A NOVEL ELLIPSOMETER DESIGN FOR THE STUDY OF LARGE THIN FILMS

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ABSTRACT

This paper describes a novel long-scanning reflection ellipsometer to characterize large thin films. The ellipsometer uses a frequency stabilized Zeeman-split He-Ne laser as the source. Two common-path left and right circularly polarized beams, with a slight frequency difference, work as the incident beams. Beat frequency signals are detected from the reflected beams on a sample, and the thin film properties are studied. An optical common-mode rejection technique is employed to minimize the effects of environmental conditions. Measurements are not sensitive to low frequency noise and ignore any electronic dc offset effects. The variations of the beam intensities of the source do not affect the experimental results. The optical system is designed to be arranged on a long air-bearing slide with an autofocus system of 0.1 μm resolution in the range of 25 mm. Measurements will cover the range from 3 μm to 600 nm. Experimental results can be taken in the ordinary experimental conditions.

1. INTRODUCTION

Ellipsometry is one of the most sensitive nondestructive optical techniques for characterizing optical thin films. The parameters of a thin film, such as refractive index and film thickness, can be provided from measurements of the ellipsometric angles, Ψ and Δ , in the instrument. These angles are described by the complex Fresnel reflection coefficients of the thin film.^[1] The measurements of ellipsometric angles is usually based on detecting the polarization state of the reflected beam compared with that of the incident beam on a sample. Various investigations of ellipsometry and its applications have been done.^[1-4] The analyses of measurements in the ellipsometric system yields the polarization effects of the sample on which a polarized beam is incident. The ellipsometric angles are given by

$$\rho = \frac{R_p}{R_s} = e^{i\Delta} \tan \Psi \quad (1)$$

where

$$\tan \Psi = \frac{|R_p|}{|R_s|}, \quad \Delta = \phi_p - \phi_s \quad (2)$$

R_p and R_s are the Fresnel reflection coefficients at a given angle of incidence, ρ is the ratio of these reflection coefficients, the subscripts p and s correspond to the parallel and perpendicular polarizations to the plane of incidence, ϕ is the phase of the reflection, Ψ is the angle whose tangent is the ratio of the amplitude attenuation reflections for the p and s polarizations, and Δ is the phase shift difference between the reflections for the p and s polarizations.

A long-scanning ellipsometer, based on the analyses of the previous ellipsometers,^[5-7] is described in this paper for studying large thin films. A Zeeman-split He-Ne laser is employed as the source. Two common-path polarized beams with a slight frequency difference enter the optical system. One beam is left circularly polarized, the other is right. Both beams are reflected on a thin film surface and received by the detectors. Therefore, beat frequency signals are produced to analyze the thin film properties. The environmental effects are minimized by using a common-mode rejection technique. The electronic dc offset and low frequency noise do not affect the measurements.

2. EXPERIMENTAL PRINCIPLE

The schematic of the reflection ellipsometer design is shown in Fig. 1. The source is a frequency stabilized longitudinal Zeeman-split He-Ne laser. It outputs two common-path beams which are left and right circularly polarized. These two beams have the same intensity but with a slight frequency difference. The beams are well collimated and expanded by transmission through a collimating lens (CL), then focused by a lens (L1) to the thin film surface under investigation. The focus spot is $3\text{ }\mu\text{m}$ diameter. Since the optical medias at the interface are dissimilar, the state of polarization of an incident beam is changed abruptly. This change is caused by the difference in the Fresnel reflection coefficients for the two linear polarizations parallel (p) and perpendicular (s) to the plane of incidence. The reflected beams from the film surface become collimated by passing through a lens (L2). A polarizing beam splitter (PBS1) divides both beams to two detector arms. The superposition of the two polarized beams causes Zeeman frequency modulation which is transferred after splitting to receivers (R1) and (R2). The outputs of the receivers R1 and R2 are two beat frequency signals which contain the information of the Fresnel reflection coefficients of the film. The signals are processed by a computer (C) to determine the elliptical angles Ψ and Δ in the ellipsometer. Therefore, the properties of the thin film are obtained. Measurements are made with an autofocus system which keeps the film surface in focus during sampling.

Fig. 1 Schematic of the ellipsometric system.

In the focus system, a collimated beam from a diode laser passes through a polarizing beam splitter (PBS2) and a quarter wave plate (QWP), then it is focused on the sample by the lens (L3). It should be noted that the depth of the focus of lens L3 is less than and located within that of lenses L1 and L2 in the vertical direction. The reflected beam passing through the L3 and the QWP becomes collimated and linearly polarized. However, its polarization has been rotated by 90° to that of the incident beam. The reflected beam is transferred by the PBS2 to an astigmatic lens (AL), so that a beam image is presented on a quad-cell detector (QD).

The autofocus system uses an astigmatic detector system.^[9-10] Astigmatic lens AL is employed to produce the tangential and sagittal images of an object. The two images do not coincide. When a collimated beam is incident on the lens, the astigmatism causes two separated focus lines instead of a focal point. The image between the two foci is an elliptical blur except at one position where the image is a circular blur. The quadrature detector (QD) is set at this position. When the incident beam is convergent or divergent, the tangential and sagittal images will be moved forward or backward. Therefore, the beam spot on the detector will become elliptical, as shown in Fig. 2.

Fig. 2 Focus error signal on the quadrature detector when the sample position is: (a) too far, (b) in focus, (c) too close.

The focus-position error signal FES produced and determined by the beam intensities on the four cells of quadrature QD is given by

$$FES = \frac{(A+C) - (B+D)}{A+B+C+D} \quad (3)$$

where A, B, C and D are the beam intensities on the four cells, respectively. The sign and amplitude of the FES decides which direction and how much the servo-motor system should move the sample to bring it into focus. The beam spot on the detector can be observed clearly on a screen (S) by using a CCD camera (CA). If the sample is too far from the lens L3, the reflected beam is convergent. The beam spot pattern on the detector is an ellipse with a larger vertical than horizontal axis. If the sample is too close to the L3, the spot pattern is an ellipse with a larger horizontal than vertical axis. The servo-motor system is able to move the sample smoothly up or down with $0.1 \mu\text{m}$ resolution in the range of 25 mm.

3. THEORETICAL ANALYSES

The analyses of the polarization states of the beams from the Zeeman-split laser through the ellipsometric system can be derived with the Jones matrix calculus. A space-fixed right-handed Cartesian coordinate system xOy is shown in Fig. 1. The coordinate plane xOy is perpendicular to the beams propagation. The Ox and Oy axes are set parallel to the directions of two polarizations of the PBS1, respectively. The Jones vectors for the optical fields of the left and right circularly polarized beams are expressed as^[8]

$$E_+ = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 \\ -i \end{bmatrix} A e^{-i\varphi_+} \quad (4)$$

$$E_- = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 \\ i \end{bmatrix} A e^{-i\varphi_-} \quad (5)$$

where

$$\varphi_+ = \omega_+ t + \varphi_{0+} \quad (6)$$

$$\varphi_- = \omega_- t + \varphi_{0-} \quad (7)$$

the subscripts + and - refer to the left and right circularly polarized beams, respectively, φ is the phase, φ_0 is the initial phase, ω is the angular frequency, and A is the amplitude of the optical field. The Jones matrices of the two polarizations of polarizing beam splitter PBS1 are expressed as

$$P_x = \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix} \quad (8)$$

$$P_y = \begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix} \quad (9)$$

The thin film under measurement is assumed to have two orthogonally linear eigenpolarizations, along which the linear polarizations parallel p and perpendicular s to the plane of incidence are reflected. The eigenpolarizations will modify the polarization states of the incident beams. When the s eigenpolarization is at an angle θ with the Ox axis, the reflection Jones matrix on the sample is written in the form

$$R_\theta = r(-\theta) R_0 r(\theta) \quad (10)$$

where $r(\theta)$ is the rotation matrix given by

$$r(\theta) = \begin{bmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{bmatrix} \quad (11)$$

and R_0 is the reflection Jones matrix with $\theta = 0$. R_0 is expressed as

$$R_0 = \begin{bmatrix} R_p & 0 \\ 0 & R_s \end{bmatrix} = \begin{bmatrix} |R_p| e^{i\phi_p} & 0 \\ 0 & |R_s| e^{i\phi_s} \end{bmatrix} = R_s \begin{bmatrix} k e^{i\Delta} & 0 \\ 0 & 1 \end{bmatrix} \quad (12)$$

where

$$k = \frac{|R_p|}{|R_s|} \quad (13)$$

k is the ratio of the amplitudes of the p and s polarizations on reflection. Therefore, the reflection Jones matrix we get is

$$R_\theta = \begin{bmatrix} k e^{i\Delta} \cos^2 \theta + \sin^2 \theta & (k e^{i\Delta} - 1) \sin \theta \cos \theta \\ (k e^{i\Delta} - 1) \sin \theta \cos \theta & k e^{i\Delta} \sin^2 \theta + \cos^2 \theta \end{bmatrix} \quad (14)$$

According to the Jones calculus, the Jones vectors for the optical fields of the linear polarized beams emerging from the PBS1 to receiver R1 are written in the form

$$E_{+x} = P_x R_\theta E_+ \quad (15)$$

$$E_{-x} = P_x R_\theta E_- \quad (16)$$

By introducing Eqs. (4), (5), (8) and (14) into Eqs. (15) and (16), respectively, we get

$$E_{+x} = \frac{1}{\sqrt{2}} \begin{bmatrix} (k e^{i\Delta} \cos^2 \theta + \sin^2 \theta) - i (k e^{i\Delta} - 1) \sin \theta \cos \theta \\ 0 \end{bmatrix} A R_s e^{-i\phi_+} \quad (17)$$

$$E_{-x} = \frac{1}{\sqrt{2}} \begin{bmatrix} (k e^{i\Delta} \cos^2 \theta + \sin^2 \theta) + i (k e^{i\Delta} - 1) \sin \theta \cos \theta \\ 0 \end{bmatrix} A R_s e^{-i\phi_-} \quad (18)$$

Similarly, the Jones vectors for the optical fields of the linear polarized beams emerging from the PBS1 to receiver R2 are expressed by

$$E_{+y} = P_y R_\theta E_+ \quad (19)$$

$$E_{-y} = P_y R_\theta E_- \quad (20)$$

By introducing Eqs. (4), (5), (9) and (14) into Eq. (19) and (20), respectively, we get

$$E_{+y} = \frac{1}{\sqrt{2}} \begin{bmatrix} 0 \\ (k e^{i\Delta} - 1) \sin \theta \cos \theta - i (k e^{i\Delta} \sin^2 \theta + \cos^2 \theta) \end{bmatrix} A R_s e^{-i\varphi_+} \quad (21)$$

$$E_{-y} = \frac{1}{\sqrt{2}} \begin{bmatrix} 0 \\ (k e^{i\Delta} - 1) \sin \theta \cos \theta + i (k e^{i\Delta} \sin^2 \theta + \cos^2 \theta) \end{bmatrix} A R_s e^{-i\varphi_-} \quad (22)$$

Therefore, the Jones vectors, E_1 and E_2 , for the total optical fields of the beams at receivers R1 and R2 are given by

$$E_1 = E_{+x} + E_{-x} \quad (23)$$

$$E_2 = E_{+y} + E_{-y} \quad (24)$$

The beam intensities I_1 and I_2 at receivers R1 and R2, expressed by the Jones vectors, E_{+x} , E_{-x} , E_{+y} and E_{-y} , are

$$\begin{aligned} I_1 &= |E_1|^2 \\ &= |E_{+x}|^2 + |E_{-x}|^2 + E_{+x} E_{-x}^* + E_{-x}^* E_{+x} \end{aligned} \quad (25)$$

$$\begin{aligned} I_2 &= |E_2|^2 \\ &= |E_{+y}|^2 + |E_{-y}|^2 + E_{+y} E_{-y}^* + E_{-y}^* E_{+y} \end{aligned} \quad (26)$$

In each equation above, the first and second terms are the dc part of the beam intensity signal. The dc part is cut off by arranging capacitors in the output electronic circuits of the receivers. The third and fourth terms are the ac part which arises from the Zeeman frequency modulation of the light source. This modulation is changed by the phase information at the thin film surface, and this information is then passed to receivers R1 and R2 where the two ac components are given by

$$I_{1ac} = E_{+x} E_{-x}^* + E_{-x}^* E_{+x} \quad (27)$$

$$I_{2ac} = E_{+y} E_{-y}^* + E_{-y}^* E_{+y} \quad (28)$$

Substituting Eqs. (17) and (18) into Eq. (27) and substituting Eqs. (21) and (22) into Eq. (28), we obtain

$$I_{1ac} = \frac{1}{2} A^2 |R_s|^2 \left[(k^2 \cos^2 \theta - \sin^2 \theta) \cos(\varphi_+ - \varphi_- - 2\theta) - k \sin 2\theta \cos \Delta \sin(\varphi_+ - \varphi_- - 2\theta) \right] \quad (29)$$

$$I_{2ac} = \frac{1}{2} A^2 |R_s|^2 \left[(k^2 \sin^2 \theta - \cos^2 \theta) \cos(\varphi_+ - \varphi_- - 2\theta) + k \sin 2\theta \cos \Delta \sin(\varphi_+ - \varphi_- - 2\theta) \right] \quad (30)$$

3.1. Measurement of the ellipsometric angle Ψ .

In Eqs. (29) and (30), I_{1ac} and I_{2ac} vary with the change of the angle θ . When θ is $n\pi$ ($n = 0, 1, 2 \dots$), Eqs. (29) and (30) become

$$I_{1ac} = \frac{1}{2} A^2 |R_s|^2 k^2 \cos(\varphi_+ - \varphi_-) \quad (31)$$

$$I_{2ac} = -\frac{1}{2} A^2 |R_s|^2 \cos(\varphi_+ - \varphi_-) \quad (32)$$

Substituting Eqs. (6) and (7) into Eqs. (31) and (32), respectively, we obtain

$$I_{1ac} = \frac{1}{2} A^2 |R_s|^2 k^2 \cos(\delta\omega t + \delta\varphi_0) \quad (33)$$

$$I_{2ac} = -\frac{1}{2} A^2 |R_s|^2 \cos(\delta\omega t + \delta\varphi_0) \quad (34)$$

where $\delta\omega = \omega_+ - \omega_-$ is the angular Zeeman frequency, and $\delta\varphi_0 = \varphi_{0+} - \varphi_{0-}$ is the initial phase difference between the two polarized beams. Thus, $\tan\Psi$ is given by

$$\tan\Psi = k = \left[\frac{I_{1ac} \text{ amplitude}}{I_{2ac} \text{ amplitude}} \right]_{\theta=n\pi}^{\frac{1}{2}} \quad (35)$$

3.2. Measurement of the ellipsometric angle Δ .

Since the signals I_{1ac} and I_{2ac} are correlative, we add Eq. (29) to Eq. (30) and subtract Eq. (30) from Eq. (29), respectively

$$I_{1ac} + I_{2ac} = \frac{1}{2} A^2 |R_s|^2 (k^2 - 1) \cos(\delta\omega t + \delta\varphi_0 - 2\theta) \quad (36)$$

$$I_{1ac} - I_{2ac} = \frac{1}{2} A^2 |R_s|^2 [(k^2 - 1) \cos 2\theta \cos(\delta\omega t + \delta\varphi_0 - 2\theta) - 2k \sin 2\theta \cos \Delta \sin(\delta\omega t + \delta\varphi_0 - 2\theta)] \quad (37)$$

The amplitude of Eq. (36) does not change with the angle θ . Eq. (37) is the function of θ . Its amplitude has a maximum (or minimum), when θ is $\frac{1}{4}(4n+1)\pi$ or $n\pi$

$$I_{1ac} - I_{2ac} = \frac{1}{2} A^2 |R_s|^2 (k^2 - 1) \cos(\delta\omega t + \delta\varphi_0) \quad (\theta = n\pi) \quad (38)$$

$$I_{1ac} - I_{2ac} = A^2 |R_s|^2 k \cos \Delta \cos(\delta\omega t + \delta\varphi_0) \quad (\theta = n\pi + \frac{1}{4}\pi) \quad (39)$$

The amplitude of Eq. (38) is same as that of Eq. (36). The ratio η of the amplitude of Eq. (39) to that of Eq. (36) is written in the form

$$\eta = \left[\frac{(I_{1ac} - I_{2ac}) \text{ amplitude}}{(I_{1ac} + I_{2ac}) \text{ amplitude}} \right]_{\theta=n\pi+\pi/4} = \frac{2|k \cos \Delta|}{|k^2 - 1|} \quad (40)$$

thus

$$|\cos \Delta| = \frac{\eta}{2k} |k^2 - 1| \quad (41)$$

where the sign of $\cos\Delta$ is determined by the k value and the wave phase difference Φ between Eqs. (38) and (39). When $k > 1$ and Φ is 0 or $k < 1$ and Φ is π , $\cos\Delta$ is positive. When $k < 1$ and Φ is π or $k > 1$ and Φ is 0, $\cos\Delta$ is negative.

The adjustment of the angle θ can be made by splitting both reflected beams into two parts with a beam splitter just before the PBS1. A half wave plate is arranged in one part to adjust θ to $n\pi$. Another half wave plate used in the other part sets θ to $\frac{1}{4}(4n+1)\pi$. Therefore, no parts in the optical system need to be moved during the thin film measurements.

3.3 Evaluation of the measurement sensitivities of the ellipsometric angles.

Eq. (35) can be written in the form

$$\tan \Psi = k = \left[\frac{I_{01}}{I_{02}} \right]_{\theta=n\pi}^{\frac{1}{2}} \quad (42)$$

where I_{01} and I_{02} are $I_{1\alpha}$ amplitude and $I_{2\alpha}$ amplitude when $\theta = n\pi$. The variation of k is expressed by

$$\begin{aligned} d(\tan \Psi) = dk &= \frac{1}{2} \left[\frac{I_{01}}{I_{02}} \right]^{\frac{1}{2}} \left(\frac{dI_{01}}{I_{01}} - \frac{dI_{02}}{I_{02}} \right) \\ &\leq \frac{1}{2} k (R_{01} + R_{02}) \leq k R_0 \end{aligned} \quad (43)$$

where $R_{01} = \left| \frac{dI_{01}}{I_{01}} \right|$ and $R_{02} = \left| \frac{dI_{02}}{I_{02}} \right|$ are the ratios of noise to signal of I_{01} and I_{02} , respectively, and R_0 is the larger one between R_{01} and R_{02} . The variation of the ellipsometric angle Ψ is obtained from Eq. (43)

$$|d\Psi| \leq k^2 R_0 \quad (44)$$

Eq. (40) can be written in the form

$$\eta = \left[\frac{I_{\alpha-}}{I_{\alpha+}} \right]_{\theta=n\pi+\pi/4} \quad (45)$$

where $I_{\alpha-} = (I_{1\alpha} - I_{2\alpha})$ amplitude, and $I_{\alpha+} = (I_{1\alpha} + I_{2\alpha})$ amplitude when $\theta = n\pi + \frac{\pi}{4}$. The variation of η caused by the system noises is expressed by

$$\begin{aligned} d\eta &= \frac{I_{\alpha-}}{I_{\alpha+}} \left(\frac{dI_{\alpha-}}{I_{\alpha-}} - \frac{dI_{\alpha+}}{I_{\alpha+}} \right) \\ &\leq \eta (R_{\alpha-} + R_{\alpha+}) \leq 2\eta R_{\alpha} \end{aligned} \quad (46)$$

where $R_{\alpha-} = \left| \frac{dI_{\alpha-}}{I_{\alpha-}} \right|$ and $R_{\alpha+} = \left| \frac{dI_{\alpha+}}{I_{\alpha+}} \right|$ are the ratios of noise to signal of $I_{\alpha-}$ and $I_{\alpha+}$, respectively, and R_{α} is the larger one between $R_{\alpha-}$ and $R_{\alpha+}$. The variation of the ellipsometric angle Δ is obtained from Eq. (41)

$$|d(\cos \Delta)| = \left| \frac{1}{2k} (k^2 - 1) d\eta + \frac{1}{2} \eta (dk + \frac{1}{k^2} dk) \right| \quad (47)$$

Substituting Eqs. (43) and (46) into Eq. (47), we obtain

$$\begin{aligned}
|d(\cos \Delta)| &\leq \frac{1}{2} \eta \left| (k - \frac{1}{k}) 2R_{ac} + (k + \frac{1}{k}) R_0 \right| \\
&\leq \frac{1}{2} \eta R \left| 3k - \frac{1}{k} \right|
\end{aligned} \tag{48}$$

thus

$$|d\Delta| \leq \frac{1}{2} \eta R \left| \frac{1}{\sin \Delta} (3k - \frac{1}{k}) \right| \tag{49}$$

where R is the bigger one between R_{ac} and R_0 . Substituting Eq. (41) into Eq. (49)

$$|d\Delta| \leq \frac{1}{2} [1 - (\eta^2/4k^2) (k^2 - 1)^2]^{-1/2} \eta R \left| 3k - \frac{1}{k} \right| \tag{50}$$

Eq. (44) can be written in the form

$$|d\Psi| \leq k^2 R \tag{51}$$

$|d\Psi|$ and $|d\Delta|$ are the variations of the measured ellipsometric angles Ψ and Δ . These variations are mainly determined by the ratios of noise to signal in the systems. Since the two polarized beams are common path in the optical systems, the optical rejection technique is able to ignore the effects of the optical and mechanical conditions. Therefore, the noises from the detectors and amplifiers are main sources to the measurement sensitivities of the ellipsometric angles. The detectors employed are from EG&G company with NEP values smaller than $10^{-13} \text{ W}/\sqrt{\text{Hz}}$. The amplifiers employed are lock-in amplifiers with noises smaller than $1.4 \text{ nV}/\sqrt{\text{Hz}}$ and with sensitivities of 1 nV . The laser source is an HP5518A Zeeman-split He-Ne laser with the beam intensity of 1.0 mW . The Zeeman frequency is 1.8 MHz . Therefore, the noise to signal ratios of I_{1ac} , I_{2ac} , $(I_{1ac} + I_{2ac})$ and $(I_{1ac} - I_{2ac})$ are calculated, better than 10^{-5} . In another words, R is smaller than 10^{-5} .

The other parameters affecting the variations of $|d\Psi|$ and $|d\Delta|$ under measurements are k and η . When k and η are assumed to be measured as $\frac{1}{2}$ and $\frac{1}{2}$, respectively, $|d\Psi|$ and $|d\Delta|$ are obtained from Eqs. (50) and (51)

$$|d\Psi| < \frac{1}{4} R < 2.5 * 10^{-6} \tag{52}$$

$$|d\Delta| < 1.5 R < 1.5 * 10^{-6} \tag{53}$$

4. ADVANTAGES OF THE DESIGN

The long-scanning reflection ellipsometric instrument design discussed here differs from the existing commercial ellipsometers such as null ellipsometers, rotating polarizer ellipsometers, and large modulation ellipsometers. A two-frequency Zeeman-split laser is used as the light source. The two common-path polarized beams work as the incident beams, so that an optical common-mode rejection technique can be used to minimize the effects of the environmental conditions. The instrument avoids varying the angle of the incident beams. A heterodyne technique is used to test the beat frequency signals instead of the regular dc signal measurements of the reflected beam intensity on the sample. The optical system is free of moving parts. This avoids any interference in the system operations. Thin film measurements are insensitive to the variations of the intensities of the incident beams. Any dc offset caused in the detector system is ignored. Measurements can be made in ordinary experimental conditions.