Current Optics and Photonics
Vol. 1, No. 1, February 2017, pp. 29-33

ISSN: 2508-7266(Print) / ISSN: 2508-7274(Online)
DOI: https://doi.org/10.3807/COPP.2017.1.1.029

Fast Analysis of Film Thickness in Spectroscopic Reflectometry using Direct Phase Extraction

Kwangrak Kim[1]*, Soonyang Kwon[2], and Heui Jae Pahk[1,2]

[1]SNUPrecision, Co., Ltd., Asan valley nam-ro 124, Dunpo-myeon, Asan-si, Chungcheongnam-do 31409, Korea

[2]School of Mechanical and Aerospace Eengineering, Seoul National University, Gwanak-ro 1, Gwanak-gu, Seoul 08826, Korea

(Received October 17, 2016 : revised November 28, 2016 : accepted January 19, 2017)

A method for analysis of thin film thickness in spectroscopic reflectometry is proposed. In spectroscopic reflectometry, there has been a trade-off between accuracy and computation speed using the conventional analysis algorithms. The trade-off originated from the nonlinearity of spectral reflectance with respect to film thickness. In this paper, the spectral phase is extracted from spectral reflectance, and the thickness of the film can be calculated by linear equations. By using the proposed method, film thickness can be measured very fast with high accuracy. The simulation result shows that the film thickness can be acquired with high accuracy. In the simulation, analysis error is lower than 0.01% in the thickness range from 100 nm to 4 um. The experiments also show good accuracy. Maximum error is under 40 Å in the thickness range 3,000-20,000 Å. The experiments present that the proposed method is very fast. It takes only 2.6 s for volumetric thickness analysis of 640*480 pixels. The study suggests that the method can be a useful tool for the volumetric thickness measurement in display and semiconductor industries.

Keywords : Metrology, Spectroscopic reflectometry, Thin film thickness
OCIS codes : (120.0120) Instrumentation, measurement, and metrology; (120.3940) Metrology; (120.4290) Nondestructive testing

I. INTRODUCTION

The measurement of micro-pattern is essential for process management in the semiconductor and display industries. In particular, measurement of film thickness is necessary during the manufacturing process. Various techniques and instruments have been used to measure film thickness. Although direct observation using SEM (Scanning Electron Microscopy) is the most reliable, it is not practical for the in-line inspection process. Ellipsometry, spectroscopic reflectometry (SR), and white-light interferometry (WLI) are conventional non-destructive measurement instruments for film thickness [1].

In particular, SR has been used for thickness measurement in many studies [2-4]. The nonlinear fitting method is the most commonly used analysis for SR. The Levenberg-Marquardt algorithm (LMA) is one of the most used algorithms. Nonlinear fitting methods are renowned as a reliable analysis due to their accuracy. However, they have also suffered from slow computing speed and the local minimum problem. These problems of the nonlinear fitting method are not critical for conventional SR measurement, however, these cannot be neglected if multiple points have to be analyzed.

The measurement of volumetric thickness using a CCD camera as a spectrum detector has been studied recently [5-12]. It is often called imaging spectroscopic reflectometry (ISR) when the volumetric thickness is measured by SR theory [8, 9]. It is time-consuming and not very practical to apply the nonlinear fitting method for ISR, because the iterative fitting process has to be conducted for every pixel. D. Kim proposed a peak detection method for the fast analysis of film thickness, but it has relatively lower accuracy

*Corresponding author: kkrak1026@gmail.com

Color versions of one or more of the figures in this paper are available online.

This is an Open Access article distributed under the terms of the Creative Commons Attribution Non-Commercial License (http://creativecommons.org/licenses/by-nc/4.0/) which permits unrestricted non-commercial use, distribution, and reproduction in any medium, provided the original work is properly cited.

Copyright © 2017 Current Optics and Photonics

and cannot measure thinner films under 1 um thickness [5].

In this paper, a fast analysis method is proposed for the measurement of transparent film thickness. The film thickness can be analyzed in a very simple way using extraction of the spectral phase change. By extracting the phase, the thickness can be calculated by linear equations. The accuracy of the proposed method is verified by simulation and experiments. Measurement speed is also examined by the experiments comparing to other methods using an ISR system.

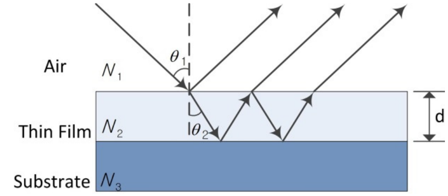

FIG. 1. Propagation of light in a thin film. Multiple reflections occur in the film layer.

II. PROPOSED METHOD

Spectroscopic reflectometry is a study that analyzes spectral reflectance to measure characteristics of materials such as thickness and refractive index. Internal interferences occur by the multiple reflections inside of the film layer. (See Fig. 1.) It is well known that spectral reflectance can be calculated by Eqs. (1) and (2) [12]. The spectral reflectance is the square of the magnitude of the complex reflection coefficient. Note that spectral reflectance is the ratio of intensities and reflection coefficient is the ratio of electromagnetic waves.

$$R = \left|r_{total}\right|^2 = \left|\frac{r_{12} + r_{23}\exp(-i2\beta)}{1 + r_{12}r_{23}\exp(-i2\beta)}\right|^2 \tag{1}$$

$$\beta(\lambda) = \frac{2\pi d}{\lambda} N_2(\lambda)\cos(\theta_2(\lambda)) \tag{2}$$

Here, N_i is the refractive index of material i and r_{ij} is the Fresnel reflection coefficient at the interface between materials i and j. The subscriptions 1, 2, and 3 mean air, film, and substrate, respectively. β is the phase change of electromagnetic waves in the film layer, and λ is the wavelength of the light. d is the thickness of the film and θ_2 is the refracted angle of transmitted light. Spectral reflectance is the function of the film thickness, refractive indices and the refracted angle.

Nonlinearity of spectral reflectance with respect to the thickness has been a major problem caused by using conventional analysis algorithms. There has been a trade-off between accuracy and computation speed for the algorithms. A nonlinear fitting method has high accuracy, however, it has slow computation speed because of its iterative process. A peak detection method can calculate thickness with high speed, but its accuracy is relatively low.

However, from the Eqs. (1) and (2) it is clear that the film thickness, d, has a linear relationship with the phase, β. If the phase is extracted from reflectance, the thickness can be calculated more easily. We propose an assumption for this purpose. The assumption is that the film material has low extinction coefficient. In many semiconductor and display applications, most film materials such as silicon dioxide, silicon nitride and photoresist have very low extinction coefficients. By this assumption the refractive index of film material, N_2, becomes a real number, thus the Fresnel reflection coefficient, r_{12}, also becomes a real number. Now there are two complex numbers in Eq. (1), and they can be rewritten as in Eq. (3).

$$\begin{aligned} r_{23}(\lambda) &= A(\lambda) + iB(\lambda) \\ \exp(-i2\beta) &= \cos(2\beta) - i\cdot\sin(2\beta) \end{aligned} \tag{3}$$

By substituting r_{23} and the exponential term in Eq. (1) with Eq. (3), the spectral reflectance can be described as in Eq. (4). By defining X as in Eq. (5) and substituting it in Eq. (4), the equation can be rearranged as in Eq. (6). Consequently, the phase β can be extracted using Eq. (7) by the relation between X and β. Figure 2 shows the process of the proposed method. From the reflectance signal, the phase is directly extracted by Eq. (7) as in Fig. 2(a) and (b). In the following equations, A, B, r_{12}, and β

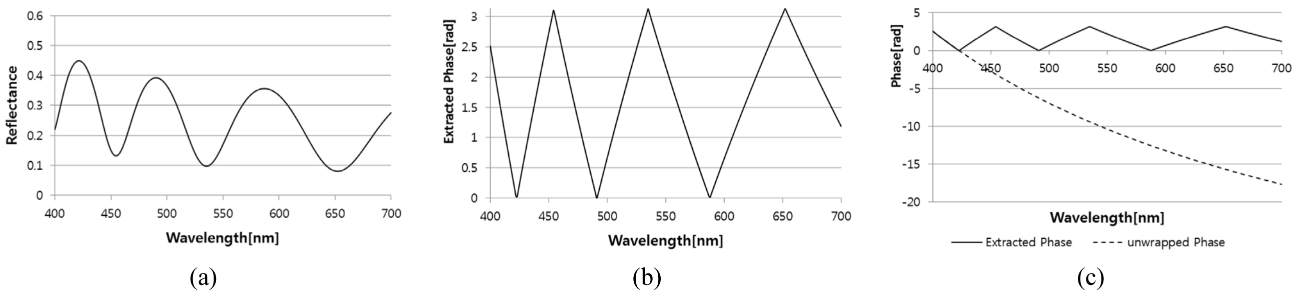

FIG. 2. The process of the proposed method. (a) Reflectance to be analyzed, (b) Phase extracted from the reflectance, (c) The extracted phase (solid line), and the result of unwrapping (dashed line).

are all the function of wavelength, but that is omitted from the notation.

$$R = |r_{total}|^2 = \frac{r_{12}^{\ 2} + (A^2 + B^2) + 2r_{12}(A\cos(2\beta) + B\sin(2\beta))}{1 + r_{12}^{\ 2}(A^2 + B^2) + 2r_{12}(A\cos(2\beta) + B\sin(2\beta))} \quad (4)$$

$$X = A\cos(2\beta) + B\sin(2\beta) \quad (5)$$

$$X = \frac{R + R \cdot r_{12}^{\ 2}(A^2 + B^2) - r_{12}^{\ 2} - (A^2 + B^2)}{2r_{12}(1 - R)} \quad (6)$$

$$\beta = \frac{1}{2}\left[\tan^{-1}(\frac{B}{A}) + \cos^{-1}(\frac{X}{\sqrt{A^2 + B^2}})\right] \quad (7)$$

In the next step, the extracted phase β has to be unwrapped. Because Eq. (7) consists of an arctangent and an arccosine function, the extracted phase has bounded values. Figure 2(c) shows the wrapped phase and the result of unwrapping. After finishing the unwrapping process, the film thickness can easily be calculated from Eq. (2).

The nonlinear reflectance equation is converted to the linear equation by using extraction of phase. The thickness of the film can be calculated from the proposed method without any iterative procedure. It can help in obtaining the film thickness much faster than by the conventional nonlinear fitting algorithm.

III. SIMULATION

The performance of the proposed method is verified by the simulation. The spectral reflectance of silicon dioxide film on a silicon substrate is theoretically modeled using Eqs. (1) and (2), then analyzed by the proposed method. The range of the film thickness is 100 nm to 4 um. The simulation result is shown in Fig. 3. The result is expressed in error [%] which is the difference between the analyzed thickness and the nominal one (the thickness used for theoretical modeling). The maximum error is lower than 0.01% when the nominal thickness is about 300 nm. The error level is maintained at a constant level regardless of the nominal thickness. It can be said that the proposed method can analyze both thin and thick film with high accuracy.

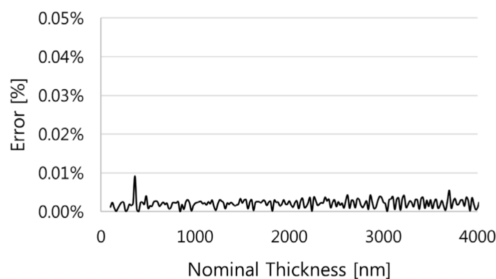

FIG. 3. The simulation result of the proposed method.

IV. EXPERIMENTS

The experiments are conducted with two reflectometer systems. First, a conventional spectroscopic reflectometer (SR) system which can measure single-spot thickness. It is designed to verify the accuracy of the proposed analysis by being compared with the result of an ellipsometer. Second, an imaging spectroscopic reflectometer (ISR) system is used. Volumetric film thickness is measured comparing computation time with other methods.

4.1. Spectroscopic Reflectometer

The SR system which consists of a reflection probe and a spectrometer was prepared for the experiments. The hardware configuration of the SR system is shown in Fig. 4. A tungsten-halogen lamp is used as light source. The power of the lamp is 100 W and the spectrum range is 300-800 nm. The wavelength range used for data analysis is 400-700 nm, which is chosen to secure sufficient light intensity. The spectrometer has about 390 valid pixels in a 400-700 nm wavelength range, and wavelength resolution is about 0.77 nm. Silicon dioxide specimens are prepared, and each sample has different film thickness. The film thickness of the specimens are pre-measured by ellipsometer, and the results are compared as nominal values.

Table 1 is the result of the experiments. The result of the proposed method ('Phase Extraction') is compared with two conventional analysis methods and the nominal values ('Ellipsometer'). It shows that the maximum difference between the nominal values and the proposed method is lower than 40 Å. The accuracy of the nonlinear fitting method is similar to that of the proposed one. On the other hand, it is clear that the peak detection method has worse performance in accuracy. Maximum error is bigger than 600 Å. Furthermore, the samples #1 and #2 cannot be measured by the peak detection method because there is no peak to detect in the reflectance of thinner film. The experiment result reveals that the phase extraction method can be used to measure film thickness with high accuracy.

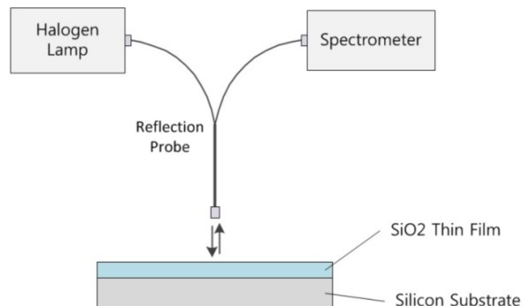

FIG. 4. Schematic of spectroscopic reflectometer system.

Table 1. Comparison of the thickness measurement results (All units are in angstrom [Å])

Sample No.	#1	#2	#3	#4	#5	#6
Ellipsometer	2918	5062	7281	10231	15392	20775
Phase Extraction	2956	5065	7243	10200	15390	20771
Nonlinear Fitting	2899	5045	7243	10195	15388	20771
Peak Detection	-	-	6724	9602	15541	20766

4.2. Imaging Spectroscopic Reflectometer

The volumetric thickness is measured by the ISR for verification of the computation speed. The hardware configuration of the ISR system for this experiment is depicted in Fig. 5. The resolution of the CCD camera is 640*480 pixels. A magnification ×50 objective lens is used, FOV of the optical system is about 95*71 um. Wavelength sweeping is conducted by AOTF (Acousto-optic tunable filter) for wavelength range 450-700 nm with 1 nm interval. The wavelength range is restricted by the specification of the AOTF. The volumetric thickness can be obtained by analyzing individual pixels and taking them together. A step thickness specimen is prepared. The thickness of the specimen varies from 850 to 900 nm.

The result of the measurement is shown in Fig. 6. Variation of film thickness is clearly measured. The horizontal profile (Fig. 6(b)) shows that the thickness of the film varies approximately from 915 nm to 845 nm.

Computation times of three analysis methods are compared in Table 2. Note that the computation time means the time to analyze more than 3 hundred thousand points. It takes 2.6 s by using Intel i5 3.2 GHz CPU and 4 GB memory. The peak detection method also shows very fast analysis, it takes 2.4 s. On the other hand, the result of the nonlinear fitting method reveals its shortcoming. It takes more than 5 min to analyze, it seems that it is hard to use this analysis for an ISR system.

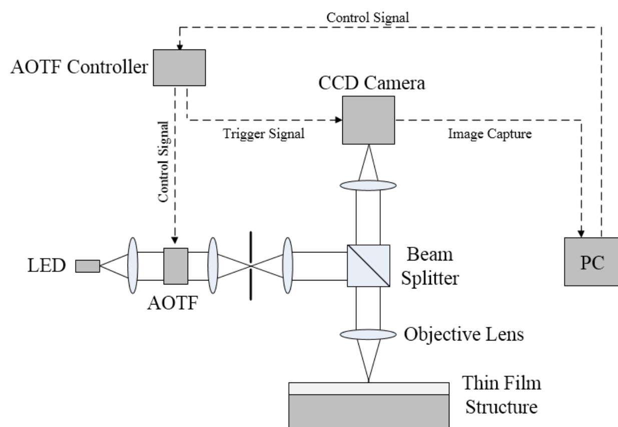

FIG. 5. Schematic of imaging spectroscopic reflectometer system.

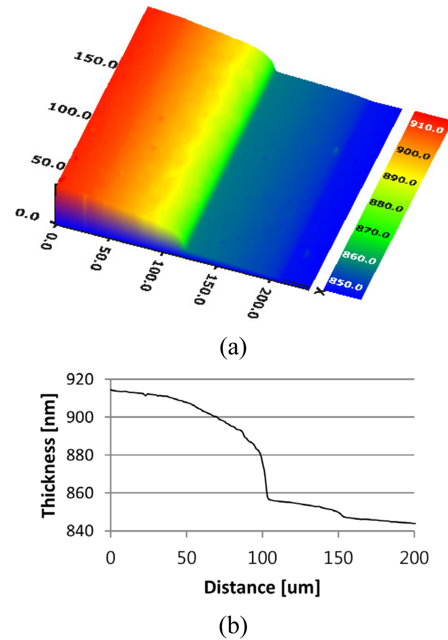

FIG. 6. Process flow of (a) wet transfer method for multilayered graphene and (b) one-step dry transfer method for multilayered graphene.

Table 2. Comparison of the computation times

	Phase Extraction	Nonlinear Fitting	Peak Detection
Computation Time (s)	2.6	320.8	2.4

V. CONCLUSION

The present study proposes a method for fast analysis of thin film thickness in spectroscopic reflectometry. In the proposed method the spectral phase change can be extracted, and film thickness can be calculated. By extracting the spectral phase, the nonlinear equation can be converted to the linear equations. There is a great improvement in calculation speed, because iterative fitting process in unnecessary in the proposed method. From the simulation result, it is verified that the method maintains high accuracy in broad thickness range. The experiments using SR and ISR also show that the proposed method can be used with high

speed and high accuracy. The maximum error is lower than 40 Å in thickness range 3,000-20,000 Å in the SR experiments. In the ISR experiment, the calculation time of the proposed method is 2.6 sec to analyze 640 *480 pixels.

In particular, the proposed method is useful for the ISR system, because it can reduce the calculation time significantly. It is very essential for the ISR. Fast analysis due to the simplicity of the calculation is the most powerful feature of the proposed method. The more important point is that the method maintains high accuracy performance with fast computation speed while improving computation speed. As mentioned in the introduction, there has been a trade-off between accuracy and speed for the conventional methods. It is shown in the result of the experiments.

There is an additional advantage of the proposed method. The advantage is that the method is free from the local minimum problem. Initial parameters such as thickness and refractive index should be specified for a nonlinear fitting algorithm generally. The local minimum point could occur, if the initial parameter is not appropriate. But, the proposed method does not need any particular user setting. On the other hand, the proposed method has some disadvantages. Refractive index of thin film cannot be analyzed simultaneously, while conventional nonlinear fitting method can do that. Measurement of multi-layer thin film structures is another limitation.

A new analysis method which is named 'Phase Extraction' is proposed in this paper, and the simulation and the experiments prove that the method has improved performances. It can be said that the method can be a useful tool for the measurement of film thickness in display and semiconductor industries.

REFERENCES

1. A. Piegary and E. Masetti, "Thin film thickness measurement: a comparison of various techniques", Thin Solid Films **124**, 249-257 (1985).
2. T. E. Benson, L. I. Kamlet, P. Klimecky, and F. L. Terry, JR, "In-situ spectroscopic reflectometry for polycrystalline silicon thin film etch rate determination during reactive ion etching", J. Electron. Mater. **25**, 955-964 (1996).
3. T. Kihara and K. Yokomori, "Simultaneous measurement of refractive index and thickness of thin film by polarized reflectances", Appl. Opt. **29**, 5069-5073 (1990).
4. U. Schnell and R. Dändliker, "Dispersive white-light interferometry for absolute distance measurement with dielectric multilayer systems on the target", Opt. Lett. **21**, 528-530 (1996).
5. D. Kim, S. Kim, H. J. Kong, Y. Lee, and Y. K. Kwak, "Fast thickness profile measurement using a peak detection method based on an acousto-optic tunable filter", Meas. Sci. Technol. **13** (2002) L1.
6. J.-W. You, S. Kim, and D. Kim, "High speed volumetric thickness profile measurement based on full-field wavelength scanning interferometer", Opt. Express **16**, 21022-21031 (2008).
7. Y.-M. Hwang, S.-W. Yoon, J.-H. Kim, S. Kim, and H.-J. Pahk, "Thin-film thickness profile measurement using wavelet transform in wavelength-scanning interferometry", Opt. Laser. Eng. **46**, 179-184 (2008).
8. M. Urbánek, J. Spousta, T. Běhounek, and T. Šikola, "Imaging reflectometry in situ", Appl. Opt. **46**, 6309-6313 (2007).
9. M. Ohlidal, I. Ohlidal, P. Klapetek, D. Nečas, and A. Majumdar, "Measurement of the thickness distribution and optical constants of non-uniform thin films", Meas. Sci. Technol. **22** (2011) 085104.
10. K. Kim, S. Kim, S. Kwon, and H. J. Pahk, "Volumetric thin film thickness measurement using spectroscopic imaging reflectometer and compensation of reflectance modeling error", Int. J. Precis. Eng. Man. **15(9)**, 1817-1822 (2014).
11. S. Kwon, N. Y. Kim, T. Jo, and H. J. Pahk, "Critical dimension measurement of transparent film layers by multispectral imaging", Opt. Express **22**, 17370-17381 (2014).
12. H. Fujiwara, Spectroscopic Ellipsometry: Principles and Applications, p. 43 (Wiley, New York, USA, 2007)