	0.00
a	B	100	79	100	0.00
	G	100	108	100	0.00
	R	100	109	100	0.00
b	B	1.00	0.41	1.00	0.00
	G	1.00	0.80	1.00	0.00
	R	1.00	0.37	1.00	0.00

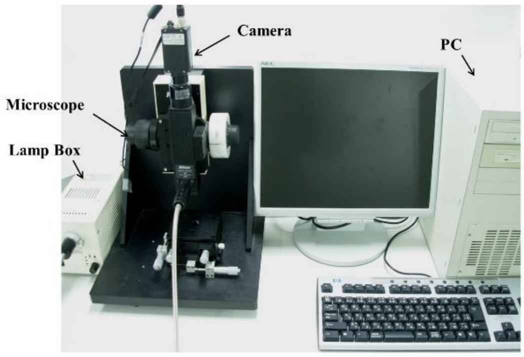


Fig. 13 Experimental equipment

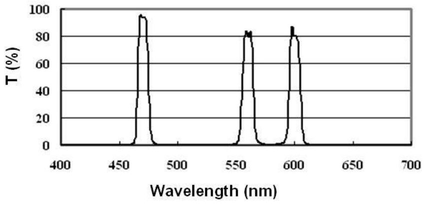


Fig. 14 Spectral transmittance of multi-bandpass filter

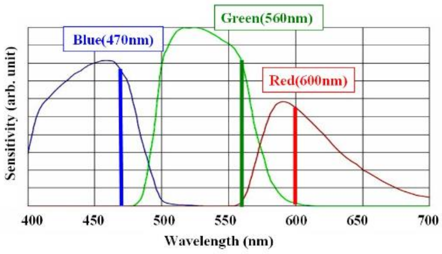


Fig. 15 Spectral sensitivity of the camera and three wavelengths used

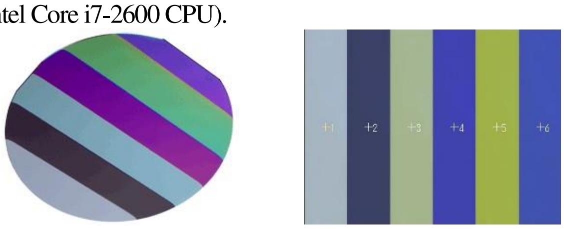
4.2 Experimental method

We used a standard film thickness sample (Mikropack; Fig. 16(a)) with a nominal physical film thickness of 0, 100, ..., 500 nm as an actual sample. An image shown in Fig. 16(b) was obtained by connecting six images of each film thickness region and removing the noise by the median filter. Six points (indicated by numbers in the figure) at the center of each film thickness region were used for the GMF method. The initial film thickness at each point was set to the nominal value, and the film thickness range was set to the nominal value ±50 nm.

4.3 Experimental results

The recipe obtained by fitting is shown in Fig. 17(a), and the correlation between the estimated film thickness and the nominal value is shown in Fig. 17(b). The estimation error was -7 to +4 nm. Figure 18 shows the film thickness at all points obtained using the recipe. The estimation is almost correct.

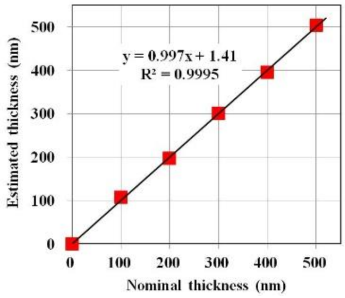
The calculation time was 6 ms for GMF and 1.2 s per 1.4 million pixels for ACOS method using a Windows PC (3.4 GHz Intel Core i7-2600 CPU).



(a) Standard sample photo (b) Image and fitting points

Fig. 16 Thickness standard and its image

	a	*b*
B	132.9	0.47
G	121.9	0.49
R	113.3	0.46



(a) Obtained recipe (b) Estimated thicknesses

Fig. 17 Fitting results of thickness standard

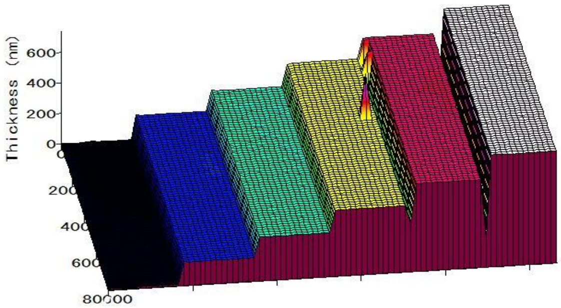


Fig. 18 Thickness estimation result of thickness standard

5. Challenges and solutions for practical use

There are some problems in the practical application of film thickness measurement by the proposed method. The results of the research so far are described below.

5.1 Local solution problem

As mentioned in Section 2.1, there are many local solutions in the GMF method. Therefore, in the case of general nonlinear programming that uses gradients, there is a possibility that a global optimal solution may not be obtained due to the initial value falling into a local solution. To solve this problem, the "multi-start method" is used in which fitting is performed using multiple initial film thickness values and the one with the best fitting is adopted.

At this time, it is important what kind of distribution the local solution has. The relationship between the film thickness error and the evaluation function (sum of squared error, SSE) depends on the wavelength used and the optical characteristics of the sample. Figure 19 shows an example of the simulation results [11][12]. In this example, the initial value must be in the range of 330 and 590 nm to get the correct film thickness value of 500 nm. Based on this and other results, the initial value tolerance was estimated to be about 80 nm.

Therefore, if the set film thickness range is greater than or equal to the set tolerance δ (default = 80 nm) at each point, the multi-start method is performed. That is, the initial value is set as the set initial value $\pm N\delta$ $(N = 1, 2, \cdots)$ and the search is executed with all combinations of the initial values at each point.

Figure 20 shows the results of an experiment similar to that in Section 4.2, using a film thickness range of nominal value ±100 nm and an initial value of nominal value +100 nm. Even if the error of the initial value is 100 nm, it converges to the correct film thickness.

Since the limit value δ was set to 80 nm, there are 3^6=729 combinations of initial values. This calculation time was 125 ms using a Windows PC (3.4GHz Intel Core i7-2600 CPU).

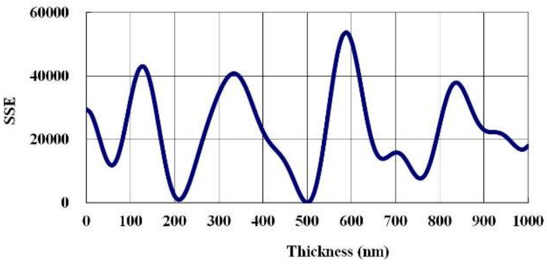


Fig. 19 SSE vs thickness (true thickness = 500nm)

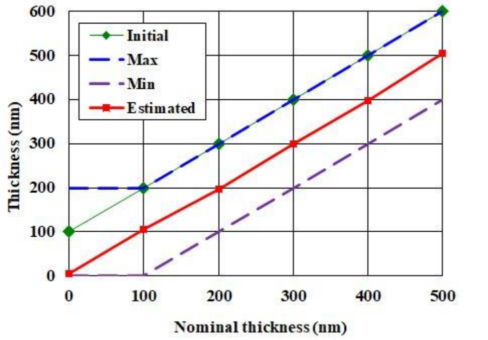


Fig. 20 Thickness estimation by multi-start method

5.2 Solid film

In order to obtain the solution of the GMF method, as shown in Eq. (4), at three wavelengths, there must be three or more points with a significant film thickness difference. However, this cannot be applied to a film whose thickness is almost constant (called a solid film). Therefore, we consider how to deal with the case where there are less than 3 points with different film thickness. In addition, we consider to utilize the data when there is a point where the film thickness is known.

Depending on whether the film thickness is known or unknown and the target number of different film thickness [1)], there are five cases (hereinafter referred to as mode [2)]) shown in Table 2. The case where the number of target points is one (solid film) is described below.

Table 2 Mode list of GMF method

Thickness	# of Points	Mode Name	Unknown Thickness	Unknown Parameters	Total Unknown Values	Observed Data	Known Values
Unknown	1	GMF-1	$t(1)$	$a(3)$ $b(3)$	3	≧3	α, β
	2	GMF-2	$t(1)$ $t(2)$	$a(1)$-$a(3)$ $b(3)$	6	≧6	β
	n (≧3)	GMF	$t(1)$ -$t(n)$	$a(1)$-$a(3)$ $b(1)$-$b(3)$	n+6	$3n$	
Known	1	GMF-1f	-	$a(1)$-$a(3)$	3	≧3	$t(1)$ $b(1)$-$b(3)$
	n (≧2)	GMF-f	-	$a(1)$-$a(3)$ $b(1)$-$b(3)$	6	$3n$	$t(1)$-$t(n)$

(1) When the film thickness is unknown

[Algorithm]

Since there is only one significant film thickness fitting point, the number of observation data is 3, and only 3 unknown variables are allowed. Therefore, the film thickness $t(1)$, the average intensity $a(3)$ and the modulation factor $b(3)$ of the R wavelength are adopted as unknown variables, and the remaining waveform parameters are calculated by the following formula on the assumption that the average intensity ratio α and the modulation factor ratio β between wavelengths is known.

$$a(1) = \alpha(1)a(3) \tag{7}$$

$$a(2) = \alpha(2)a(3) \tag{8}$$

$$b(1) = \beta(1)b(3) \tag{9}$$

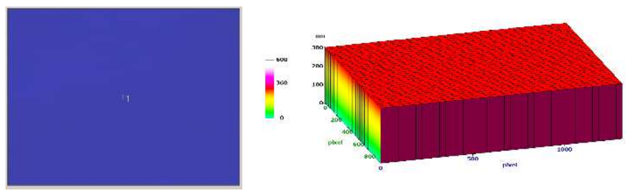
$$b(2) = \beta(2)b(3) \tag{10}$$

Here, $\alpha(1)$ and $\alpha(2)$ are the average intensity ratios between the wavelengths, which are considered to be device constants that do not depend on the brightness of the illumination but on the spectral characteristics of the illumination and the camera. Therefore, they can be obtained in advance by means such as using another measurement target.

Furthermore, $\beta(1)$ and $\beta(2)$ are the modulation ratios between the wavelengths, which are also considered to be sample constants that do not depend on the brightness of the illumination but mainly depend on the optical characteristics of the sample. Therefore, it can be obtained in advance by other measurement results of the same sample, or by means such as the following method of using a sample of known film thickness.

[Experiment #1]

When the average intensity ratio α and the modulation ratio β are calculated from the recipe obtained in Section 4, $\alpha(1) = 1.17$, $\alpha(2) = 1.02$, $\beta(1) = 1.07$, $\beta(2) = 1.07$ are obtained. Using this as known information, the film thickness of the solid film was estimated for the image with a nominal film thickness of 300 nm (Fig. 21(a)). Figure 21(b) shows the result of measurement with the fitting point as one point in the center of the image. The average in-plane film thickness was 299 nm, and the standard deviation was 0.52 nm.



(a) Target image with fitting point (b) Measurement results

Fig. 21 Thickness estimation of solid film

[Experiment #2]

We show that the GMF-1 mode compensates for changes in the illumination intensity. From the images with a nominal film thickness of 300 nm shown in Fig. 21(a), images with 10% and 20% reduction in intensity were created and the film thickness was estimated. Figure 22 shows the relationship between the obtained average film thickness and the amount of intensity reduction. Although there is an error in the film thickness estimation when the intensity is reduced, it can be seen that if the recipe is created in the GMF-1 mode (displayed as 1pt recipe), it can be measured without being affected by the intensity change.

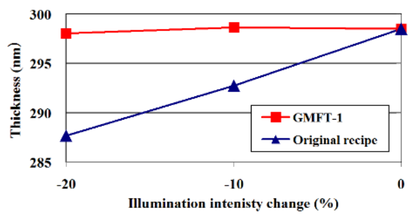


Fig. 22 Estimated thickness vs intensity reduction

[1)] The target number of different film thickness means the number of sample regions where the film thickness (t) is significantly different.

[2)] The mode selection is for GMF fitting (recipe creation), and the ACOS method makes no distinction. That is, $a(1)$ to $a(3)$ and $b(1)$ to $b(3)$ are saved in the recipe data as before.

(2) When the film thickness is known

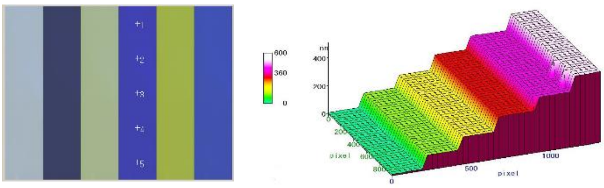
[Algorithm]

There may be one sample with a known film thickness. For example, when there is a film thickness standard sample for calibration, or when the film thickness value measured by another film thickness meter is obtained. When the film thickness is known, the only unknown variable is the waveform parameter. Since there are 3 observed values, up to 3 parameters can be set as unknown variables among 6 waveform parameters. Therefore, the average intensity $a(1)$ to $a(3)$ is unknown, and the modulations $b(1)$ to $b(3)$ are estimated from the refractive index of the film and the substrate, or obtained by other means in advance, and let them the known sample constant.

[Experiment]

Using the standard film thickness image of Fig. 16(b), we assumed that the film thickness value of #4 in this image was known to be 300 nm. The film thickness distribution was measured in GMF-1f mode, using the modulation $b(1)$ to $b(3)$ obtained in Section 4.3.

Figure 23(a) shows the target image and the points used for GMF fitting with known film thickness. Figure 23(b) shows the film thickness distribution obtained with the range 0 to 600 nm, and the film thickness in all regions could be measured with an error of 10 nm or less.



(a) Target image with fitting points (b) Measurement results

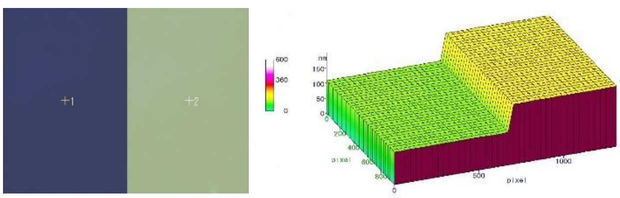
Fig. 23 Thickness estimation in case of one known thickness

5.3 Step film

In the industrial world, there are many needs to measure the film thickness step difference in the coating or pattern processing processes. In this case, there are two points where the film thickness is different, which corresponds to mode GMF-2. There are six unknown variables, film thicknesses $t(1)$ and $t(2)$, average intensities $a(1)$ to $a(3)$, and modulation $b(3)$, and fitting is performed with the modulation ratio β known.

[Experiment]

An image with nominal film thicknesses of 100 nm and 200 nm were captured using the same method as in Section 4.2. Figure 24(a) shows the image and fitting points. Figure 24(b) shows the measurement results in GMF-2 mode with the same modulation ratio β as the experiment in Section 5.3. The film thickness step can be measured. The average film thickness in each region was 108 nm and 199 nm, and the difference from the nominal value was +8 nm and -1 nm.



(a) Two fitting points (b) Measurement results

Fig. 24 Thickness estimation of step film

6. Conclusion

We have proposed a fast and high-accuracy film thickness profiling method. It estimates the model parameters and the thicknesses of plural points simultaneously by least squares fitting an interference model to multi-wavelength intensity data.

The most significant feature of this technique is that the optics is simple and no calibration is required. The validity of the proposed method has been proved by computer simulations and actual experiments.

We are currently working on extending our technique for practical applications.

In the future, we would like to improve the robustness by improving the algorithm and put it into practical use.

References

[1] H. Kubota: Thin film and its applications, Seisan Kenkyu, **3**(11), 415-418 (1951) (in Japanese).

[2] S. Parthasarathy et al.: A color vision system for film thickness determination, Proc. IEEE Conf. Robotics and Automation, 515-519 (1987).

[3] M. Kubo et al.: Flying Height Measurement of a Head Slider Using Color Image Processing Technique, Trans. of the Japan Soc. of Mechanical Engineers, C, **54** (503) 1401-1406 (1988) (in Japanese).

[4] M. Hartl, I. Krupka, R. Poliscuk, M. Liska: Computer-aided evaluation of chromatic interferograms, Fifth International Conference in Central Europe on Computer Graphics and Visualization, 45-54 (1997).

[5] M. Eguchi and T. Yamamoto: Measuring separation gap and visualizing a real contact area using white light spacer interferometry and HSV color space: verification for resolution of 3nm thickness, J. of Japanese Soc. of Tribologists, **52** (5) 381-388 (2007) (in Japanese).

[6] S. Toyooka, N. Hayasaka, M. Kataguchi and F. Kobayashi: Spectral based estimation of optical path difference of interference colors, Optical Review, **5** (4) 207-211 (1998).

[7] D. Kimura et al.: Nano-level shape measurement by color analysis of multi wavelength LED light interference images, Proc. of DIA (Dynamic Image Processing for Real Application) WS 2010, 187-191 (2010) (in Japanese).

[8] S. Hata, D. Kimura, M. Kaneda, S. Morimoto and H. Kobayashi: Nano-level 3D shape measurement system using color analysis method of RGB interference fringes, Proc. SPIE, **8000**, 800008 (2011).

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

[10] K. Kitagawa: Multi-wavelength single-shot interferometry without carrier fringe introduction, Proc. SPIE, **8000**, 800009 (2011).

[11] K. Kitagawa: Single-shot multi-wavelength interferometry without carrier fringe introduction, Proc. of Vision Engineering Workshop (ViEW) 2011, 456-463 (2011) (in Japanese).

[12] K. Kitagawa: Single-shot surface profiling by multi-wavelength interferometry without carrier fringe introduction, Journal of Electronic Imaging

(unpublished).
[13]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 (2012) (in Japanese).
[14]K. Kitagawa et al.: Development of Multi- Wavelength Single-Shot Interferometry and Its Practical Application, J. Jpn. Soc. Precis. Eng., **78** (2) 112-116 (2012) (in Japanese).
[15]K. Kitagawa: Three-Wavelength Single-Shot Interferometry, Proc. of JSPE Autumn Meeting, 179-180 (2008) (in Japanese).
[16]K. Kitagawa and H. Sugihara: Speed Improvement of Automatic Film Thickness Measurement System for Inkjet-Based Color Filters Based on Three-Wavelength Single-Shot Interferometry - By Using a Multi-Wavelength Filter and GPU -, Proc. of JSPE Autumn Meeting, 781-782 (2010) (in Japanese).
[17]K. Kitagawa et al.: Automatic Film Thickness Measurement System for Inkjet-Based Color Filters Based on Three-Wavelength Single-Shot Interferometry, J. Jpn. Soc. Precis. Eng., **78** (1) 86-91 (2012) (in Japanese).
[18]R. Fletcher and M.J.D. Powell: A rapidly convergent descent method for minimization, Computer Journal, **6**, 163-168 (1963).

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