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Analytical Study of Precision Optical Glass Surface and Its Effect on Some Polarimetric Parameters

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Abstract

The performance of many optical glass elements depends on the structure of the surface. The high refractive index of flint glass is advantageous in constructing some optical elements (lenses, prisms, beam splitters, …). Also, high achromaticity and size reduction in oblique incidence TIR (total internal reflection) phase retarders require high-index glass. The present work is interested in studying the optical properties of the thin surface layer formed on TIR rhomb retarder at different wavelengths to indicate the extent to which this surface layer affects the performance of this TIR rhomb retarder and show how to overcome this effect.

Keywords

Optical Glass, Ellipsometry, Oblique Incidence Retarder, Surface Layer and Retardance

1. Introduction

The optical glass used in manufacturing optical elements or devices is subjected to mechanical polishing, chemical etching, or other processes to improve the quality of its surfaces. The performance of many optical glass elements depends on the structure of the surface. Thus, a clean and smooth surface with a similar composition to that of the bulk glass is essentially required in many optical elements. However, these requirements cannot be always fulfilled, particularly because of surface treatment, glass degradation, environmental effects, and other factors that lead to the formation of surface layer. Single homogeneous surface film model and effective medium model describing nano roughness of the surface are usually considered in studying the formed surface layers [1] [2] [3] [4].

Quality control of a functional surface of optical glasses must be precise to give an optimally functional state, enough rapid and economic. There are many methods for measuring the surface roughness of glasses such as image processing, microscopes, stylus type instruments, profile tracing instruments, etc., [5]. The contact methods for the determination of roughness are undesirable because they are destructive and let prints on the tested surface. Ellipsometric technique can be used to determine the optical constants, the surface thickness and roughness of the bulk optical glass. It has several advantages over other methods. Among these are the simplicity of measurement and the ease of sample preparation. Besides, it is non-destructive and requires only a very small sample size.

Ellipsometry can be conveniently divided into two parts, the first is the measurement technique for determining ψ and Δ, which describe the change in amplitude and phase in the reflected wave. The second is the theory required to relate the optical parameters of the thin film formed on the substrate, (the refractive index n, the extinction coefficient k, and the thickness d) to the measured values of ψ and Δ.

Figure 1, represents a thin film of thickness d and optical constants n_l, k_l over the substrate. E_P and E_s are the components of the incident field in the plane of incidence and perpendicular to the plane of incidence. The components of the reflected field are R_P and R_s.

For the incident and the reflected fields, suppressing the propagation factor,

$$E_P = E_{0P}e^{i\alpha_P} ,$$

$$E_s = E_{0s}e^{i\alpha_s} ,$$

$$R_P = R_{0P}e^{i\beta_P} ,$$

$$R_s = R_{0s}e^{i\beta_s} .$$

where (α_p, α_s) and (β_p, β_s) are the phases of the incident and reflected components, introducing the complex reflection coefficients ρ_p, ρ_s relating the reflected field components to the incident field components.
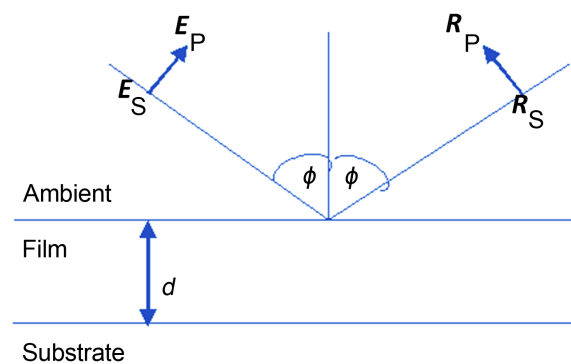

Figure 1. Film/substrate structure. d is the film thickness, p and s are the parallel and perpendicular components of the incident and reflected light, and Φ is the angle of incidence.

$$R_p = \rho_p E_p,$$

$$R_s = \rho_s E_s.$$

Defining a complex relative amplitude attenuation ρ as

$$\rho = \rho_p / \rho_s$$

Then,

$$\rho = \left[\left(R_{0p}/E_{0P} \right) \middle/ \left(E_{0s}/E_{0S} \right) \right] e^{i(\beta - \alpha)}$$

where $\alpha = \alpha_p - \alpha_s$ and $\beta = \beta_p - \beta_s$.

We can express $\Delta = (\beta - \alpha)$ and $\tan\psi = \left(R_{0p}/E_{0P} \right) \middle/ \left(E_{0s}/E_{0S} \right)$.

So,

$$\rho = \tan\psi \, e^{i\Delta} = f(n, k, d)$$

which is called the fundamental equation of ellipsometry. By finding the values of ψ and Δ using ellipsometric analysis at a definite angle of incidence Φ and the value of n_g (the refractive index of the glass) known in advance, the problem seems to relate these values to n, k, and d [6].

The present work was initiated by the fact that on calibrating an oblique-incidence $\lambda/4$ phase retarder [7], **Figure 2** at wavelength (589 nm), it was found that the device provided a retardance of $\square$ 87°, *i.e.*, 3° less than the theoretically calculated value.

This difference could be attributed to several factors including error in the external angle of incidence, birefringence in the bulk glass, a manufacturing error in the acute angle α or formation of surface layers on the reflecting surfaces. This device belongs to a class of total internal (TIR) phase retarder known as oblique-incidence retarders. In this class, the angle of (TIR) θ are not of fixed value but varies with the refractive index n of the used glass (or equivalently, with the wavelength λ of the incident light) [8] [9].

Such that,

$$\theta = \alpha + t$$

And

$$t = \sin^{-1}(\sin i / n)$$

where α is the angle between the entrance face and the reflecting surface, i is the angles of incidence and t is the angle of refraction. From the previous equation, we notice that, for the same value of incidence i, the angle of t will vary with n (or with λ). Thus, θ is no longer of fixed value and the retardance is expressed as:
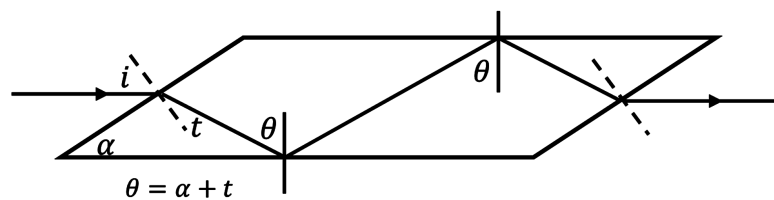

Figure 2. Oblique incidence $4/\lambda$ phase retarder, $n_g = 1.70002$ at 589 nm.

$$\delta = f(n, \theta)$$

where, $\theta = f_1(n)$ and $n = f_2(\lambda)$.

Present work is interested in studying the optical properties of the thin surface layer formed on this TIR rhomb retarder which is made of flint glass (n_g = 1.70002 at 589 nm) at spectral wavelengths from (400 - 800) nm in steps 100 nm and will study the effect of this formed layer on the performance of this TIR rhomb retarder. The effective medium approximation can then be used to analyze the measured ellipsometric values assuming the effective medium layer to consist of a physical mixture interface of air and glass.

2. Experimental Work

We studied the surface layer formed on one of the two reflecting faces of TIR rhomb retarder shown in Figure 2, which is made of flint glass (n_g = 1.70002 at 589 nm). The measuring equipment used is Spectroscopic ellipsometer PHE103 (Angstrom Advanced Inc.). It is an automated version supported by analyzing software. The sample is placed on a motorized stage that is controlled by the software and enables fine adjustment of incidence angle and the ellipsometric angles are measured with accuracy ±0.01°. A schematic diagram of the ellipsometer is presented in Figure 3 which consists of a light source, polarizer, analyzer, a quarter-phase plate (compensator), Φ is the angle of incidence and detecting system. The angle of incidence Φ was set at (Φ = 60°, 65°, 70°). The measurements were carried out in the spectral wavelengths from (400 - 800) nm in steps 100 nm and temperature of (20 ± 0.05)°C.

3. Results

The values of the ellipsometric parameters ψ and Δ according to the angles of incidence within the interval 60° and 70° are gathered in Table 1 and Figure 4 and Figure 5.

The values obtained from Table 1 allow drawing up Table 2 and Figure 6 for the values of n_b (the refractive index of the layer formed on the surface of the glass) versus the spectral wavelengths from (400 - 800) nm in steps 100 nm for different angles of incidence.
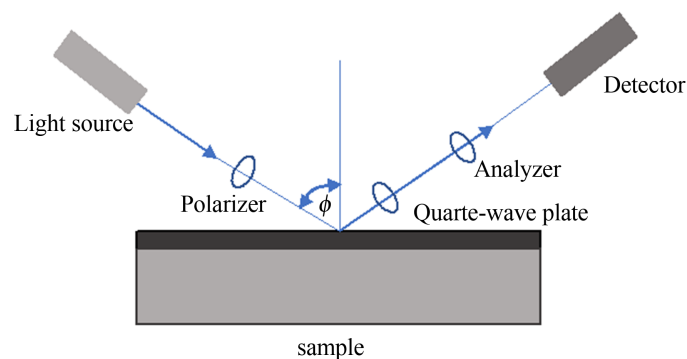

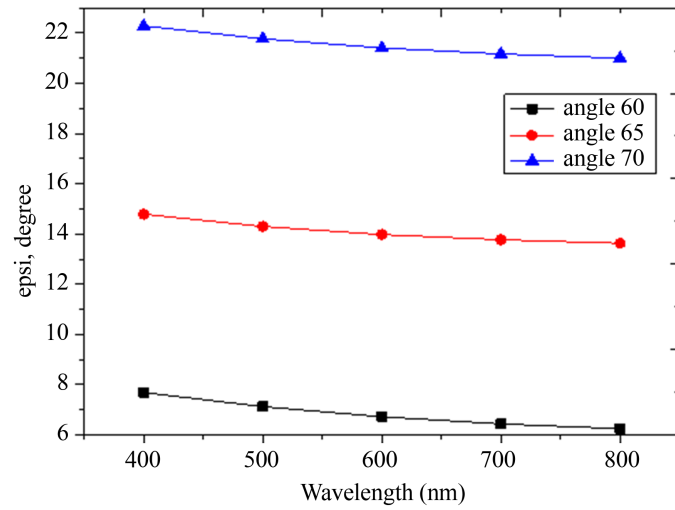**Figure 3.** Ellipsometric schematic diagram.

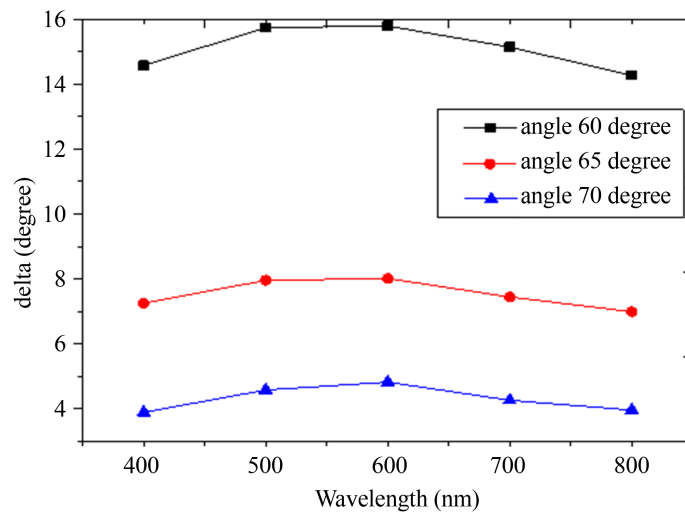**Figure 4.** The variation of Ψ versus the wavelength for different angles of incidence.

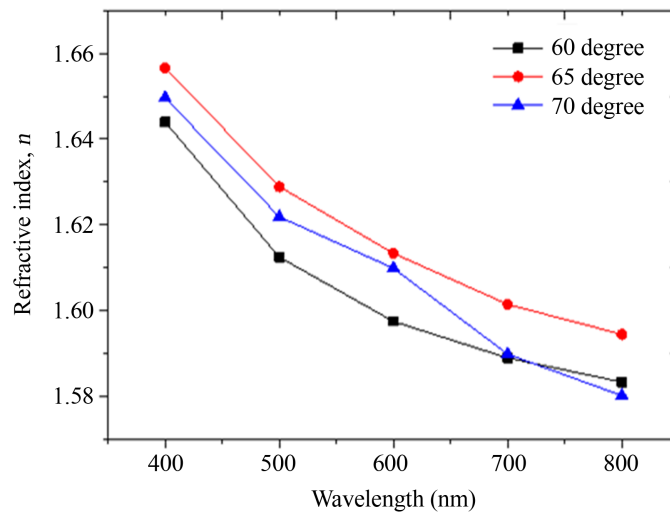**Figure 5.** The variation of Δ versus the wavelength for different angles of incidence.

Figure 6. The variation of n_f versus the wavelength for different angles of incidence.

Table 1. Values of ψ and Δ versus the wavelengths for different values of angle of incidence.

Wavelength, λ nm	$\Phi = 60°$		$\Phi = 65°$		$\Phi = 70°$	
	Ψ (°)	Δ (°)	Ψ (°)	Δ (°)	Ψ (°)	Δ (°)
400	7.69	13.57	14.79	7.26	22.28	3.9
500	7.13	15.74	14.30	7.96	21.77	4.59
600	6.73	15.79	13.98	8.02	21.41	4.83
700	6.44	15.14	13.77	7.45	21.17	4.27
800	6.25	14.27	13.63	7.00	21.00	3.97

Table 2. Values of the refractive index versus the wavelengths for different angles of incidence.

Wavelength, λ nm	n_f ($\Phi = 60°$)	n_f ($\Phi = 65°$)	n_f ($\Phi = 70°$)
400	1.6440	1.6566	1.6466
500	1.6125	1.6289	1.6489
600	1.5975	1.6134	1.5934
700	1.5890	1.5915	1.5899
800	1.5834	1.5945	1.5802

The values of the thickness of the formed layer d_f according to the angles of incidence within the interval 60° and 70° showed in Table 3.

Table 4 and Figure 7 show the differences between the refractive index for the formed layer n_f at the angle of incidence 60° and that of the glass substrate n_s.

From the analytical studying of the glass surface using ellipsometric method, The average n_f for 60°, 65° and 70° angles of incidence at 589 nm wavelength equals 1.6000 and d_f was extracted from Table 3 equals 122 nm.

4. Discussion

The experimental results showed a reduction of approximately 0.10 than the refractive index of the glass of the rhomb for all wavelengths. The main factor for this reduction in the formation of a surface layer on the sides of the rhomb, which in turn, explains the large reduction in the retardance value of the rhomb (−3°) during the calibration of the rhomb retarder. Other factors are the polishing effects and internal stresses [10]. In many optical measurements the surface layer, usually present on most glasses, is neglected either because it does not affect the measurement, or its effect is negligible. However, for measurements made using polarized light, particularly in ellipsometric measurements, the homogeneity of the studied surface is extremely important [11].
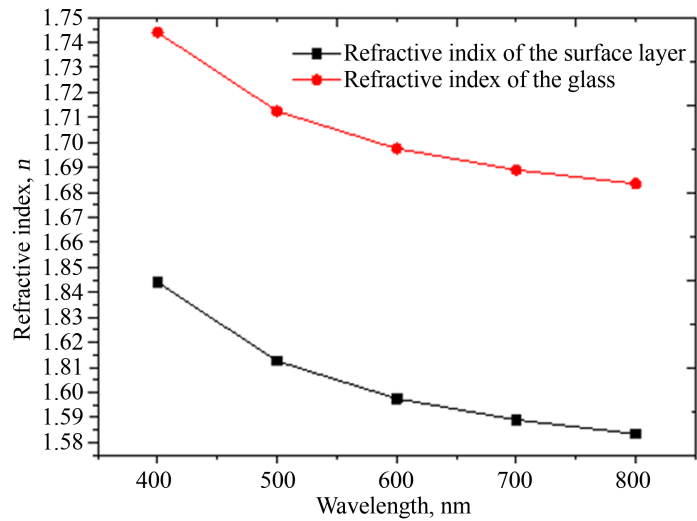
According to the relation,

Figure 7. The differences between the refractive index for the formed layer n_f at the angle of incidence 60˚ and that of the glass substrate ns.

Table 3. Values of the thickness of the formed layer versus the angle of incidence.

Angle of incidence, Φ (˚)	d_f (nm)
60	121
65	120
70	125

Table 4. The refractive index of the formed layer and that of the glass versus the wavelength at Φ = 60˚.

Wavelength, λ nm	n_f (Φ = 60˚)	n_s
400	1.6440	1.7440
500	1.6125	1.7125
600	1.5975	1.6975
700	1.5890	1.6890
800	1.5834	1.6834

$$\theta = \alpha + t = \alpha + \sin^{-1}\left(\sin i/n\right),$$

where i and t are the angles of incidence and refraction on the entrance face.

We notice that the angle t varies with n. Thus, θ is no longer of fixed value and in this case the retardance is expressed as

$$\delta = f\left(n, \theta\right)$$

where $\theta = f_1\left(n\right)$ and $n = f_2\left(\lambda\right)$.

The retardance of our rhomb could be adjusted to a value close to 90˚ by a small variation in the external angle of incidence i [12]. We note that variations in the external angle of incidence i could be compensated with the variation of n. Thus, the device retardance can be adjusted will by simply changing angle i.

5. Conclusion

This work describes the use of ellipsometry as a precise and accurate technique to test and monitor changes of surfaces of optical components because of the manufacturing or by environmental surroundings, which affects some optical measurements such as the retardance value of TIR rhomb retarder, to adjust and make corrections in the result values.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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