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Volumetric Thin Film Thickness Measurement using Spectroscopic Imaging Reflectometer and Compensation of Reflectance Modeling Error

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In this paper, volumetric thin film thickness is measured using the spectroscopic imaging reflectometer, which consists of a microscopy optic system, variable bandpass filter and CCD camera. The volumetric thickness profile can be measured by using each pixel of the CCD camera as a spectrum sensor. The causes of reflectance modeling errors are explained, and equations for compensation are proposed. For the verification of system performance and proposed equations, the thickness of silicon oxide thin film is measured. Ellipsometer and AFM measurement results are used as nominal thicknesses for comparisons with the result of spectroscopic imaging reflectometer. From the comparisons, it is verified that the proposed equations can improve accuracy of measurement. It can be said that the proposed equations can properly compensate the error due to Gaussian distribution of filtering and lens NA.

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NOMENCLATURE

r^p, r^s = Fresnel's reflection coefficients
R^p, R^s = Total reflection coefficients
R = Reflectance
λ = Wavelength of light
θ_1 = Incidence angle
θ_2 = Refraction angle (or reflection angle)
$\tilde{\theta}_{1,NA}$ = Effective incidence angle
$\tilde{\theta}_{2,NA}$ = Effective refraction (or reflection) angle
ϕ_{max} = Maximum incidence angle by NA of objective lens

1. Introduction

The measurement of transparent thin film has been a very important tool for the management of products in the display and semiconductor industries. As the patterns in semiconductor wafers and display panels are getting smaller and more complicated, volumetric thin film thickness measurement of small areas has become essential. Conventional useful tools for measurement of transparent thin film are the spectroscopic reflectometer, white-light interferometer, and ellipsometer.[1] In particular, the spectroscopic reflectometer has been used for measurement of thin film thickness and refractive index in many cases.[2-7] Schnell measured the absolute distance and the thickness of silicon oxide film using the least-square fitting between the measured signal and the theoretically calculated phase.[7] Recently the nonlinear fitting algorithm is commonly used for improvement of measurement accuracy in spectroscopic reflectometry.

Conventional reflectometers, however, can only measure just one spot in a single measurement process. Thus new instrument has been desired that can measure the volumetric thin film thickness profile over some small area. Recently there have been some efforts to measure the volumetric thin film thickness. In many cases, white-light interferometry is used for measurement of volumetric thin film thickness. S.-W. Kim used vertical scanning white-light interferometry for the simultaneous measurement of thin film thickness and surface height profile.[8] Spectral reflectance is extracted from the interferogram using Fourier transform, Levenberg-Marquardt nonlinear fitting algorithm is used for the fitting with theoretical reflectance. Wavelength scanning interferometry also can be used for the measurement of volumetric thin film thickness. D. Kim used AOTF (Acousto-optic Tunable Filter) for wavelength scanning, two-step measurement method for measurement of surface height profile and thin film thickness is proposed.[9] Fast computation time can be obtained using peak detection method, but relatively thinner film under 1um cannot be measured. J.-W. You also proposed the two-step measurement method[10] and the advanced two-step measurement method which can be conducted without mechanically moving parts.[11] The total interference and the self-interference are separated using polarizers, AOTF and two CCD cameras. Y.-M. Hwang measured thin film thickness and surface height profile simultaneously using wavelength scanning interferometer, and wavelet transform is applied for the phase retrieval.[12]

There are some researches that analyze self-interference only for measurement of thin film thickness. M. Urbánek measured volumetric thin film thickness using imaging reflectometer.[13] Intensity maps of selected wavelength are recorded by CCD camera, spectral reflectance is analyzed by Levenberg-Marquardt nonlinear fitting algorithm. M. Ohlidal also measured volumetric thin film thickness and refractive index of the film simultaneously using imaging reflectometer.[14] The hardware configurations used in these studies have relatively large field of view and lateral resolution because they do not implement a microscopic optical system. In order to measure small patterns in semiconductor or display panel, smaller field of view is essential.

In this paper, volumetric thin film thickness in small area is measured accurately using spectroscopic imaging reflectometer and compensation of modeling error. Variable bandpass filter is used for wavelength scanning and CCD camera is used as the detector of spectrum. The bandpass filter and objective lens of microscopy, however, can be causes of some distortion of spectral reflectance. In order to compensate the distortion, equations for compensation are proposed. For verification of the effectiveness of the equations for compensation, thickness of silicon oxide film is measured by the proposed system. The experiments clearly show that the equations can reduce the difference between reference thickness measured by ellipsometer and the thickness measured by proposed system. The experiments also show that the equations are much more effective for thicker film and with objective lens of higher NA.

2. Spectroscopic Imaging Reflectometer

In this section, the theory of spectroscopic reflectometry is introduced and measurement of volumetric thin film thickness using spectroscopic imaging reflectometer is explained.

Spectroscopic reflectometry is based on the characteristics that spectral reflectance of thin film varies with the thickness of film and the refractive indices of the materials. Spectral reflectance is measured and compared with the theoretical spectral reflectance signals calculated at a certain thin film thickness. Nonlinear regression algorithm such as Levenberg-Marquardt algorithm can be used for the comparison process.

Fresnel reflection coefficients, r^p and r^s, at the interface of two materials can be calculated using Eq. (1). Fresnel reflection coefficients are the function of the complex refractive index, N, of materials[15] and the angle of incidence. The superscript p indicates the electromagnetic vector, which is parallel to the incident plane, and superscript s indicates the electromagnetic vector, which is perpendicular to the incident plane. The subscript number 12 means light incident from material 1 to material 2 (as in Fig. 1). θ_1 is the incident angle or reflected angle, and θ_2 is the refracted angle.

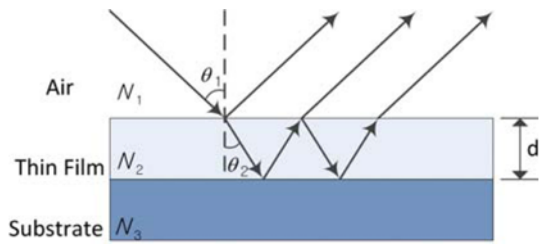

Fig. 1 Propagation of light in a thin film, Multiple reflections occur in the film layer

$$r^p{}_{12} = \frac{N_2 cos(\theta_1) - N_1 cos(\theta_2)}{N_2 cos(\theta_1) + N_1 cos(\theta_2)}$$
$$r^s{}_{12} = \frac{N_1 cos(\theta_1) - N_2 cos(\theta_2)}{N_1 cos(\theta_1) + N_2 cos(\theta_2)} \quad (1)$$

Fig. 1 shows the behavior of the light propagating into a thin film. Inside the film, light experiences multiple reflections at the two interfaces (air-film interface and film-substrate interface). Considering the multiple reflections, the total reflection coefficients, R^p and R^s, can be calculated using Eq. (2).[16] In Eq. (2), d is the thickness of the thin film, ë is the wavelength of light. â is the phase delay during the single reflection process in the thin film layer. The resultant spectral reflectance can be calculated as the square of R^p or R^s. Superscripts p and s do not matter, because the incident light is symmetric with respect to the optical axis.

$$R^p = \frac{r^p{}_{12} + r^p{}_{23} \exp(-j2\beta)}{1 + r^p{}_{12} r^p{}_{23} \exp(-j2\beta)}$$
$$R^s = \frac{r^s{}_{12} + r^s{}_{23} \exp(-j2\beta)}{1 + r^s{}_{12} r^s{}_{23} \exp(-j2\beta)} \quad (2)$$
$$\beta = 2\pi \frac{d}{\lambda} N_2 cos(\theta_2)$$

Fig. 2 shows the schematics of spectroscopic imaging reflectometer. As depicted in Fig. 2, a variable bandpass filter is placed between the light source and the optics for wavelength scanning, and the filter can be moved by a linear stage. A CCD camera is used as a spectrum detector. A microprocessor sends synchronized control signal to the stage and the camera. As depicted in Fig. 3, a linear variable filter is a wedged filter, whose spectral properties vary linearly along the long side of the filter. The filtering wavelength varies linearly with respect to the position of the incident light. As the filter changes the wavelength of filtering, the camera captures the image. After the acquisition process is completed for the range of wavelength, each pixel of the camera stores the information of the spectrum and the corresponding position. By analyzing the spectrum of each pixel based on the spectroscopic reflectometry principles, volumetric thin film thickness can be obtained.

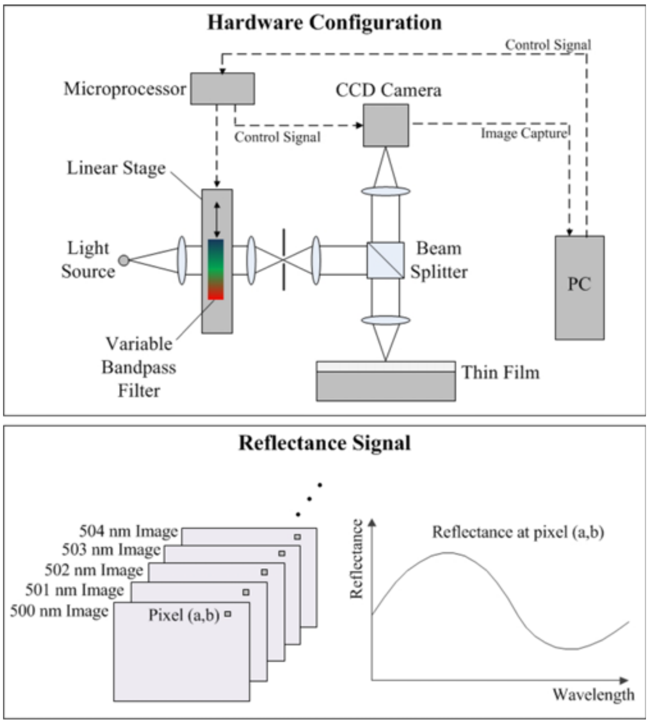

Fig. 2 Schematics of spectroscopic image reflectometer, A variable bandpass filter is used for wavelength scanning. After acquisition process, each pixel of CCD camera has spectrum data

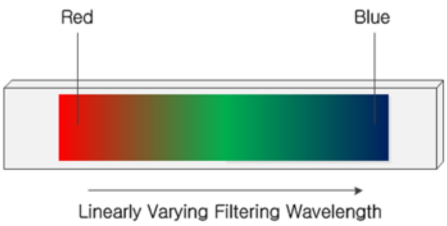

Fig. 3 Variable bandpass filter, The filtering wavelength varies linearly with respect to the position of the incident light

Some advantages can be obtained from this hardware configuration. The spectrum data of higher resolution in wavelength domain can be obtained by controlling the bandpass filter. Conventionally filter wheel has been used for imaging reflectometer, spectral resolution of imaging reflectometer is normally 5 or 10 nm with filter wheel. On the other hand, 1 nm resolution can be achieved with variable bandpass filter. Higher resolution enables accurate analysis in the fitting process. Faster measurement time is another advantage. Wavelength scanning can be conducted in 2 s for wavelength range 400 to 700 nm. AOTF can be used for wavelength scanning as an alternative of the variable bandpass filter. However, the optic system can be constructed with lower cost when the variable bandpass filter is used.

3. Compensation of Reflectance Modeling Error

In this section, in order to achieve higher accuracy with performance, errors that can occur on the spectroscopic imaging

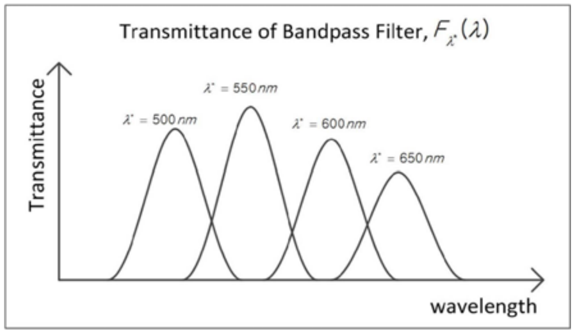

Fig. 4 Transmittance of the bandpass filter for each central wavelength of filtering

reflectometer are explained, and equations for compensation can be proposed as follows.

First, there can be an error that occurs during the bandpass filtering of light. Light passing through a bandpass filter has the Gaussian distribution spectrum. This makes the amplitude of the reflectance curve smaller, and the magnitude of error becomes greater. In order to compensate for this kind of error, Eq. (3) can be proposed as follows.

$$\tilde{\Re}_{bandpass}(d,\lambda) = \frac{\int_{-\infty}^{\infty} F_{\lambda*}(\lambda)\Re(d,\lambda)(d\lambda)}{\int_{-\infty}^{\infty} F_{\lambda*}(\lambda)d\lambda} \tag{3}$$

$$F_{\lambda*}(\lambda) = E_0(\lambda)\exp\left[-\frac{1}{2}\left(\frac{\lambda-\lambda*}{\sigma}\right)^2\right] \tag{4}$$

$F_{\lambda*}(\lambda)$ is the transmittance function of the bandpass filtering, where $\lambda*$ is the central wavelength of the filtering. The transmittance of bandpass filtering is assumed as a Gaussian distribution. $E_0(\lambda*)$ is the light intensity at wavelength $\lambda*$, and σ is a factor for the bandwidth of the Gaussian distribution. As thicker film has usually a shorter period in the spectral reflectance curve, this compensation is expected to give more effectiveness for thicker film.

Second, there can be an error that occurs due to the NA (numerical aperture) of the objective lens of the microscopy. Normally θ_1 and θ_2 in Eqs. (1)~(2) can be treated as zero, because the incident light is reflected perpendicular to the surface of thin film, in the probe type spectroscopy reflectometer. When a greater magnification objective lens is used, the incident angle also becomes larger in the microscopy system. In the case of a 50x magnitude objective lens that has 0.55 NA, the maximum incident angle can be more than 30 degrees. Pliskin et al. proposed the effective angle according to the numerical aperture of an objective lens.[17] Eq. (5) is the effective angle $\tilde{\theta}_{2,NA}$ in integral form. They used the effective angle instead of θ_2 in Eq. (2), and calculated the reflectance modeling accurately. In this paper, $\tilde{\theta}_{1,NA}$ can be calculated from Eq. (6) using the Snell's law, and effective angle $\tilde{\theta}_{1,NA}$ and $\tilde{\theta}_{2,NA}$ can be used instead of θ_1 and θ_2 in Eq. (1).

$$cos\tilde{\theta}_{2,NA} = \frac{\int_0^{\phi_{max}}(2\pi L\cdot sin\phi)(L\cdot d\phi)cos\theta_2}{\int_0^{\phi_{max}}(2\pi L\cdot sin\phi)(L\cdot d\phi)} \tag{5}$$

$$cos\tilde{\theta}_{2,NA} = \frac{N_2}{N_1}cos\tilde{\theta}_{2,NA} \tag{6}$$

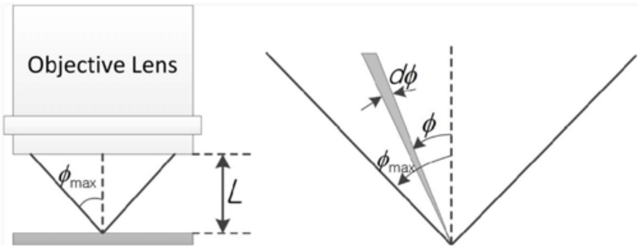

Fig. 5 The numerical aperture of an objective lens

Fig. 5 shows the cone of the incident light from the objective lens to thin film, where definitions of the terms of Eqs. (5)~(6) explained, ϕ is the incident angle, and ϕ_{max} is the maximum incident angle, which is calculated from the NA value of the objective lens, and L is the working distance of the objective lens. In Eq. (5), the integral is conducted only for angle ϕ, because the distribution and path of light is symmetrical with respect to the optical axis.

4. Experiments

Experiments are conducted, in order to verify the effectiveness of the proposed method. Silicon dioxide thin film on silicon substrate is measured by the spectroscopic imaging reflectometer instrument, and analyzed with two different methods; One is the conventional theoretical modeling method of Eqs. (1)~(2), and the other is the proposed modeling method of Eqs. (3)~(6). Ellipsometer and AFM measurements are conducted, for the reference thickness of silicon dioxide.

The configuration of the spectroscopic imaging reflectometer for the experiments is described in Fig. 2. A 150 W tungsten-halogen lamp that emits 380~850 nm wavelength range is used. Commercially available variable bandpass filter is used, and the filter has a 400~700 nm filtering range, and 10~18 nm bandwidth. The size of the camera sensor 7.4 um and sensor array is 640*480. Three objective lenses are used. Table 1 shows the field of view (FOV), NA and spatial resolution of the optic system.

Tables 2 and 3 show the measurement results of uniformly deposited silicon dioxide film samples. In Table 2, five samples are measured by spectroscopic imaging reflectometer with 10x objective lens, in order to find out the effect of the proposed equations with respect to the thin film thickness. In Table 3, sample #3 is measured by spectroscopic imaging reflectometer with 10x, 20x and 50x objective lenses respectively, in order to find out the effect of the proposed equations with respect to the NA value. As results of the spectroscopic imaging reflectometer, values in the tables are the average of all pixels from the 640*480 camera. Ellipsometer measurement results are added in the table, as the reference thickness value.

From the Table 2, it can be noted that the difference between the conventional method and the reference thickness (Ellipsometer) increases up to 9.8 nm, as film thickness increases. On the other hand, the proposed method shows much smaller difference such as maximum 1.9 nm for the sample #5. From this result, we can conclude that the proposed equations for compensation for bandpass filtering can successfully correct the reflectance curve, and that they are observed to be more effective for the thick film measurement.

Table 1 FOV, NA and spatial resolution for the objective lens in use

Magnification	10x	20x	50x
FOV [um]	473.6*355.2	236.8*177.6	94.7*71.0
NA	0.30	0.40	0.55
Spatial Resolution [um]	0.740	0.370	0.148

Table 2 Measurement results of samples #1-5. Each sample has different film thickness. A 10x Objective Lens is used. All units are in nm

Sample	#1	#2	#3	#4	#5
Conventional	86.4	296.7	524.8	1051.0	1400.4
Proposed	87.7	299.1	529.0	1061.4	1412.1
Ellipsometer	87.2	298.4	528.5	1060.1	1410.2

Table 3 Measurement results of sample #3. Various magnification objective lenses are used. All units are in nm

Obj. Lens	10x	20x	50x
Conventional	524.8	519.3	510.2
Proposed	529.0	528.8	529.3
Ellipsometer		528.5	

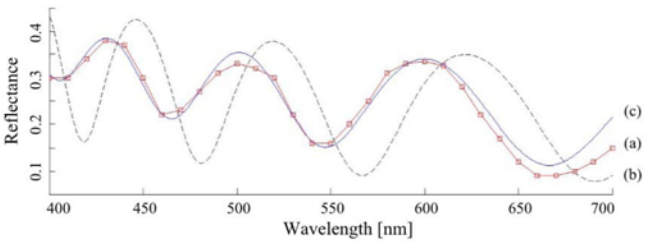

Fig. 6 Reflectance profiles comparisons, Profile (a) is extracted from the measurement result of sample #4 with a 50x obj. lens. Profile (b) is from the conventional theoretical modeling, and Profile (c) is from the proposed equations, where thickness d=1060.1 nm

From the Table 3, the difference between conventional method and the reference value increases, as the higher magnification lens is used. Because the higher NA value of the objective lens forms a large incident angle, the conventional method cannot correctly measure the thickness. On the other hand, for the measurement results with the proposed method, it is observed that the effect of NA is successfully eliminated. In particular, in the case of a 50x objective lens, the proposed method measured 529.3 nm for the 528.5 nm reference thickness, while the conventional method measured 510.2 nm. Thus the difference is greatly reduced from 18.3 to 0.8 nm.

Fig. 6 shows the equations can make a difference in the reflectance profile. Profile (a), the squared line, is the reflectance measured from sample #4 using the 50x objective lens. The profile (b), the dashed line, is the conventional theoretical reflectance model where the thickness d is 1060.1 nm, which is the reference value from the ellipsometer. As shown in Fig. 6, profiles (a) and (b) have quite different characteristics in the amplitude and position of curve. On the other hand, profile (c), the solid line, is the reflectance calculated from the proposed equations at the same thickness. The profile (c) shows very good matching with

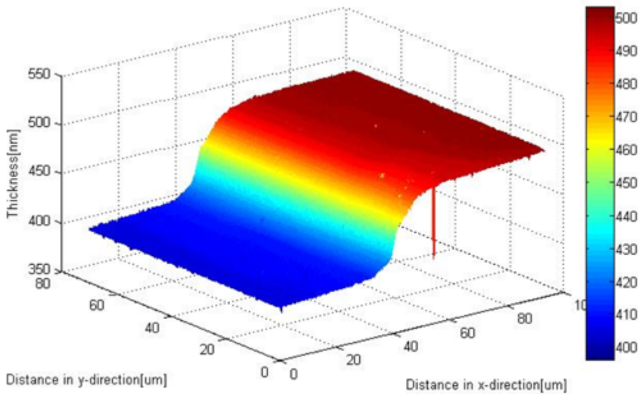

Fig. 7 The measurement result of the spectroscopic image reflectometer, The volumetric thickness of silicon oxide film is measured

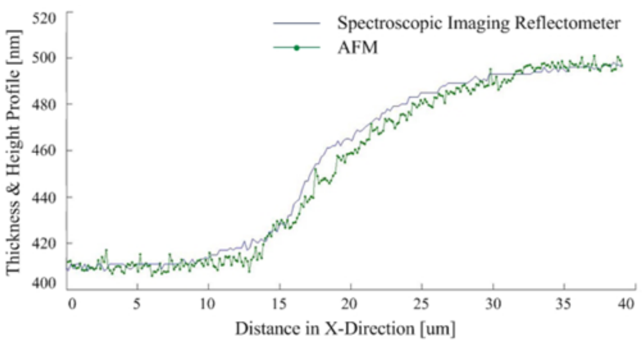

Fig. 8 Profile comparison between the AFM and spectroscopic imaging reflectometer results

profile (a). If the proposed equations are not applied, the error will increase in the nonlinear fitting process, and there will be discrepancy in the resultant thickness.

The following are the measurement results of a silicon dioxide sample that has step thickness. In order to verify the thickness profile of step thickness, AFM measurement is conducted, and compared with the spectroscopic imaging reflectometer measurement. The 50x magnification objective lens is used for the spectroscopic imaging reflectometer.

In Fig. 7, the volumetric thickness profile measured from the spectroscopic imaging reflectometer is shown. The inclined part between the two planar parts are also measured well. For clear verification of the result, one-dimensional profiles extracted along the x-direction are compared in Fig. 8. In order to improve visibility for profile comparison, an appropriate flattening process is conducted and some offset is applied on the AFM result.

It is observed that there is a difference of up to 10nm in the inclined region, and this may be due to the possibility that light scattering on the inclined surface can affect the result of thickness measurement. Clearly, the two profiles look very similar in spite of such discrepancy.

5. Conclusion

In this paper, the spectroscopic imaging reflectometer is introduced for the measurement of the volumetric thin film thickness. A variable bandpass filter and a CCD camera are used for the acquisition of the spectrum. The spectrum of higher resolution in wavelength domain can be obtained from the system and the accuracy of the fitting process can be improved.

In order to achieve higher accuracy with performance, the Gaussian distribution spectrum of bandpass filtered light and the incident angle due to objective lens NA are mentioned as the causes of errors, and Eqs. (3)~(6) are proposed to compensate these errors. Using the proposed equations, the difference between measured reflectance and theoretical reflectance is greatly reduced when compared with the conventional theory. The distortion of the spectral reflectance is corrected by the proposed equations.

From the measurements of the samples in various thin film thickness, it is observed that the compensation for the Gaussian distribution spectrum is more effective when it is used for the thick film. From the measurements of the samples in various objective lens, the compensation for NA shows a good result when a higher magnification objective lens is used. In particular, the compensation for NA is especially useful, because a higher magnification objective lens is much essential for the small microstructure in the display and semiconductor industries. From the comparison of profiles between AFM and spectroscopic imaging reflectometer, it is clear that the volumetric thickness profile from the spectroscopic imaging reflectometer shows the shape of the thickness distribution.

Therefore the volumetric thin film thickness is successfully measured using the spectroscopic imaging reflectometer and the proposed equations for compensation. The proposed method can achieved very high performance in accuracy of thickness measurement.

REFERENCES

1. Piegari, A. and Masetti, E., "Thin Film Thickness Measurement: a Comparison of Various Techniques," Thin Solid Films, Vol. 124, No. 3, pp. 249-257, 1985.

2. Lukes, F. and Schmidt, E., "Another Method for the Determination of Silicon Oxide Thickness," Solid-State Electronics, Vol. 10, No. 3, pp. 264-266, 1967.

3. Ohlídal, I., "Immersion Spectroscopic Reflectometry of Multilayer Systems. I. Theory," Journal of Optical Society of America A, Vol. 5, No. 4, pp. 459-464, 1988.

4. Benson, T. E., Kamlet, L. I., Klimecky, P., and Terry, F. L., "In-Situ Spectroscopic Reflectometry for Polycrystalline Silicon Thin Film Etch Rate Determination during Reactive Ion Etchinc," Journal of Electronic Materials, Vol. 25, No. 6, pp. 955-964, 1996.

5. Hauge, P., "Polycrystalline Silicon Film Thickness Measurement from Analysis of Visible Reflectance Spectra," Journal of Optical Society of America A, Vol. 69, No. 8, pp. 1143-1152, 1979.

6. Kihara, T. and Yokomori, K., "Simultaneous Measurement of Refractive Index and Thickness of Thin Film by Polarized Reflectances," Applied Optics, Vol. 29, No. 34, pp. 5069-5073,

1990.

7. Schnell, U., Gray, S., and Dändliker, R., "Dispersive White-Light Interferometry for Absolute Distance Measurement with Dielectric Multilayer Systems on the Target," Optics Letters, Vol. 21, No. 7, pp. 528-530, 1996.

8. Kim, S. W. and Kim, G. H., "Thickness-Profile Measurement of Transparent Thin-Film Layers by White-Light Scanning Interferometry," Applied Optics, Vol. 38, No. 28, pp. 5968-5973, 1999.

9. Kim, D., Kim, S., Kong, H. J., Lee, Y., and Kwak, Y. K., "Fast Thickness Profile Measurement using a Peak Detection Method based on an Acousto-Optic Tunable filter," Measurement Science and Technology, Vol. 13, No. 7, Paper No. L1, 2002.

10. You, J. W., Kim, S., and Kim, D., "High Speed Volumetric Thickness Profile Measurement based on Full-Field Wavelength Scanning Interferometer," Optics Express, Vol. 16, No. 25, pp. 21022-21031, 2008.

11. You, J. W., Kim, D., Ryu, S. Y., and Kim, S., "Simultaneous Measurement Method of Total and Self-Interference for the Volumetric Thickness-Profilometer," Optics Express, Vol. 17, No. 3, pp. 1352-1360, 2009.

12. Hwang, Y. M., Yoon, S. W., Kim, J. H., Kim, S., and Pahk, H. J., "Thin-Film Thickness Profile Measurement using Wavelet Transform in Wavelength-Scanning Interferometry," Optics and Lasers in Engineering, Vol. 46, No. 2, pp. 179-184, 2008.

13. Urbánek, M., Spousta, J. I., Behounek, T., and Sikola, T., "Imaging Reflectometry in Situ," Applied Optics, Vol. 46, No. 25, pp. 6309-6313, 2007.

14. Ohlídal, M., Ohlídal, I., Klapetek, P., Neèas, D., and Majumdar, A., "Measurement of the Thickness Distribution and Optical Constants of Non-Uniform Thin Films," Measurement Science and Technology, Vol. 22, No. 8, Paper No. 085104, 2011.

15. Hecht, E., "Optics," Addison-Wesley, 4th Ed., pp. 113, 2001.

16. Fujiwara, H., "Spectroscopic Ellipsometry: Principles and Applications," John Wiley & Sons, pp. 43, 2007.

17. Pliskin, W. and Esch, R., "Effect of Numerical Aperture of Microscope Objectives on Film Thickness Determinations," Journal of Applied Physics, Vol. 39, No. 7, pp. 3274-3276, 1968.