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Reduction in thickness error of optical coatings by dividing thick layers and monitoring with multiple witness glasses

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We present a monitoring strategy based on using two pieces of witness glass, which are brought to the measuring position in a specially chosen sequence, each witness glass is monitored by one single wavelength. To reduce the thickness error, some thick layers are divided into two layers and monitored by different witness glasses. Theoretical analysis and experimental results have demonstrated that the proposed monitoring strategy can achieve spectral performance close to the theoretical design.

1. Introduction

Accurate and reliable control of layer thickness is essential to improve the spectral performance of the coating, and to meet the theoretical design requirement [1–4]. A variety of monitoring methods have been developed to control the layer thickness [1,5–12], of which turning point method is the most developed and mature, with an attractive feature of error self-compensation mechanism [5,13]. However, the change in transmittance with thickness becomes zero at the turning point [5,14], as well as the noise of the monitoring system [1], makes it difficult to detect the turning point precisely and accurately [15]. Considerable works have been done to enhance the monitoring precision, and consequently improve the coating performance [1,2,6,14–19]. Lee et al. [1] proposed a monitoring method based on selecting the most sensitive monitoring wavelength. Tikhonravov et al. [6] developed an approach to choose monitoring strategy based on minimizing the thickness deviations by selecting an appropriate monitor wavelength for every layer. Lai et al. [18] used two monitoring wavelengths to ensure that every layer has a sensitive terminal point. All these works aim at reducing the layer thickness error.

In this paper, we present an optical monitoring approach based on using two pieces of witness glass, which are brought to the measuring position in a specially chosen sequence, transmittance of each witness glass is monitored by one single wavelength for each. To reduce the thickness error, some thick layers are divided into two layers and monitored by different witness glasses. Both theoretical simulation and experimental results demonstrate that the proposed monitoring method can achieve better optical performance than that using the turning point method.

2. Methods

Let us assume that we are dealing with the normal incidence and lossless case. For a multilayer coating, the characteristic matrix method is used for calculation and is given by the following formula [5]:

$$\begin{bmatrix} B \\ C \end{bmatrix} = \begin{bmatrix} \cos\ \delta & \dfrac{i}{n(\lambda)}\sin\ \delta \\ in(\lambda)\sin\ \delta & \cos\ \delta \end{bmatrix} \begin{bmatrix} 1 \\ \alpha + i\beta \end{bmatrix} \tag{1}$$

where, $\delta = 2\pi nd/\lambda$, $n(\lambda)$ is the refractive index of the current layer, λ is the monitoring wavelength, α and β are the real and imaginary parts of the equivalent admittance of the previously stacked layers, respectively.

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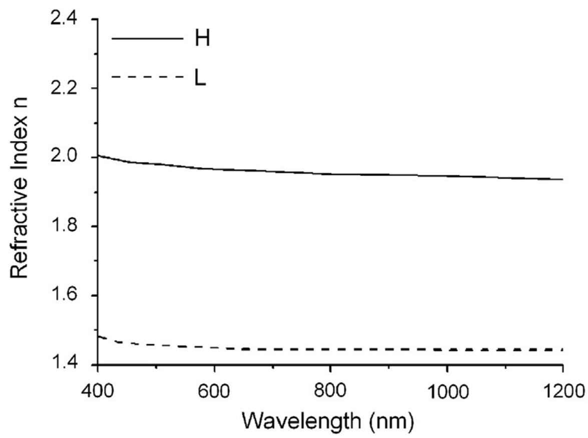

Figure 1. Refractive indices of HfO_2 and SiO_2 layer as a function of wavelength.

The corresponding transmittance at the termination point can be predicted as following [5,19]:

$$T = 4\alpha / \left[(1+\alpha)\cos\ \delta - \frac{\beta \sin\ \delta}{n(\lambda)} \right]^2 + \left[\left(\frac{\alpha}{n(\lambda)} + n(\lambda) \right) \sin\ \delta + \beta \cos\ \delta \right]^2 \quad (2)$$

However, the deposition might not be stopped precisely at the theoretical termination point. When the actual thickness overshot Δd (named thickness error) from the target thickness d which should realize the termination point, the transmittance deviates ΔT from the transmittance at the termination point, $T_d(\lambda)$; the transmittance $T_{d+\Delta d}(\lambda)$ at the actual termination point can be written as,

$$T_{d+\Delta d}(\lambda) = T_d(\lambda) + \Delta T \quad (3)$$

For a given ΔT, we can obtain the Δd of each layer by solving Eq. (3), and can also plot the expected thickness error Δd of each layer as a function of monitoring wavelength λ.

A film with a layer structure S/HLHLHLHL/A is used as an example. HfO_2 and SiO_2 are chosen as high (H) and low (L) refractive index materials, and H and L have a quarter-wave optical thickness at the reference wavelength. The refractive indices of witness glass (S) and the incident medium (A) are 1.52 and 1.0, respectively; the reference wavelength is 1064 nm, and the monitoring wavelength is chosen from a wavelength range from 400 nm to 800 nm.

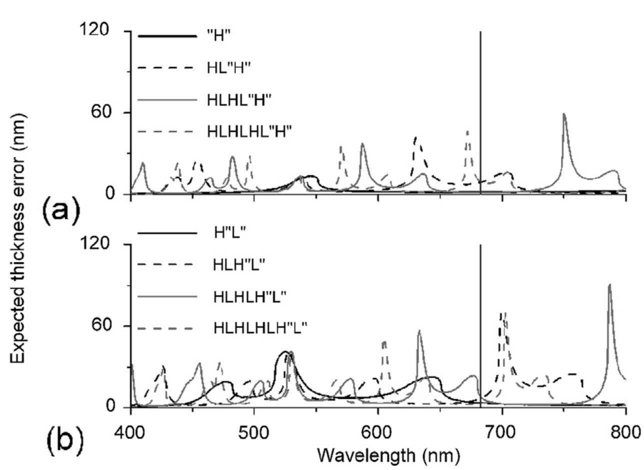

Figure 2. Expected thickness error as a function of monitoring wavelength. (a) High refractive index layer "H"; (b) Low refractive index layer "L".

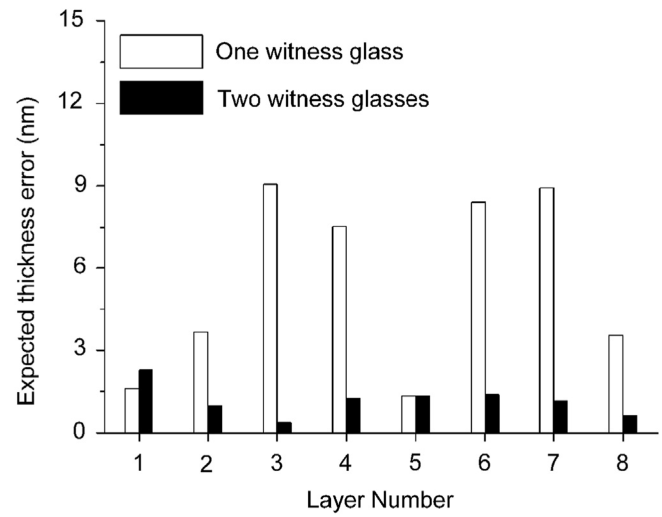

Figure 3. Expected thickness error when monitored with one and two witness glasses, respectively.

In order to determine the refractive index n, HfO_2 and SiO_2 single-layer coatings are deposited on glass substrates at temperature of 200 °C by e-beam evaporation with using a Leybold 1110 coating machine. The deposition rate of HfO_2 is about 0.3 nm/s, while the deposition rate of SiO_2 is about 0.6 nm/s. Ambient oxygen pressure are about 2×10^{-4} mbar and 5×10^{-5} mbar during HfO_2 and SiO_2 deposition, respectively. A Perkin Elmer Lambda 1050 spectrophotometer is used to measure the transmittance of a bare glass and coated glass at normal incident angle, and thin film design software, TFCalc (Software Spectra, Inc.) is employed to evaluate the refractive indices of both materials from the measured transmittance. The numerically fitted values are presented in Fig. 1 and used in the optical layer designs for this work. The coating condition in this work are fixed into the above-mentioned ones for HfO_2 and SiO_2 deposition, and OMS 3000 (Leybold) is used to determine the layer thickness during the coating process.

Here, we assume that a constant overshoot of 0.2% in transmittance would occur in the deposition process of each layer. The corresponding thickness error of each layer to the transmittance overshoot is evaluated for various monitoring wavelengths and shown in Fig. 2.

It is obvious from Fig. 2 that the expected thickness error varies with monitoring wavelength, and a monitoring wavelength of 683 nm would be chosen because the maximum thickness error in Hs and Ls are smaller than that at the other monitoring wavelengths. The thickness error of each layer at 683 nm is given by the white bars in Fig. 3. Unfortunately, the thickness error of this level may not be acceptable to obtain well enough optical performance

Table 1
Monitoring strategy for different designs.

Witness glass no.	1	2
Layer no. (Design 1)	1, 2, 4–1st, 5–1st, 6–16, 19–34	3, 4–2nd, 5–2nd, 17, 18, 35, 36
Layer no. (Design 2)	1, 2, 3–1st	3–2nd, 4–30
Layer no. (Design 3)	1–1st, 2–1st, 3–1st, 4–1st, 5–38	1–2nd, 2–2nd, 3–2nd, 4–2nd