Investigation the use of rotating linearly polarized light for characterizing SiO_2 thin-film on Si substrate

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ABSTRACT

This research is based on the Fresnel's equations and the ellipsometric technique that investigate the sample of SiO_2 thin-film on Si substrate. The investigation is made by a probing beam which is in the form of a rotating linearly polarized light generated by the polarizing Mach-Zehnder interferometer (pMZi). The detection of the changed polarization states of the incident light due to reflection on the sample surfaces led to a set of unique characteristics describing a thin-film substrate system in terms of ellipsometric parameters ψ and Δ. SiO_2 thin-films were chosen to study because of their well known characteristics. The accuracy of measurements was confirmed by comparisons to calculated values derived from Fresnel's equations and a standard instrument. The results clearly reveal a feasibility of using the rotating linearly polarized light produced by pMZi for a non-destructive characterization of the thin-film system.

Keywords: Ellipsometric technique, ellipsometric parameters, rotating linearly polarized light, polarizing Mach- Zehnder interferometer.

1. INTRODUCTION

The ellipsometry is a well-known optical technique widely used as an analytical scheme for characterizing optical constants of optical surfaces and thickness of thin-films. The technique is based on the detection of the polarization change of the reflected light due to a thin-film substrate. The technique normally employs a linear polarized light as a probing beam whose azimuth can be controlled by various means such as a rotating polarizer [1], a rotating half wave retarder [2], acoustooptic cells [3] and interferometric arrangement [4 -6]. In this study, the polarizing Mach-Zehnder interferometer (pMZi) was arranged to generate the rotating linearly polarized light. The azimuth of the light was controlled via the phase modulation technique. Based on the combination of the interferometry and the ellipsometry, a simple scheme for the thin-film characterization was carried out. Two specific orientations, parallel and perpendicular, of the reflected beam could clearly be identified by a reference signal provided by the set up. The extracted data in terms of intensities from the reflected signal and the appropriately rearranged Frenel's equations for the thin-film substrate system allow the determination of the ellipsometric parameters ψ and Δ which, in turn, can be used to characterize the thin-film sample under investigation.

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2. THEORETICAL BACKGROUND

The system under investigation in this study is a substrate covered by a single layer thin film (Fig.1). The reflection coefficients of the system according to the Fresnel reflection is given by [7]

$$r_\nu = \frac{r_{01\nu} + r_{12\nu}\exp(-2i\beta)}{1 + r_{01\nu}r_{12\nu}\exp(-2i\beta)}, \qquad \nu = p,\ s \tag{1}$$

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where r_{01v} and r_{12v} are the ambient-film (0-1) and thin film-substrate (1-2) interface Fresnel reflection coefficients for parallel p and perpendicular s directions with respect to the plane of incidence. β known as the film phase thickness is functions of refractive indices N_0 and N_1 of ambient and thin film, respectively, incident angle φ_0 in the ambient, wavelength λ and film thickness d . The β is given by [8]

$$\beta = 2\pi(d/\lambda)(N_1^2 - N_0^2 \sin\varphi_0)^{1/2} \tag{2}$$

The ratio of the complex Fresnel reflection coefficients $\boldsymbol{R_p/R_s}$ is defined to be the ellipsometric function ρ . The arrangement of the ellipsometric function in terms of the ellipsometric parameters ψ and Δ is given as $\rho = \tan\psi \exp(i\Delta)$. This is evident that with the detection of the beam reflected from a particular sample at specific directions with respect to the plane of incidence, the characteristics of the sample in terms of ellipsometric parameters can be worked out.

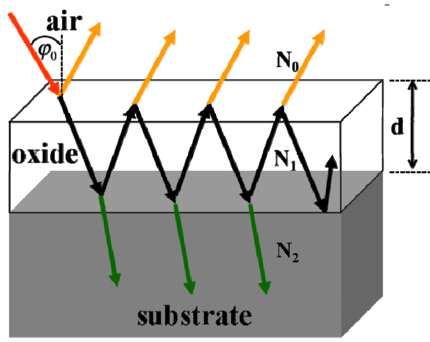


Fig. 1 Thin-film substrate system; N_0, N_1 and N_2 : refractive indices of ambient (air), film (SiO_2) and substrate (Si), respectively; φ_0 : incident angle; d : thickness.

3. METHODLOGY

Fig. 2 shows the pMZi which generates the rotating linearly polarized light.

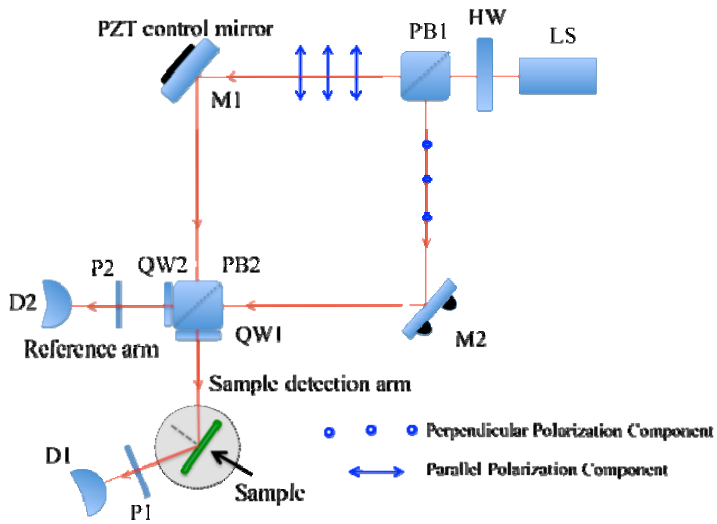


Fig. 2 This illustrates the experimental arrangement of the polarizing Mach-Zehnder interferometer which generates the rotating linearly polarized light. LS = HeNe Laser Source, HW = Half Wave retarder, PB1 = Polarizing Beamsplitter, PB2 = Polarizing Beamsplitter with Quarter Wave retarders (QW) attached at the output sides, M1,2 = Mirrors, PZT = PiezoElectric Transducer, D1,2 = PhotoDetectors.

The linear polarized light emitted from the HeNe laser (LS) can be adjusted to an appropriate direction by a half wave retarder (HW). The adjusted light beam is then equally divided into two orthogonal linearly polarized components; i.e. perpendicular and parallel, to the plane of incidence by the first polarizing beam splitter (PB1). Each beam is then guided by a mirror (M1 or M2) to the second polarizing beam splitter (PB2) where the beams recombine. The attached quarter wave retarders (QW1 and QW2) on each output side of the PB2 transform the orthogonal linearly polarized beams into two circularly polarized beams with opposite handedness. The combination of the two orthogonal circularly polarized beams results in a linearly polarized light orientated at an azimuth angle. There are two important points to mention before we proceed to the theoretical analysis of the application part. One is that the PZT controlled mirror driven by a sinusoidal signal introduces the phase modulation and causes the rotation of the resultant linearly polarized light. The other is that the outputs from the PB2 are composed of two beams; namely, the sample detection and the reference beams. Both beams are identical in terms of the polarization state but their intensities are rather different. This is because, in practice, the PB2 allows not only the major beam or high-intensity rotating linearly polarized light at the sample output side but also the minor beam or low-intensity one with exactly the same state of polarization at the reference output side. This is due to the imperfection of the polarizing beam splitter. In some optical experiments, this minor beam is probably unwanted but in this arrangement the beam becomes a benefit for a simple signal processing. Therefore, the low-intensity portion received by D2 can be used as a reference signal which acts effectively as a temporal pointer to identify states of polarization of the light detected by D1.

The detailed analysis of the pMZi can be found elsewhere [9]. In this report, the output beam which is in the form of the rotating linearly polarized is the main concern. The output beam represented in terms of Jones matrices after either QW1 or QW2 can be described as

$$E_{\text{output},\phi'} = E\begin{bmatrix}\sin\phi \\ \cos\phi\end{bmatrix}\exp\left\{i\left(\phi+\varepsilon\right)\right\} \tag{3}$$

Where E is the amplitude of the beam, ϕ is an angle associated with the azimuth of the output beam with respect to a reference and ε is an additional phase term. This should be noted that the Jones vector for both reference and sample detection signals are similar to each other except the intensity of the sample detection signal is more intense than the reference signal.

The sample under investigation is placed at one end of the outputs of the pMZi as shown in Fig. 2. The light reflection from the sample provides required information for characterizing the thin-film system in terms of the ellipsometric parameters ψ and Δ. The output beam after reflection from the sample $E_{\text{output, }\phi}^{\text{sample}}$ can simply be analyzed by Jones calculus as follows,

$$E_{\text{output, }\phi}^{\text{sample}} = P_{45} S E_{\text{output, }\phi}$$

$$= \underset{\text{Polarizer}}{\begin{bmatrix} \frac{1}{2} & \frac{1}{2} \\ \frac{1}{2} & \frac{1}{2} \end{bmatrix}} \underset{\text{Sample}}{\begin{bmatrix} r_p & 0 \\ 0 & r_s \exp(i\Delta) \end{bmatrix}} \underset{\text{Incident beam}}{\begin{bmatrix} E\sin\phi \\ E\cos\phi \end{bmatrix}} \exp\left\{i\left(\phi+\varepsilon\right)\right\} \tag{4}$$

Where P_{45} is the Jones matrix for the polarizer oriented at 45^0 with respect to the plane of incidence, S is the Jones matrix for the sample, r_p and r_s are the reflection coefficients of the sample and Δ is the phase difference introduced by the sample.

The intensity detected by the photodetector D1 is found to be

$$I_{\text{output, }\phi}^{\text{sample}} = \frac{1}{2}\left[R_p \sin^2\phi + R_s \cos^2\phi + \sqrt{R_p R_s}\sin 2\phi \cos\Delta\right] \tag{5}$$

Where $R_p\left(=r_p^2\right)$ and $R_s\left(=r_s^2\right)$ are reflectances in the direction parallel and perpendicular, respectively, to the plane of incidence. Because the angle ϕ is controllable via the phase modulation, three specific values of azimuth angles are chosen. They include $\phi = 0^0, 45^0$ and 90^0. Their corresponding intensities can be written as,

$$I_{\text{output, }0^0}^{\text{sample}} = \frac{R_s}{2} \tag{6}$$

$$I_{\text{output, }90^0}^{\text{sample}} = \frac{R_p}{2} \tag{7}$$

and

$$I_{\text{output, }45^0}^{\text{sample}} = \frac{1}{2}\left[\frac{R_p}{2} + \frac{R_s}{2} + \sqrt{R_p R_s}\cos\Delta\right] \tag{8}$$

These three measured intensities can be used to calculate the ellipsometric parameters ψ and Δ. By substitution R_p and R_s from Eqs. (6) and (7) into Eq. (8), the intensity becomes

$$I_{\text{output, }45^0}^{\text{sample}} = \frac{1}{2}\left[\frac{I_{\text{output, }0^0}^{\text{sample}}}{2} + \frac{I_{\text{output, }90^0}^{\text{sample}}}{2} + \sqrt{\left(I_{\text{output, }0^0}^{\text{sample}}\right)\left(I_{\text{output, }90^0}^{\text{sample}}\right)}\cos\Delta\right] \tag{9}$$

This clearly allows the determination of Δ. In addition, the amplitude ratio upon reflection between $I^{\text{sample}}_{\text{output, }0^0}$ and $I^{\text{sample}}_{\text{output, }90^0}$ gives the parameter ψ from

$$\psi = \tan^{-1}\left(\sqrt{\frac{I^{\text{sample}}_{\text{output, }90^0}}{I^{\text{sample}}_{\text{output, }0^0}}}\right) \tag{10}$$

The reference signal detected by a photodetector D2 from the other output of pMZi has a similar pattern to the sample detection signal but its intensity is much lower. This is used to specify the corresponding direction for the three intensities in the sample detection signal (Fig. 3).

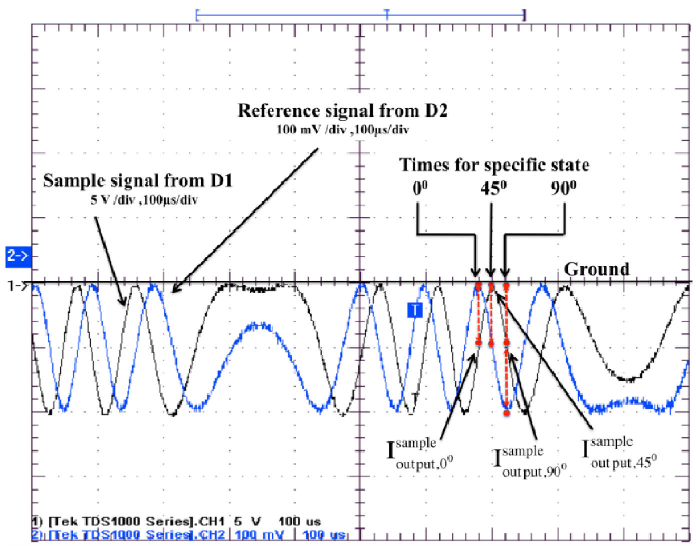


Fig. 3 A screenshot from an oscilloscope shows the reference and detection signals. Three specific states from the detection signal can simply be identified by the reference signal.

For a single layer film, the change in the polarization state of polarized light reflected from a sample can be described in terms of the ellipsometric parameters ψ and Δ . This time, the two parameters of a given film substrate are not only a function of the angle of incidence but also the thickness of the thin film. Thus, for a chosen thin film system, a set of ψ and Δ values determined over a range of incident angles will vary from one value of the film thickness to another. A comparison between the experimental and calculated values were made. The calculated values were generated by a simple numerical methods and their trends were curve fitted with a mathematics program [10]. This should be noted that the calculated curves of the ellipsometric parameters ψ and Δ were calculated from known values, measured by a standard instrument, of thin film thickness and index of refraction.

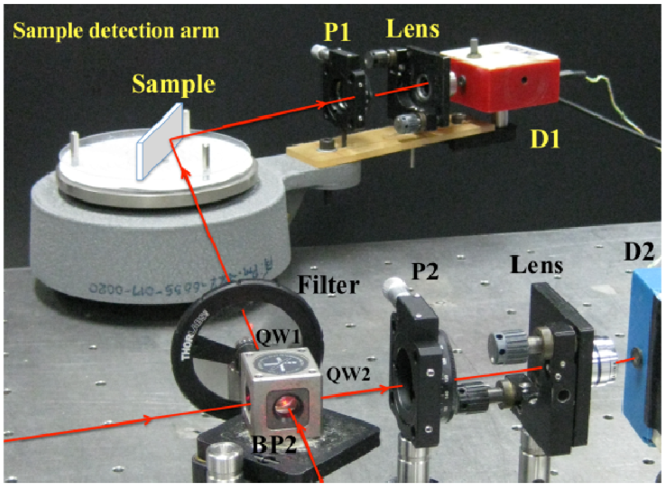
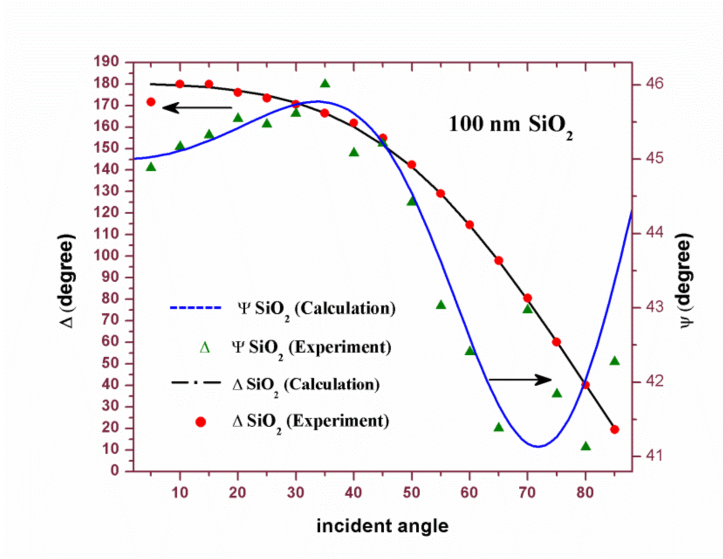


Fig. 4 The arrangement of sample detection and reference detection arms : PB2 = polarizing beam splitters, QW1 and QW2 = quarter wave retarders, P1 and P2 = polarizers and D1 and D2 = photodetectors.

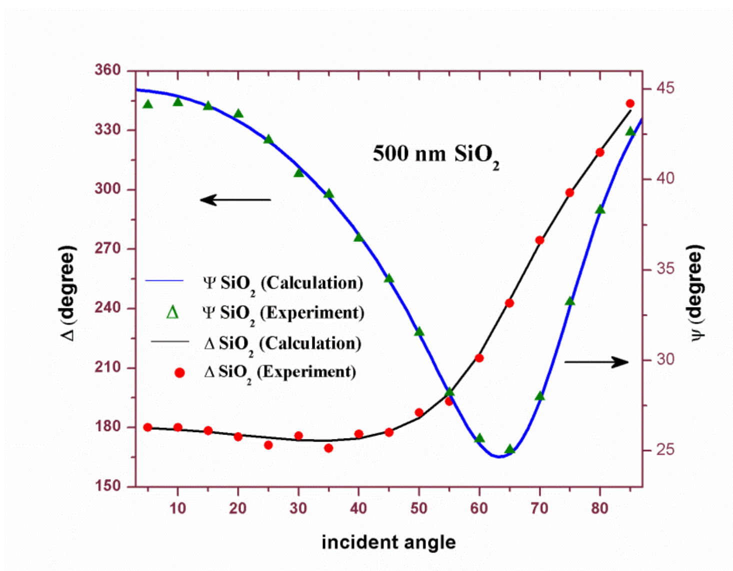
Fig. 4 shows the extended part from the pMZi to accommodate the reference and sample detection units. This should be noted that, in the sample detection arm, the rotating linearly polarized light was incident on the thin film sample at a set of incident angles. The reflected light was then detected by so called the sample detection unit, which is mainly composed of a polarizer P1 oriented at 45^o with respect to the plane of incidence and a photodetector D1. The signal reflected from the sample along with the reference signal were transferred to a computer for a further signal processing. Because the incident light changes its orientation due to the PZT modulation unit, a simple signal processing based on two-signal comparison could be applied and the required reflection coefficients R_p and R_s could subsequently be determined. Then, this step was followed by the calculation of the ellipsometric parameters for each sample.

4. EXPERIMENTAL RESULTS

The measurements of Si substrate covered with two different thicknesses (100 nm and 500 nm) of SiO_2 were carried out using the rotating linearly polarized light from the pMZi. The measured values of ψ and Δ were conducted for incident angles from 5^0 to 85^0 with an interval of 5^0. The experimental results were found to be in a good agreement with those of reference values as can be seen from Fig 5. The calculated values were determined from the theory mentioned in the previous section by substituting all initial data such as refractive indices of ambient ($N_0 = 1.00$), SiO_2 film ($N_1 = 3.88 - i0.002$ i) and Si substrate ($N_2 = 1.46$) and known thicknesses into Eq. (2). This was followed by the calculation of R_p and R_s from Eq. (1). The ψ and Δ were then worked out for incident angles from 5^0 to 85^0. The initial data were measured by a commercial variable-angle spectroscopic ellipsometer from the Optical Coating Laboratory, National Electronics and Computer Technology (NECTEC), Thailand.



(a)



(b)

Fig. 5 Measured characteristic curves of (a) 100 nm SiO_2 film and (b) 500 nm SiO_2 film on Si substrates in terms of ψ and Δ exactly follow the corresponding calculated curves. The calculated values were generated by a computer program with initial data obtained from a commercial ellipsometer.

5. CONCLUSIONS

This study clearly shows that the rotating linearly polarized light from the pMZi could be used to characterize the thin-film substrate system in terms of ellipsometric parameters. The measured values were found to be highly accurate. This success was made possible due to important features of the rotating linearly polarized light. These are (1) the rotation of the polarized light solely depends on the optical modulation, (2) the rotation of the polarized light allows a number of required intensities to be continuously collected and (3) the state of polarization can simply be identified by the reference signal. In addition, this study also suggests that such a probe beam coupled with a thin film sensing material may form a sensitive optical sensing system.

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