Proceedings of the Optical Society of Korea Annual Meeting 2001 (2001. 2. 15~16)

Calibrations in rotating compensator spectroscopic ellipsometry

회전보상기를 이용한 분광타원기술에 있어서의 캘리브레이션

Ilsin An
Department of Physics, Hanyang University, Ansan, Korea
ilsin@hepth.hanyang.ac.kr

Abstract
Rotating-compensator type ellipsometer was developed for spectroscopic measurements. For accurate data reduction, the azimuths of transmission axises of polarizer and analyzer, and the angular position of the fast axis of compensator should be determined through calibration process. In this paper, we present various calibration methods.

1. Introduction

Retarder has been used in a single wavelength null ellipsometry mostly as a quarter-wave plate[1]. The main purpose of adopting this optical element was to provide null condition in conjunction with a linear polarizer in polarizer-retarder-sample-analyzer configuration. Meanwhile, the recent use of this element in rotating element ellipsometry was to avoid linear polarization upon reflection and to get additional information from the non-ideal surface of sample[2]. As the sensitivity becomes poorer when the reflected beam becomes closer to linear polarization in rotating polarizer(RPE) or analyzer ellipsometry(RAE), the use of a quarter waveplate is appropriate to transform the linear polarization into circular polarization. For this purpose, however, an exact quarter-wave retardation is not necessary. Thus compensator can be employed for broadband retardation.

For data reduction in conventional RPE (or RAE), calibration process is mandatory if one wants accurate measurements. The angular positions of optical elements relative to the plane of incidence are determined in the calibration process and there are many different kinds of calibration methods are developed[3]. As the sensitivity of each calibration method depends on measured ellipsometry angles, users need to select proper calibration method for their experiments. Similar results were found in a rotating compensator ellipsometry (RCE)[4]. We report here several calibration processes for RCE system equipped with a multichannel detector.

2. Data Reduction

Figure 1 shows a schematic of the rotating-compensator ellipsometer used for this work. It consists of: (1) Xe arc lamp, (2) Glan-Taylor polarizer, (3) sample, (4) MgF_2 compensator, (5) Glan-Taylor analyzer, (6) spectrograph, and (7) multichannel detector with 2048 pixels. The polarizer, analyzer, and compensator are under position control.

When the compensator rotates with a angular frequency of ω, the light level at detector shows the following behavior:

$$I(t) = I_0\{1+\alpha_2\cos2(\omega t - C_S)+\beta_2\sin2(\omega t-C_S)+\alpha_4\cos4(\omega t-C_S)+\beta_4\sin4(\omega t-C_S)\} \qquad (1)$$

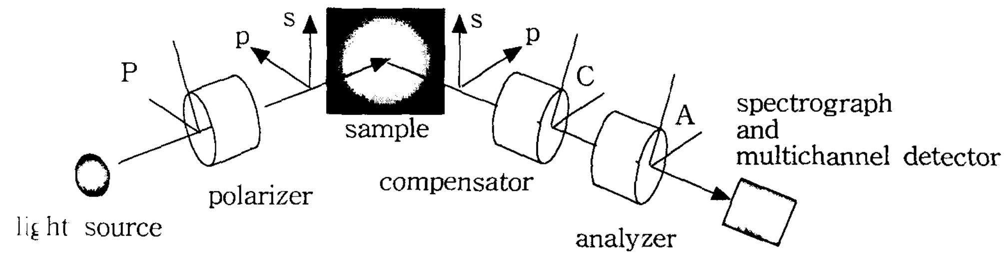


Fig. 1 Schematic representation of rotating compensator multichannel ellipsometry. P and A are the azimuths of transmission axises of polarizer and analyzer, respectively. C is the azimuth of the fast axis of compensator. The parallel and perpendicular directions to the plane of incidence are denoted as p and s with arrow.

where $-C_S$ is the angular position of the fast axis at the moment of data acquisition. The normalized Fourier coefficients in Eq. (1) are related to the optical properties of sample, retardance of compensator, and the azimuth angles of optical components.

Thus, the conventional ellipsometry angles (Δ, Ψ) can be obtained from these Fourier coefficients and the absolute values of A, P, and C, which are measured from the plane of incidence. In real experiment, however, the measurement begins from time t=0 without knowing the value of C_S in advance. Moreover, sample alignment can be different from measurement to measurement resulting in the variation of the plane of incidence. Thus, along with C_S the scale readings of analyzer and polarizer corresponding to the plane of incidence, {A_S, P_S}, are also determined during calibration process to get A, P and C.

3. Calibration

It was proposed that the following calibration procedure which is quite similar to the residual calibration method developed by Aspnes for RAE[3]. In order to determine C_S, A_S, and P_S, measure {α'_2, β'_2, α'_4, β'_4} near P_S to get

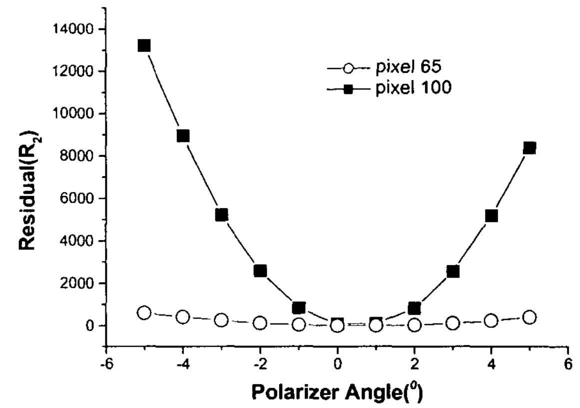
$$R_2(P) = I_0^2(\alpha_2'^2+\beta_2'^2)$$
$$\propto (\tan\Psi\sin\Delta)^2\ (P'-P_S)^2; \qquad P'\approx P_S \qquad (2)$$

Here primed notations imply non-calibrated parameters. Thus, P_S can be obtained from the parabolic behavior of R_2 as shown in Fig. 2(filled squares). However, the sensitivity of this procedure to determine P_S becomes poorer as Δ approaches 0 or 180° as can be seen in Fig. 2(open circles). To avoid this, we define Θ_4 and expand it P_S near and P_S+90° to deduce following expressions. P_S can be determined from the cross section of these two linear functions(see Fig. 3) and the sensitivity of this method to determine P_S increases as Δ approaches 0 or 180° .

$$\Theta_4(P') = \frac{1}{2}\tan^{-1}\left(\frac{\beta'_4}{\alpha'_4}\right) \approx 2C_S + A + \cot\Psi\cos\Delta(P' - P_S) \qquad P' \approx P_S. \tag{3a}$$

$$\Theta_4\left(P' + \frac{\pi}{2}\right) = \frac{1}{2}\tan^{-1}\left(\frac{\beta'_4}{\alpha'_4}\right) \approx 2C_S + A + \tan\Psi\cos\Delta(P' - P_S) \qquad P' \approx P_S + \frac{\pi}{2} \tag{3b}$$

This method is similar to the phase calibration method developed by De Nij et al. for RAE(3) and complementary to the previous one.



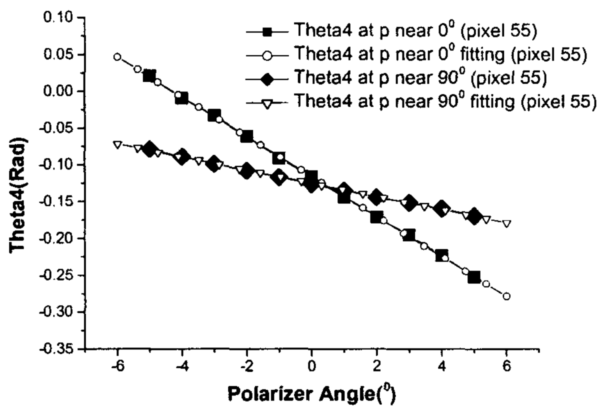


Fig. 2 (left) R_2 values obtained from two different photon energies. Crystalline silicon was used for measurement.

Fig. 3 (right) Θ_4 values measured at two different polarizer zones. Crystalline silicon was used for measurement.

The problem associated with the second method is the lengthy time required to measure at two different zones. Thus we propose spectroscopic Θ_4 method, in which P_S can be obtained from two linear function of Θ_4 corresponding two different photon energies collected at a single zone.

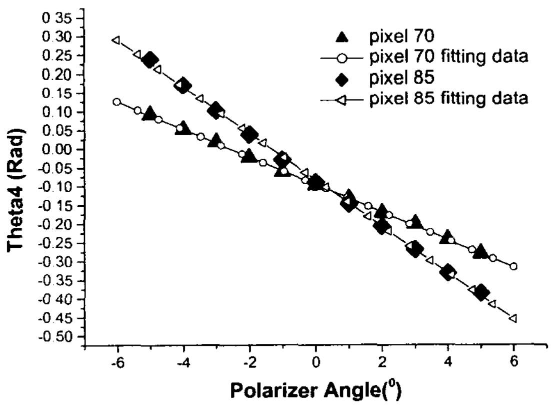


Fig. 4 Θ_4 values corresponding two different photon energies measured at a single polarizer zone.

As we employs multichannel detection system, there is no loss of measurement time. The result is as good as obtained from two zone method(compare Fig. 3 and Fig. 4).

Once P_S is obtained A and C_S can be determined from $\Theta_4(P_S)$ and following Θ_2.

$$\Theta_2 = \frac{1}{2}\tan^{-1}\left(-\frac{\alpha'_2}{\beta'_2}\right) = -(C_S + A) \tag{4}$$

Another method we propose to get P_S is intensity calibration. If we set the polarizer transmission axis close to 0° (or 90°) relative to the plane of incidence, I(t) in Eq. (1) can be approximated as following,

$$I_0(A) \sim -|r_p|^2 (A' - A_S)^2 + C_0, \quad \text{when } A \sim 0°, P \sim 0° \tag{5a}$$

$$I_0(A) \sim |r_s|^2 (A' - A_S)^2 + C_1, \quad \text{when } A \sim 0°, P \sim 90° \tag{5b}$$

, where $C_{0(1)}$ is a constant. These are parabolic functions of analyzer angle A and thus A_S is found from parabolic fitting of measured intensities. In this method, setting the polarization axis close to the plane of incidence (POI) is not that difficult because POI does not vary much from one measurement to another. Similar expressions to get P_S can be deduced if we switch A and P.

4 Summary

We developed rotating compensator type spectroscopic ellipsometry. Many calibration methods were briefly discussed. Spectroscopic single zone phase function method and intensity calibration method were proposed.

Acknowledgment

This work was supported by grant No. (2000-1-11400-008-2) from the Basic Research Program of the Korea Science & Engineering Foundation.

References

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(3) See references in *Ellipsometry* (in Korean) written by Ilsin An, Hanyang University Press, 2000
(4) More detailed description of the system will be presented somewhere else.