Determining thickness of films on a curved substrate by use of ellipsometric measurement

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ABSTRACT

The three intensity polarizer-sample-analyzer imaging ellipsometry is used to measure the ellipsometric parameters (Ψ, Δ). In addition to the ellipsometric parameters, we introduce an extra angle α to measure the of the azimuth deviation of polarizer. After careful calibration, we found this deviation can indicate how much the surface normal slanted from the plane; then it can be used to deduce the thickness profile coated on a cylindrical lens. Using this technique, we not only can determine the radius curvature of the curved surface, we also can calculate the thickness of the thin film coated on a curved surface.

Keywords: imaging ellipsometry, thin film thickness, curved surface

1. INTRODUCTION

Optical measurement in determining the properties of thin-films is an important procedure in semiconductor and optical coating industry. Ellipsometry is widely used to characterize the thin film thickness and optical constants accurately and none destructively. Because the theory of deducing the physical parameters from the ellipsometric measurement technique depends on the incident angle [1], the conventional ellipsometric measurement is only valid on the flat surface; its accuracy can be strongly degraded by tilting or curving surfaces. The film thickness in the lens coating industry is monitored by quartz crystal and characterized by interferometer [2], while the powerful technique of ellipsometry has been restricted in flat surface. In the development of alignment algorithms for ellipsometry [3], we were able to prove that the azimuth deviation α of polarizer can be used to characterize the deviation between the incident angle and surface normal [4]. With this additional parameter, we not only can used the three intensity measurement method to measure the surface refractive index profile of a flat surface, such as GRIN lens; we also can measure the surface refractive index profile of a curved surface [5], such as a Plano-convex lens. Using the azimuth deviation of polarizer, we extended the three intensity measurement method to measure film thickness on a slant SiO_2/Si sample and a coated cylindrical lens.

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2. THEORETICAL BACKGOUND

The PSA imaging ellipsometer is illustrated in Fig.1 (a). Ellipsometric parameters ψ and Δ are defined as

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

where r_p and r_s are the reflection coefficients of the linearly polarized light parallel (p) and perpendicular (s) to the incident plane, respectively. The measured intensity can be written as

$$I = I_0(\sin^2 P\sin^2 A + \tan^2\Psi\cos^2 P\cos^2 A + 0.5\tan\Psi\cos\Delta\sin 2P\sin 2A) \tag{2}$$

where the azimuths P and A are the transmission axis of the polarizer and analyzer. When P=45°, the reflected intensity is distributed in an elliptical forms, such as shown in Fig.1 (b), can be formulated as

$$I(A) = \frac{L}{2}\cos^2(A-\theta) + \frac{T}{2}\sin^2(A-\theta) \tag{3}$$

where L and T are the magnitudes of the maximum and the minimum intensities, and θ is the azimuth of the maximum intensity. By comparison of Eq. (2) and Eq. (3), one can easily prove that

$$\tan 2\theta = \frac{\cos\Delta\sin 2P\sin 2\Psi}{\cos 2P - \cos 2\Psi}; \tag{4}$$

$$\frac{(L-T)^2}{4LT}\sin^2(2\theta) = \cot^2\Delta. \tag{5}$$

Moreover, Eq. (3) can be simplified as

$$I(A) = B(1 + C\cos 2A + D\sin 2A), \tag{6}$$

where the parameter B, C, and D can be written in term of L, T, and θ, i.e., B = 0.5(L+T), C = (L-T)cosθ/(L+T), and D = (L-T)sinθ/(L+T). It is easy to prove the parameters B, C and D can be measured by the intensities of A = 0°, 60° and 120°:

$$B = \frac{1}{3}[I(0°) + I(60°) + I(120°)] \qquad C = 2 - \frac{1}{B}[I(60°) + I(120°)] \qquad D = I(60°) - I(120°)$$

and the following:

$$\tan 2\theta = \frac{D}{C} \qquad L = \frac{DB}{\sin 2\theta} + B \qquad T = 2B - L. \tag{7}$$

Rewriting Eq. (2) in terms if cos 2A and sin 2A then comparing the result with Eq. (6), one can also prove that

$$\tan^2\Psi = \frac{1+C}{1-C}\tan^2 P. \tag{8}$$

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Since P and A can be carefully calibrated to the flat surface, such as water [5], one can obtain the ellipsometric parameters of a flat surface from three intensity measurements. It has been proved the deviation of polarizer, α can be obtained by the same measurements in order to measure the tilting of the surface [5]. Assuming the curved surface normal deviates from the normal of flat surface at byα, one can easily prove the followings:

$$P = +45^\circ \quad \tan^2\Psi = \frac{(1+C_1)(1+\sin 2\alpha)}{(1-C_1)(1-\sin 2\alpha)};$$

$$P = -45^\circ \quad \tan^2\Psi = \frac{(1+C_2)(1+\sin 2\alpha)}{(1-C_2)(1-\sin 2\alpha)}, \tag{9}$$

where $C_1$and C_2 are the corresponding parameters at $P = +45^\circ$ and $P = -45^\circ$, respectively. Ψ and α can be deduced by the three intensity measurements from the following relations:

$$\sin 2\alpha = \frac{1-\sqrt{\frac{(1+C_1)}{(1-C_1)}\frac{(1-C_2)}{(1+C_2)}}}{1+\sqrt{\frac{(1+C_1)}{(1-C_1)}\frac{(1-C_2)}{(1+C_2)}}} \quad ; \tag{10}$$

$$\tan\Psi = [\frac{(1+C_1)}{(1-C_1)}\frac{(1-C_2)}{(1+C_2)}]^{\frac{1}{4}}; \tag{11}$$

and Δ can be deduced from Eq. (5). By flatten/untilt the curved surface; one can obtain the film thickness through the regular ellipsometric deduction technique.

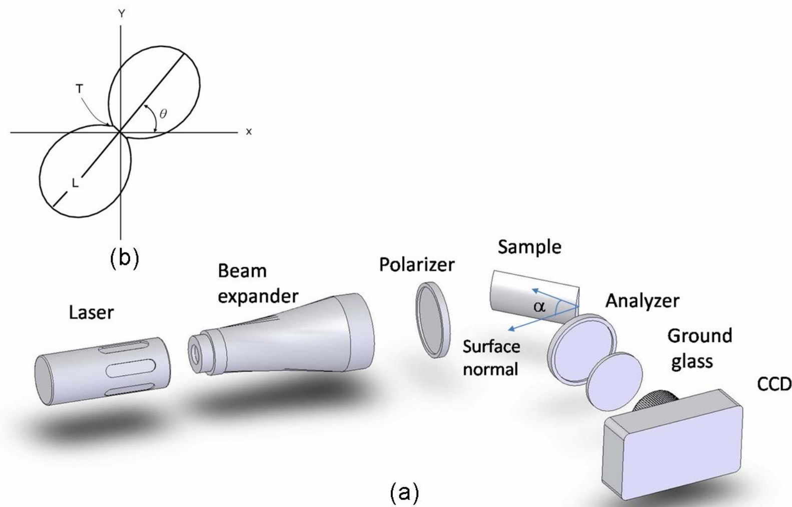

Fig.1. (a) Experimental setup of the PSA ellipsometer; (b) The elliptically distributed intensity on the right is under various azimuth angles of A in the polar coordinates.

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3. EXPERIMENT

According to reference 6, one can measure the azimuth angles of the polarizer, analyzer to the incident plane analytically. The light source (Melles Groit 05-STP-901, λ=632.8 nm stabilized He-Ne laser) illuminated to the sample at the incident angle of 70°. The light passed through a polarizer whose azimuth was set at 45° and the sample was placed on a ganiometer. The analyzer was mounted on a motor-controlled rotator, and three radiances were measured by a power-meter (Thorlabs PDA55) while the azimuth of analyzer was set at 0°, 60° and 120°. For calibrating the tilting effect of a plane, we put a spacer under the edge of a well calibrated SiO_2/Si thin-film wafer with thickness of 129 nm, and measured its ellipsometric parameters before and after tilting at the incident angle of 70°; then we repeated the experiment after rotating (around z-axis) the sample, such as shown in Fig. 2. After the preliminary investigation of the tilted surface, we applied this technique to measure the film thickness coated on a cylindrical lens by an imaging ellipsometry. Indium-tin oxide (ITO) thin films were deposited on a cylindrical convex lens (Thorlabs: LJ1144L2) and a flat glass by magnetron sputter without addition of ambient oxygen. According to reference 5, we utilized the imaging ellipsometry to measure the coated cylinder lens and flat glass; their coated film thickness can be used to confirm with each other. The laser beam was expanded to cover the area with a diameter of 15 mm; the intensity was measured by a CCD camera.

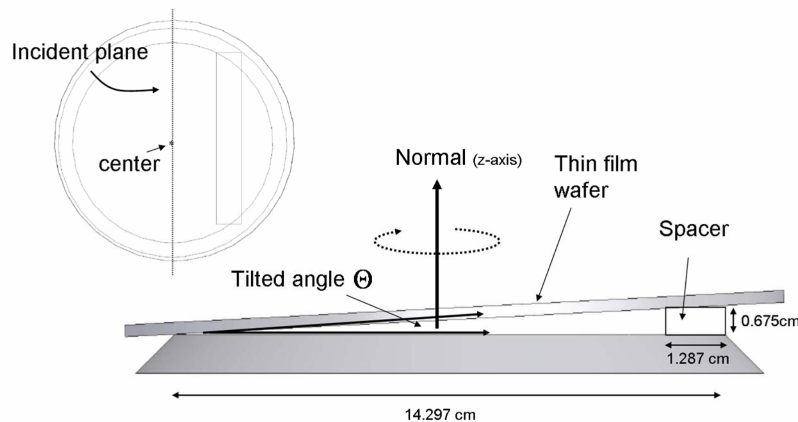

Fig. 2. Schematic configuration of the slanted sample

4. RESULTS

The measured ellipsometric parameters of the well calibrated thin film before and after tilting are listed in Table 1.

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Table 1. The ellipsometric measurements of the tilted and untilted sample.

Position	Sample condition	Ψ (deg)	Δ (deg)	α (deg)	$\Delta\alpha$ (deg)	θ *) (deg)	$\Delta\theta$ (deg)	Θ *) (deg)
1	Untilted	69.28	90.35	0.02	2.59	69.76	1.35	2.92
	Tilted	69.68	99.42	-2.57		68.41		
2	Untilted	69.08	90.40	0.06	2.75	69.73	1.06	2.94
	Tilted	66.69	97.71	-2.69		68.67		
3	Untilted	90.42	90.42	0.06	2.95	69.75	0.08	2.94
	Tilted	89.71	89.71	-2.89		69.83		

* θ is the incident angle; Θ is the tilted angle

The three direction cosines relation: $cos^2\Theta = 1-(sin^2\Delta\theta + sin^2\Delta\alpha)$

One can easily prove [5] that the variation of α can be used to measure the slant angle of the surface normal on the plane perpendicular to the incident plane; the variation in incident angle (Δθ) can be used to measure the slant angle of the surface normal on the incident plane. The three direction cosines of the surface normal are tilted from (0, 0, 1) to (sinΔθ, sinΔα, cosΘ) by the spacer. Θ obtained from the ellipsometric measurements is 2.93°, which is almost the same as what have been obtained from the geometric setup (Fig. 2), i.e. 2.90°. Using least square fitting in α, such as shown in Fig. 3, we can estimate the radius of cylindrical lens to be 259.56 mm. This result is also comparable with its specific value $248.79\ mm \pm 1\%$, provided by the manufacture.

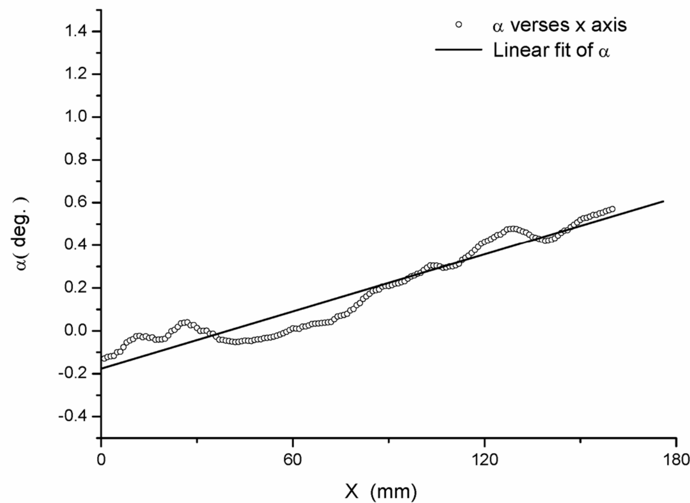

Fig. 3. Imaging ellipsometric study of the cylindrical lens: the open circles are α at x-axis of the lens, and the solid line indicates the best linear fit of this relationship.

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After this careful calibration in bending angle, we are able to correct the ellipsometric parameters and deduce the thickness profile in this imaging ellipsometry, as shown in Fig. 4, which is $100 \pm 4.3\ nm$ on the cylindrical lens surface; while the film thickness of the coated flat glass measured by this imaging ellipsometer is $97 \pm 6\ nm$, such as shown in Fig. 5. Moreover, we also measured the film thickness of the flat glass by a surface profiler (Tencor Alpha Step 500) obtained the similar result.

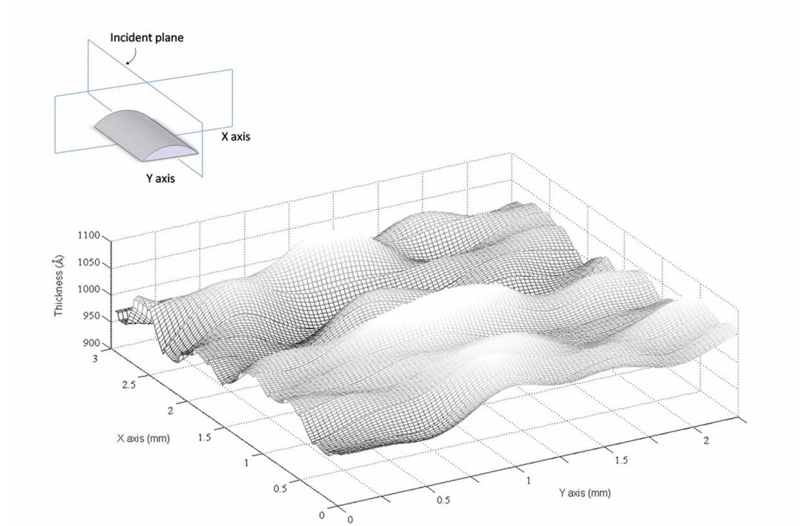

Fig. 4. Imaging ellipsometric measurement of thickness profile of the coated thin film on cylindrical lens

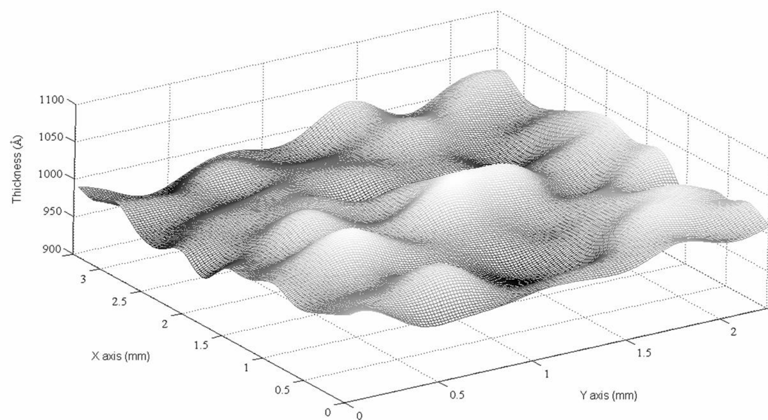

Fig.5. Imaging ellipsometric measurement of thickness profile on flat glass

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5. CONCLUSION

The PSA imaging ellipsometry, the azimuthal deviation α of polarizer can be obtained analytically. This additional parameter provides the feasibility of measuring the thin film on slanted/curved surface. After careful calibration, one not only obtain a two-dimensional ellipsometric parameters, one can also deduce its morphology of the surface. Just like what has been achieved for a GRIN lens [4] by this imaging ellipsometry, we also can investigate the stress distribution in thin film fabrication.

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