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In situ calibration technique for photoelastic modulator in ellipsometry

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Abstract

The modulation amplitude of a phase modulator is calibrated under a fixed incident angle in photoelastic modulation (PEM) ellipsometry. In addition to its modulation amplitude (Δ_o), we also calibrated its static phase retardation at 632.8 nm. The ellipsometric parameters of a sample were measured by a multiple harmonic intensity ratio technique and proved that ellipsometric parameters can be obtained under various modulation amplitudes. Since the physical size of PEM is constant, we calibrated the modulation amplitude at multiple wavelengths by setting the Δ_o value at 0.383 for 568.2 nm. These calibrations provided enough information for establishing an in situ/real time spectroscopic ellipsometry.

Keywords: In situ; Calibration; Photoelastic modulator; Ellipsometry

1. Introduction

Since photoelastic modulation (PEM) can provide a resonance frequency for synchronous detection, PEM ellipsometry is able to measure the optical properties in real time [1] with minimum background noise. Other than the synchronous detection, there is no moving part in PEM ellipsometry; the parasitic error caused by the beam deviation in rotating polarizer/analyzer ellipsometry [2] is also eliminated. However, in contrast to the rotating element set-ups, the modulation amplitude of PEM has to be adjusted precisely to the zero point of the zero order Bessel function in order to obtain accurate measurements with PEM ellipsometry [3]. Following the study of the alignment technique for PEM ellipsometry at a fixed incident angle [4], we calibrate, in this work, the phase modulation amplitude of PEM in situ for checking the scale provided by the vendor. This calibration technique is achieved by using the multiple harmonic intensity ratios (MHIR), which are obtained from the Fourier analysis of a data acquisition system (DAQ). In this technique, four harmonics are used, which are not available in the conventional lock-in amplifier; the advantage of using the DAQ is clearly demonstrated. In the theoretical analysis, the MHIR (1f/3f and 2f/4f) proved to be independent of the sample's characteristics and the azimuth positions of the optical components. Since the signal to noise ratio can be influenced by a weak signal, two experimental set-ups (a reflection style and a transmission style) are not only used to determine the phase modulation but also to investigate the frequency response of this technique. By comparing the digitized oscilloscope waveform of half-wave retardation, we found a 4% offset in the display.

Other than using the modulation amplitude at $J_o(\delta_o)=0$ for various wavelengths [3], we proved that the ellipsometric parameters can be measured under any phase modulation amplitude. By setting the phase modulation amplitude at 0.383 for 568.2 nm, we determined the modulation amplitude at other wavelengths by the multiple harmonic intensity ratio technique; the results are well fitted to the invariant relation of the product of modulation amplitude and the wavelength, i.e. the physical thickness of the PEM cell. These calibrations provide enough information for constructing an in situ/real time spectroscopic ellipsometry.

2. Theoretical background

The basic set-up of the PEM ellipsometry is shown in Fig. 1. The ellipsometric parameters Ψ and Δ are defined as follows

$$\tan\Psi e^{i\Delta}=\frac{r_p}{r_s}, \tag{1}$$

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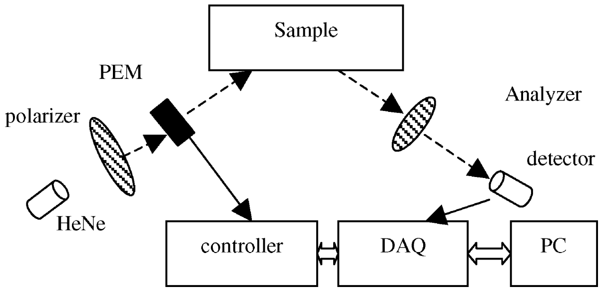

Fig. 1. The schematic set-up of PEM ellipsometry.

where r_p and r_s represent the complex reflection coefficient of parallel and perpendicular components of polarized light. If the azimuth angle of the initial linear polarized light is set at −45°, the measured intensity can be simplified as

$$I(A)=0.5I_0\left[\sin^2 A+\tan^2\Psi\cos^2 A - \tan\Psi\sin 2A(\cos\Delta\cos\Delta_p+\sin\Delta\sin\Delta p)\right]. \qquad (2)$$

Since the phase retardation of PEM is modulated as $\Delta_p=\delta_o\sin\omega t$, one can substitute the Fourier expansions of the harmonic functions into Eq. (2), and obtain the following relations between the measured intensity and its corresponding harmonic component:

$$I_{dc}(A)=0.5I_0\left[\sin^2 A+\tan^2\Psi\cos^2 A - \tan\Psi\cos\Delta J_o(\delta_o)\sin 2A\right],$$

$$I_{(2m+1)f}(A)=-I_0\left[\tan\Psi\sin\Delta J_{(2m+1)}(\delta_o)\times\sin 2A\right]\sin(2m+1)\omega t;\quad m=0,$$

$$1I_{2nf}(A)=-I_0\left[\tan\Psi\cos\Delta J_{2n}(\delta_o)\sin 2A\right]\times\cos 2n\omega t;\quad n=1,2 \qquad (3)$$

It is very interesting to notice that the even/odd harmonics are related by the similar physical parameters except for the orders of its Bessel function. By using the intensity ratio technique, we can determine the modulated amplitude of PEM but avoid the effect of its physical set-up, i.e.

$$\frac{I_{1f}}{I_{3f}}=\frac{J_1(\delta_o)}{J_3(\delta_o)};\quad \frac{I_{2f}}{I_{4f}}=\frac{J_2(\delta_o)}{J_4(\delta_o)}. \qquad (4)$$

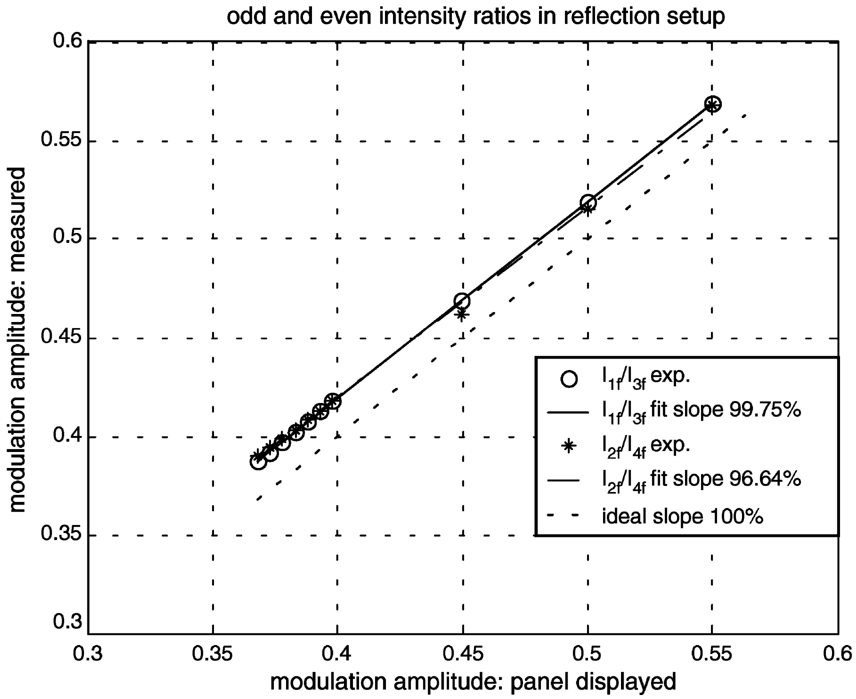

Fig. 2. The calibration of modulation amplitude in the reflection set-up: both odd (○) and even (*) intensity ratios are measured, the ideal line is when measured values = displayed values.

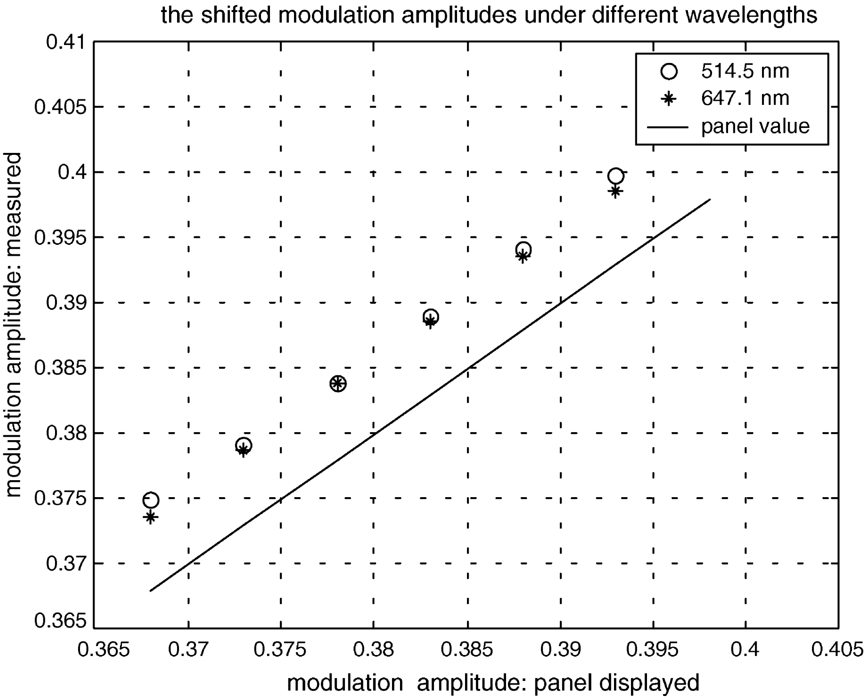

Fig. 3. The calibration of modulation amplitude under different wavelengths: 514.5 nm (○), 647.1 nm (*) and panel displayed values (line).

It is obvious that these ratios are independent of the azimuth position of the analyzer and the physical parameters of the examined sample. Furthermore, this multiple harmonic intensity ratio technique can also be used to determine the ellipsometric parameters Ψ and Δ. That is by setting $A = \pm 45°$, in the following expressions

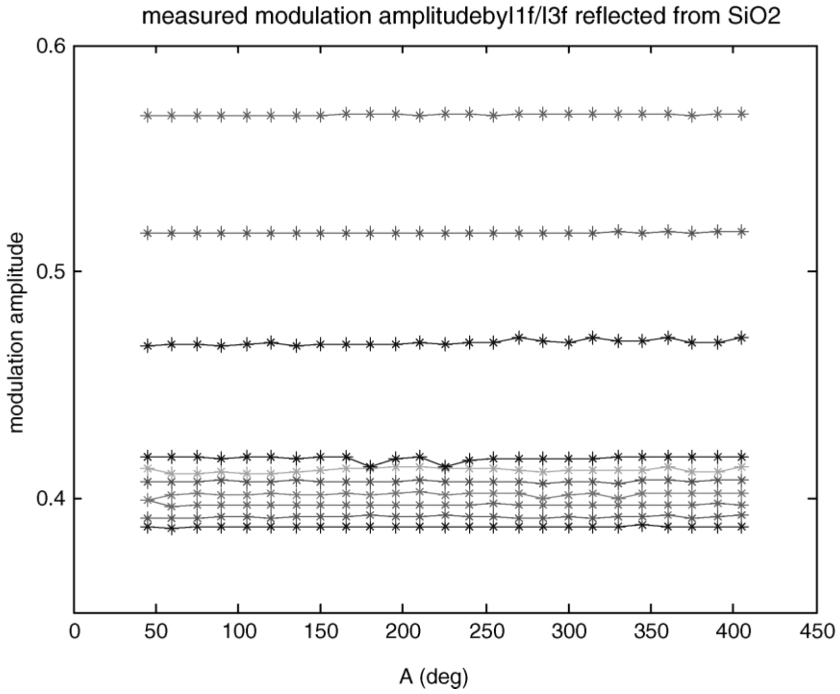

Fig. 4. The modulation amplitude distribution vs. azimuth position of analyzer: The intensity ratios of 1f/3f are measured in the reflection setup. A SiO_2 thin film of 365 Å is measured at the incident angle of 70°

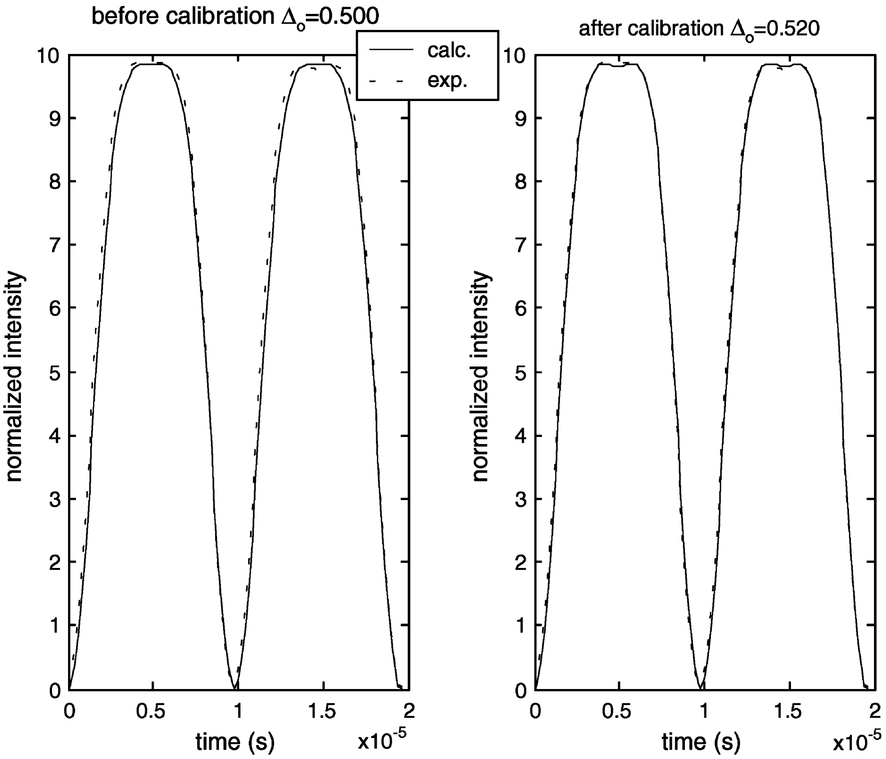

Fig. 5. The digitized oscilloscope waveform of half-wave retardation in the transmission setup: $P=-45°$ and $A=45°$; the solid line are the calculated waveform of 0.50λ (right) and 0.52λ (left).

$$\sin 2\Psi=\frac{\sqrt{\left(\frac{I_{1f}(45°)}{J_1(\delta_o)}\right)^2+\left(\frac{I_{2f}(45°)}{J_2(\delta_o)}\right)^2}}{I_{dc}(45°)+I_{dc}(-45°)},$$

$$\tan\Delta=\frac{I_{1f}(45°)J_2(\delta_o)}{I_{2f}(45°)J_1(\delta_o)}, \qquad (5)$$

one can obtain Ψ and Δ independently. The static phase retardation (Δ_i) of PEM is embedded in the ellipsometric parameter of Δ, which can be confirmed by transmission ellipsometry. The temporal intensity distribution of the P-PEM-A setup can be written as

$$I(t)=I_0\left[1-\cos(\Delta_i+\delta_o\sin\omega t)\right], \qquad (6)$$

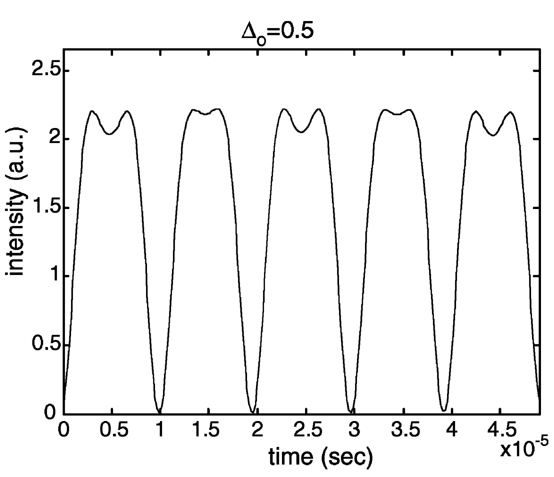

Fig. 6. The digitized oscilloscope retardation waveform of half-wave retardation at $P=45°$ and $A=-45°$

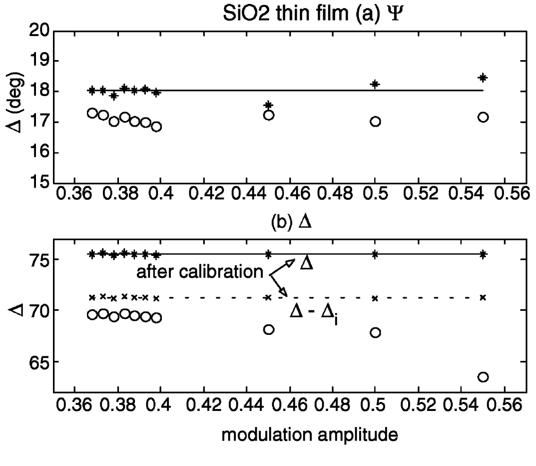

Fig. 7. The ellipsometric parameters vs. the modulation amplitudes: A SiO_2 thin film of 365 Å is measured at the incident angle of 70° and $\lambda=632.8$ nm. (a) Ψ: before calibration (○) ; after calibration (*); (b) Δ: before calibration (○) ; after calibration (×) ; after introduce the static phase retardation (*).

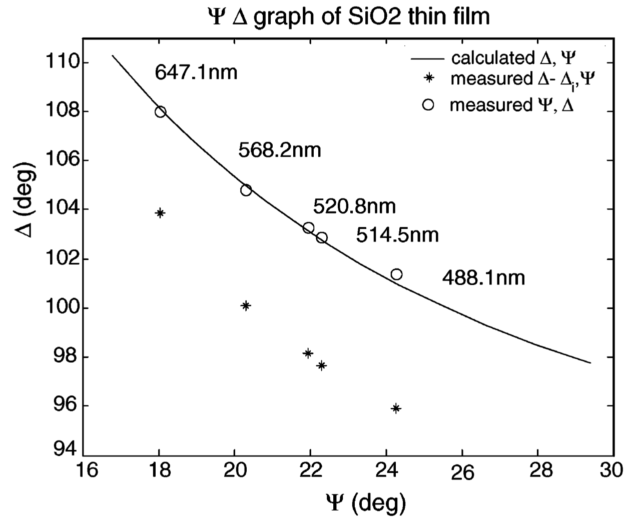

Fig. 8. Ψ and Δ graph of SiO_2 thin film at the incident angle of 70° with the discrete wavelengths of a KrAr tunable laser.

if $P=45°$ and $A=-45°$ This waveform can be compared with the digitized oscilloscope waveform obtained by the DAQ system. The Fourier expansion of the intensity at $P=45°$, namely the multiple harmonics, can be expressed as

$$I_{mf}(A) = -I_0\left[\sin\Delta_i J_m(\delta_o)\sin 2A\right]\sin m\omega t \quad m=1,3$$

$$I_{nf}(A) = I_0\left[\cos\Delta_i J_n(\delta_o)\sin 2A\right]\cos n\omega t; \quad n=2,4. \tag{7}$$

The static phase retardation can be obtained by taking multiple harmonic ratios. According to Eq. (5), one can measure the ellipsometric parameters at any modulation amplitude. Since in an in situ/real time ellipsometric system, all the physical settings, such as azimuth of polarizer, optic axis of PEM, incident angle and the modulation amplitude of PEM should be fixed. For spectroscopic measurement, the modulation amplitude should be set at a particular wavelength, i.e. $\Delta_o\lambda_o=$ constant, the corresponding modulation of different wavelengths should be calculated instead of resetting the system.

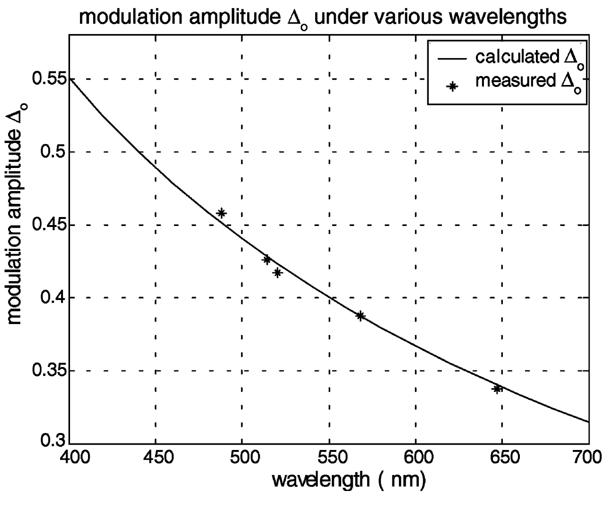

Fig. 9. The modulation amplitude of PEM vs. wavelengths, by setting $\Delta_o=0.383$ at $\lambda=568.2$ nm.

3. Experimental details

A data acquisition system (NI PCI-6111) was used in the PEM (Hinds PEM90/CF50) ellipsometry; for comparison, we chose a SiO_2/Si thin film of 365 Å thickness at the incident angle of 70°, whose Δ was closer to 90° as with the testing sample. We systematically aligned all the azimuth positions by a fixed incident angle alignment technique; then set the strain axis of PEM at 0°, with P and A at $-45°$ and 45°, respectively. The amplitude of modulation was varied from 0.368 to 0.550λ with closer steps approximately 0.383λ, under the following wavelengths of a KrAr tunable laser: 647.1, 568.2, 520.8, 514.5 and 488.0 nm. In addition to the d.c. component, four more harmonic intensities were obtained. After deducing the modulation amplitudes by using the intensity ratios of I_{1f}/I_{3f} (odd-ratio) and I_{2f}/I_{4f} (even-ratio), we then compared it with the display provided by the vendor. This intensity ratio technique was also employed to measure the modulation amplitude at various wavelengths by setting the modulation amplitude at 0.383λ for 568.2 nm. By studying the static retardation, a transmission set-up was measured with a HeNe laser wavelength of 632.8 nm; the digitized oscilloscope waveforms of half-wave retardation were recorded and analyzed.

4. Results and discussion

The modulation amplitudes of PEM were obtained from the multiple harmonic intensity ratios, as shown in Fig. 2; the modulation amplitudes are parallel shifted from the displayed value by 0.02λ and the slope of I_{1f}/I_{3f} is almost equal to 1, since $\cos\Delta<\sin\Delta$ of a SiO_2 thin film at the incident angle of 70°. To avoid the effect of weak signal, we used the odd intensity ratio to measure the sample under reflection. By comparing the modulation amplitudes at different wavelengths, we found that the shifted values are the same, such as shown in Fig. 3. The modulation amplitudes were also measured under various azimuth positions of the analyzer, and just as expected from Eq. (4), the modulation amplitude determined by this intensity ratio technique was independent of the analyzer's azimuth position, as shown in Fig. 4. In the transmission setup, with $P=-45°$ and $A=45°$, the digitized oscilloscope waveform of half-wave retardation were compared with the theoretical waveform of

0.50 and 0.52λ retardation, respectively, such as shown in Fig. 5. However, a clear asymmetry occurred, as $P=45°$ and $A=-45°$; this is shown in Fig. 6. This phenomenon can be explained by the existence of static retardation in PEM [5]. After considering the static retardation, we found that the measured ellipsometric parameters of a standard SiO_2 thin film under various wavelengths were well fitted to its calculated values, as shown in Figs. 7 and 8. Values of static retardations other than at 632.8 nm are calculated by neglecting its dispersion. A standard calibration process is proposed to calibrate the modulation amplitude of PEM, which can be carried out without changing the operation setup. The main purpose of our research is trying to establish multiple wavelength ellipsometry for in situ/real time measurements, the modulation amplitude has to be set as a constant for a particular wavelength in the process of measurement. Since the physical path of PEM is invariant, the modulation amplitude should be inversely proportion to the wavelength; by taking the modulation amplitude at 0.383λ for 568.2 nm, we calculated the corresponding modulation amplitude for other wavelengths, and the measured values are well fitted to our expectation, as shown in Fig. 9. After this calibration, we believe there is enough information for the construction of an in situ/real time spectroscopic ellipsometry.

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