A compact in-situ ellipsometer using the liquid crystal variable retarder

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ABSTRACT

For monitoring the optical properties of material under a dynamical processing, we design a compact in-situ ellipsometry by using a liquid crystal (LC) phase retarder. Since the key issue of an accurate ellipsometer is the alignment of each optical component in the system, hence we not only proposed the alignment procedure, we also calibrated the phase retardation of LC retarder for this in-situ ellipsometry. The azimuths of polarizers and phase retarders can be aligned by the analytical solutions of the azimuthal deviations. The phase retardation can be directly determined by the intensity ratio technique.

Keywords: Ellipsometry, in-situ ellipsometer, liquid crystal variable retarder.

1. INTRODUCTION

The ellipsometry features mainly in characterizing the optical properties of materials, such as the complex refraction indices, thickness, and surface roughness [1-4]. The main advantages of applying the ellipsometry in material science are its non-contact scheme, thus it is suitable to measure various samples nondistructively, i.e., bulk materials, liquids, the surfaces of solids, and multi-layered thin films [5]. A fast in-situ ellipsometric system is helpful in monitoring a dynamical procedure, such as monitoring in the film deposition or etching system. The photoelastic modulator has been widely used in real time ellipsometric system [6-7] to monitor the dynamic process. Recently, because the fast development in display industry, both the price and the quality of liquid crystal (LC) phase retarder have been improved. Since the LC phase retarder is much cheaper than the photoelastic modulator (PEM), and its switching time can reach 10 ms. We thus propose to insert an LC variable retarder, instead of PEM, in the traditional polarizer-sample-analyzer reflective ellipsometric system, this can form an ellipsometer without any mechanical rotation. By applying the different voltage in LC retarder to control the phase retardation, we can obtain the ellipsometric parameters by calculation, thus obtain the optical parameters of sample.

In this paper, we present a compact LC based in-situ ellipsometer, which reduces the cost of the system. Utilizing the LC variable retarder, the polarization state of the reflective beam can be changed within 10 milliseconds; this feature can employ the ellipsometer for real-time measurements. To implement the LC based ellipsometry for its required accuracy, the alignment procedure of the optical system, including the polarizer, analyzer and LC retarder have been discuss and demonstrated. The phase retardation of the LC retarder as a function of the applied voltage was also characterized by our calibration method. The theoretical formulation of the proposed alignment and calibration procedures were described in detail.

2. OPTICAL SETUP OF OUR IN-SITU ELLIPSOMETRY

The compact LC based in-situ ellispsometric system is shown in Figure 1. He-Ne laser, the light source, passes through a polarizer and reflects from the sample. Then, the reflected light passes through a LC phase retarder, a quarter-wave plate and an analyzer. The detector is located at output plane for measuring the output intensity; a polarizer-sample-LC retarder-quarter wave plate-analyzer (PSLQA) system is setup for ellipsometric measurements. The angle between the

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transmission axis of the polarizer and x-axis is 45 degree. The optic axes of the LC retarder and the quarter wave plate are along x-axis and 45 degree to x-axis, respectively. The transmission axis of the analyzer is along y-axis.

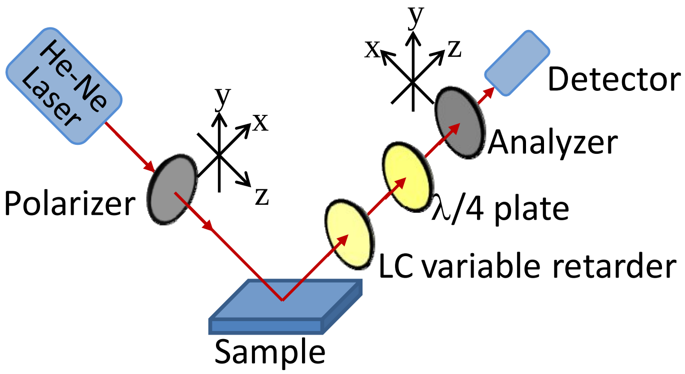

Figure 1. The architecture of optical ellipsometry with LC variable retarder.

The ellipsometric parameters ψ and Δ are defined with $r_p / r_s = \tan\psi\, e^{i\Delta}$, in which r_p and r_s are the reflection coefficients of the linearly polarized states parallel and perpendicular to the incident plane, respectively [1]. According to the optical setup in Figure 1, assume that the intensity of the incident beam is I_0, then the output beam intensity can be derived as the follows,

$$I(\phi) = \frac{I_0}{4}\left[\sec^2\psi - 2\sin(\phi+\Delta)\tan\psi\right], \tag{1}$$

where ϕ is the phase retardation of the LC retarder, which is controlled by the applied voltage of the LC phase retarder. By measuring the output intensities with three different phase retardations, i.e. ϕ = 180°, 120°, and 60°, then the ellipsometric parameters (ψ, Δ) of the sample can be obtained from the following equations,

$$\Delta = \tan^{-1}\left(\sqrt{3}X\right),\ \psi = \frac{1}{2}\sin^{-1}\left(\frac{Y}{\sin\Delta}\right),$$
$$\text{where } X = \frac{I(120)-I(60)}{2I(180)-3I(120)+I(60)} \text{ and } Y = \frac{I(120)-I(60)}{I(180)-I(120)+I(60)}\ . \tag{2}$$

Once we obtain the ellipsometric parameters from Eq. (2), the optical properties of the sample can be calculated, i.e. the complex refractive index and the thickness. However, only three output intensities have to be detected, which is so-called the three intensity technique. The measurement time is dependent on the response time of the LC phase retarder. In our case, the switching frequency of the LC phase retarder (from THORLABS, part number LCC1111A) is about 100Hz [8]. Thus, our LC based ellispsometric system can be used for in-situ measurement and the response time can reach 100ms.

3. ALIGNMENT PROCEDURE OF THE ELLIPSOMETRIC SYSTEM

The alignment and calibration procedure of ellipsometry are essential issues for the required accuracy in ellipsometry. Hence, we proposed the alignment procedure of the ellipsometer. In this procedure, the azimuths of optic components are aligned in sequence, and then the phase retardation of the LC retarder also can be determined by our method. Figure 2 shows the flowchart of alignment procedures. There are five steps are needed to align each optical element in this ellipsometric system. For Step 1 and 2, the polarizer and analyzer can be well aligned to the incident plane by the analytical solutions of the azimuthal deviation in a polarizer-sample-analyzer (PSA) system. Next, the optic axis of the quarter wave plate is aligned with the polarizer-sample-quarter wave plate-analyzer (PSQA) system in Step 3 of Figure 2. Finally, the LC retarder can be aligned and calibrated by the PSLQA system in Step 4 and 5.

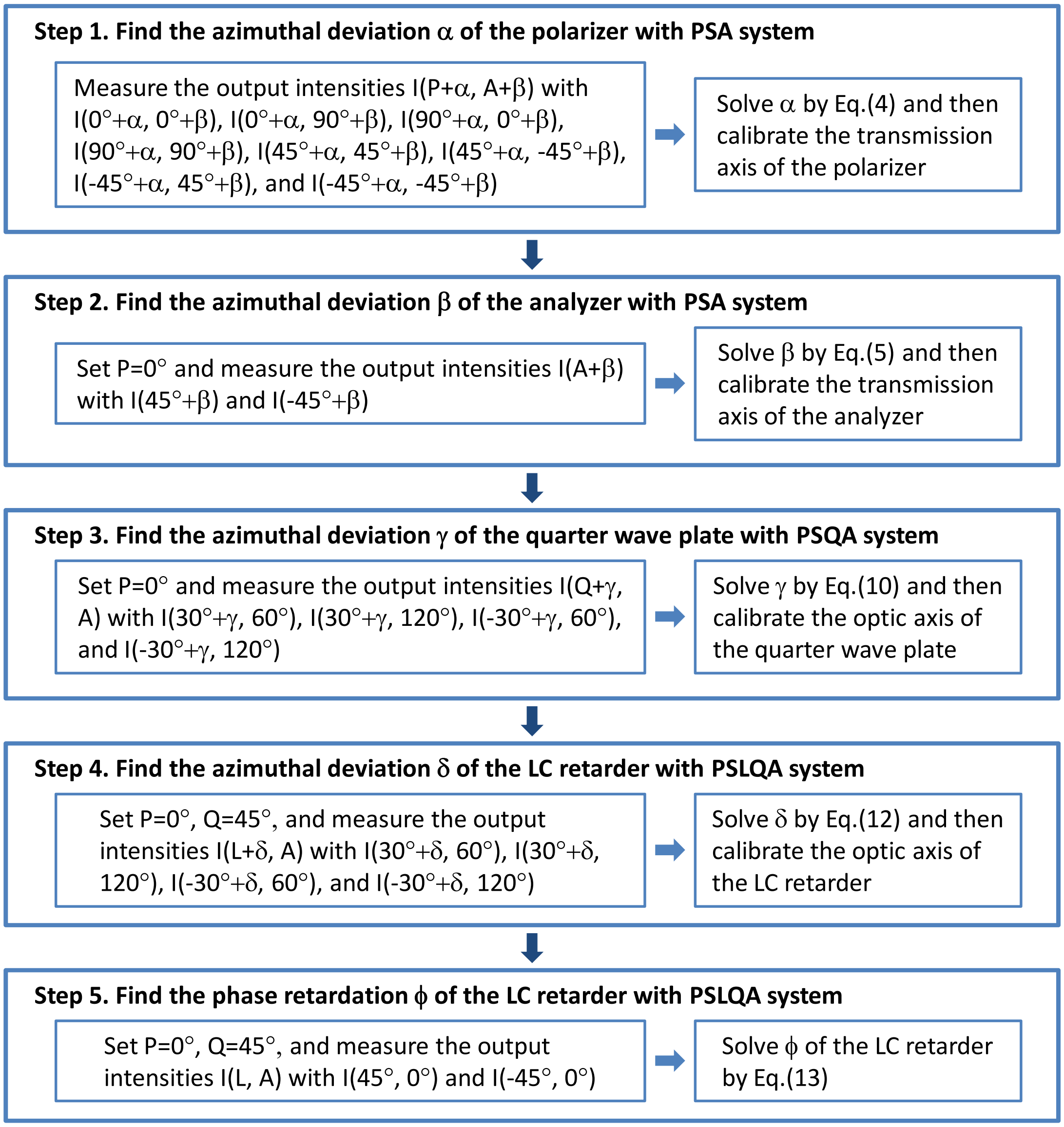

Figure 2. The flowchart of the calibration procedure of the ellipsometer.

In Figure 2, the symbols P, L, Q, and A are represented the azimuths of the polarizer, LC retarder, quarter wave plate, and analyzer, respectively. Assume that the azimuthal deviation angles corresponding to the polarizer, LC retarder, quarter wave plate, and analyzer are α, β, γ, and δ, respectively, and the phase retardation of the LC retarder is ϕ. Following the alignment processes summarized in Figure 2, those azimuthal deviation angles of each optical element, α, β, γ, δ, and ϕ all can be figured out. All steps of the alignment procedure are developed from the analytical solutions of the azimuthal deviation and the phase retardation, according to the relating optic system. The theoretical formulations of the alignment procedures are described in the following sections.

3.1 Alignment of the polarizer and analyzer

First, we setup the PSA system to align the polarizer and analyzer. Assume the azimuthal deviation of P and A are α and β, respectively, thus the azimuths of the polarizer and analyzer are P+α and A+β. The output intensity of the PSA system can be expressed with

$$\begin{aligned} I(P+\alpha, A+\beta) = I_0 \Big[&\frac{1}{2}\cos\Delta \sin 2(P+\alpha)\sin 2(A+\beta)\tan\psi + \sin^2(P+\alpha)\sin^2(A+\beta) \\ &+ \cos^2(P+\alpha)\cos^2(A+\beta)\tan^2\psi \Big]. \end{aligned} \tag{3}$$

To calibrate the polarizer, we start from the intensities measured with the selected the azimuths combinations of P and A. The azimuthal combinations are shown in Step 1 in Figure 2. The azimuthal deviation α can be deduced by

$$\tan 2\alpha = \frac{I(-45^\circ+\alpha,-45^\circ+\beta) - I(45^\circ+\alpha,45^\circ+\beta) + I(-45^\circ+\alpha,45^\circ+\beta) - I(45^\circ+\alpha,-45^\circ+\beta)}{I(0^\circ+\alpha,0^\circ+\beta) - I(90^\circ+\alpha,90^\circ+\beta) + I(0^\circ+\alpha,90^\circ+\beta) - I(90^\circ+\alpha,0^\circ+\beta)}. \tag{4}$$

After adjusting the azimuth of the polarizer to −α, we can calibrate the analyzer by measuring the intensities with P = 0°, A = 45°+β and −45°+β. The azimuthal deviation β can be obtained by the following formula

$$\sin 2\beta = \frac{I(0^\circ,-45^\circ+\beta) - I(0^\circ,45^\circ+\beta)}{I(0^\circ,-45^\circ+\beta) + I(0^\circ,45^\circ+\beta)}. \tag{5}$$

According to Eqs. (4) and (5), the transmission axes of the polarizer and analyzer can be calibrated by performing Step 1 and Step 2 of Figure 2 in sequence.

3.2 Alignment of the quarter wave plate

After the alignment of the polarizer and analyzer, the quarter wave plate is added into the PSA system to form the PSQA system. Furthermore, if the LC retarder is added into PSQA system and it is so called PSLQA system. Then, the LC retarder can be calibrated by the PSLQA system. The output intensity of both PSQA and PSLQA systems can be written as a general elliptical distribution,

$$I(A) = B\cos^2 A + C\sin^2 A + D\sin 2A. \tag{6}$$

The parameters B, C, and D are functions of P, L, Q, A, ϕ, and (ψ, Δ) of the sample. The functions are determined by the setup of the corresponding optical system. The three output intensities measured at A = 0°, 60°, and 120° can be used to solve the parameters B, C and D of Eq. (6) by

$$B = I(0),\ C = \frac{2I(60) + 2I(120) - I(0)}{3},\ D = \frac{I(60) - I(120)}{\sqrt{3}}. \tag{7}$$

Considering the alignment of the quarter wave plate, the output intensity of a PSQA system can be described by Eq. (6) with

$$\begin{aligned} B &= \frac{1}{2}\Big[\sin^2 2Q\sin^2 P + \left(2-\sin^2 2Q\right)\cos^2 P\tan^2\psi + \sin 2P\sin 2Q\left(\cos\Delta\cos 2Q + \sin\Delta\right)\tan\psi\Big], \\ C &= \frac{1}{2}\Big[\left(2-\sin^2 2Q\right)\sin^2 P + \sin^2 2Q\cos^2 P\tan^2\psi - \sin 2P\sin 2Q\left(\cos\Delta\cos 2Q + \sin\Delta\right)\tan\psi\Big], \\ D &= \frac{1}{4}\Big[\left(\cos 2P - 1\right)\cos 2Q\sin 2Q + \left(\cos 2P + 1\right)\cos 2Q\sin 2Q\tan^2\psi \\ &\quad + 2\sin 2P\left(\cos\Delta\sin^2 2Q - \sin\Delta\cos 2Q\right)\tan\psi\Big]. \end{aligned} \tag{8}$$

To deduce the azimuthal deviation of Q by setting P = 0°, Eq. (8) can be further simplified to be

$$\tan^2\psi = \frac{4D}{\sin 4Q}. \tag{9}$$

Assume that the azimuthal deviation of the quarter wave plate is γ and then expand the analytic Eq. (9) as follows:

$$\text{When } Q = 30° + \gamma \quad \Rightarrow \quad \tan^2\psi = 8D_1 \Big/ \left(-\sin 4\gamma + \sqrt{3}\cos 4\gamma\right), \tag{10.a}$$

$$\text{When } Q = -30° + \gamma \quad \Rightarrow \quad \tan^2\psi = 8D_2 \Big/ \left(-\sin 4\gamma - \sqrt{3}\cos 4\gamma\right). \tag{10.b}$$

where D_1 and D_2 are the corresponding parameters at Q = 30°+γ and Q = –30°+γ, respectively. The deviation γ can be obtained by taking the ratio of Eqs. (10.a) and (10.b), and therefore the optic axis of the quarter wave plate can be aligned by executing the Step 3 shown in Figure 2.

3.3 Alignment of the LC variable retarder

After aligning the λ/4 plate, the azimuth of the LC retarder can be calibrated under the PSLQA system. By setting Q = 45°, the corresponding parameters of the output intensity can be written in the form of Eq. (6), except the corresponding parameters are

$$\begin{aligned}
B &= \frac{1}{4}\Big[(1-\cos 2P)(1+\sin 2L\sin\phi) + (1+\cos 2P)(1-\sin 2L\sin\phi)\tan^2\psi \\
&\quad +2\sin 2P\left(\cos\Delta\cos 2L\sin\phi + \sin\Delta\cos\phi\right)\tan\psi\Big], \\
C &= \frac{1}{4}\Big[(1-\cos 2P)(1-\sin 2L\sin\phi) + (1+\cos 2P)(1+\sin 2L\sin\phi)\tan^2\psi \\
&\quad -2\sin 2P\left(\cos\Delta\cos 2L\sin\phi + \sin\Delta\cos\phi\right)\tan\psi\Big], \\
D &= \frac{1}{4}\Big[(\cos 2P-1)\cos 2L\sin 2L(1-\cos\phi) + (\cos 2P+1)\cos 2L\sin 2L(1-\cos\phi)\tan^2\psi \\
&\quad +2\sin 2P\left(\cos\Delta\left(\cos^2 2L\cos\phi + \sin^2 2L\right) - \sin\Delta\cos 2L\sin\phi\right)\tan\psi\Big].
\end{aligned} \tag{11}$$

Set P = 0°, we can obtain

$$\tan^2\psi = \frac{4D}{(1-\cos\phi)\sin 4L}. \tag{12}$$

The azimuthal deviation of LC retarder δ can be obtained by the same method of the quarter wave plate, which is the Step 4 in Figure 2. Notably, the D parameters at L = 30°+δ and L = –30°+δ should be measured at a fixed phase retardation ϕ, which ensures the cancellation of the term $(1-\cos\phi)$ in the intensity ratio.

3.4 Calibration of the retardation of the LC retarder

After aligning the azimuth of the LC retarder, the retardation ϕ can be determined. As P = 0° and Q = 45°, one can prove that

$$\tan^2\psi = \frac{2B}{1-\sin 2L\sin\phi}. \tag{13}$$

By measuring the B parameters at L = 45° and L = –45° with a fixed ϕ, substituting the resultant B and L into Eq. (13), and then taking the ratio, the retardation can be analytically solved. The process to deduce the retardation is described in Step 5 of Figure 2. Since ϕ depends on the driving voltage and temperature, this calibration process can benefit the direct measurement of the exact phase retardation needed in the LC based ellipsometry.

4. OPTICAL CHARACTERISTIC OF LIQUID CRYSTAL PHASE RETARDER

After performing the alignment procedure of the ellipsometric system, the optical properties of the LC phase retarder can be characterized in experimental. Since the phase retardation of the LC retarder is controlled by the driving voltage, the variation of phase retardation induced by changing the voltage was measured at the room temperature of 23.2°C. The experimental result presented in Figure 3. It shows that the phase retardation decreases from 220 degree to 10 degree as the voltage increasing from 0 V to 10 V. Since the phase retardation provided by the LC retarder depends on the temperature, the voltage related to a desired retardation might change. However, owing to the experimental retardation-voltage curve, the driving voltages corresponding to retardations of 180°, 120° and 60° needed in our ellipsometer can be obtained quickly. By measuring the phase retardations of two selected applied voltages around the target retardation, the driving voltage can be calculated by interpolation. To decide the voltages of the three target retardations, 6 data points of measurement are enough, which is easy to carry out before the experiment, this technique can ensure the minimization of system errors.

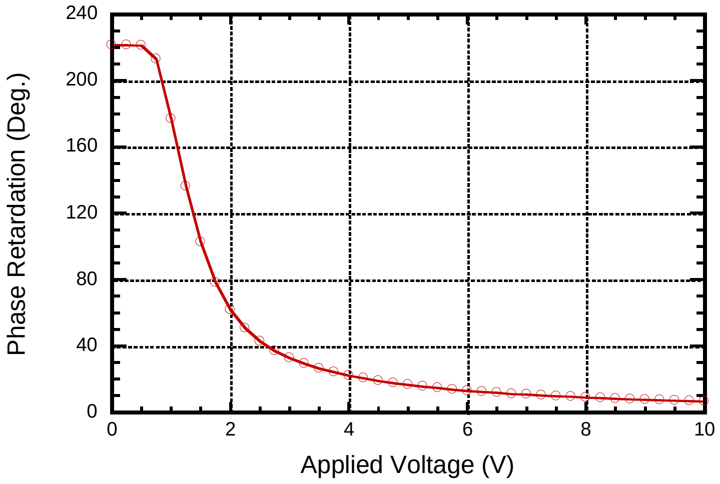

Figure 3. Experimental measurement for the phase retardation of the LC variable retarder as the function of applied voltage.

5. CONCLUSION

In this paper, we demonstrated the alignment and calibration procedure for a compact liquid crystal (LC) based in-situ ellipsometer. The LC variable retarder used in the ellipsometer provides fast switching for phase retardation, which can be employed in the real-time measurements. To implement our ellipsometry, the alignment and calibration procedure of the optical system, including the polarizer, analyzer, quarter wave plate and LC retarder has been discussed and demonstrated. We also proposed a direct determination technique for the phase retardation of LC variable retarder; this can improve the performance of the ellipsometer in its precision, efficiency and reliability.

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