Spectral polarimetry-based measurement of the thickness of a thin film

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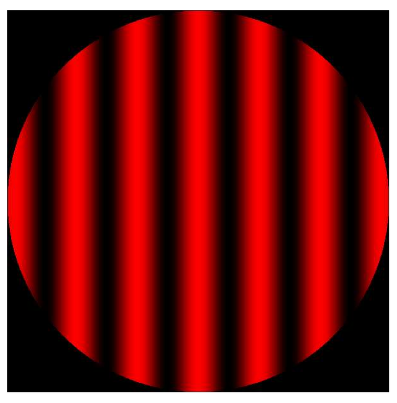


1. Abstract

A simple polarimetry configuration is used for measuring the thickness of a nonabsorbing thin film on an absorbing substrate from the ratio between the spectral reflectances of p- and s-polarized components reflected from the thin-film structure. The spectral reflectance ratio measured at a fixed angle of incidence is fitted to the theoretical one to obtain the thin-film thickness provided that the optical constants of the thin-film structure are known. This procedure is used for measuring different thicknesses of a SiO_2 thin film on a Si substrate. Moreover, an approximate linear relation between the thin-film thickness and a wavelength of the maximum of the reflectance ratio for a specific angle of incidence is revealed when the substrate is weakly absorbing.

2. Measurement method

To measure the reflectance ratio $\Re^e(\lambda)$, a three-step procedure with a spectrometer can be used [1]:

$$\Re^e(\lambda) = \frac{R_p^e(\lambda)}{R_s^e(\lambda)} = \frac{I_p(\lambda) - I_{bkg}(\lambda)}{I_s(\lambda) - I_{bkg}(\lambda)}. \quad (1)$$

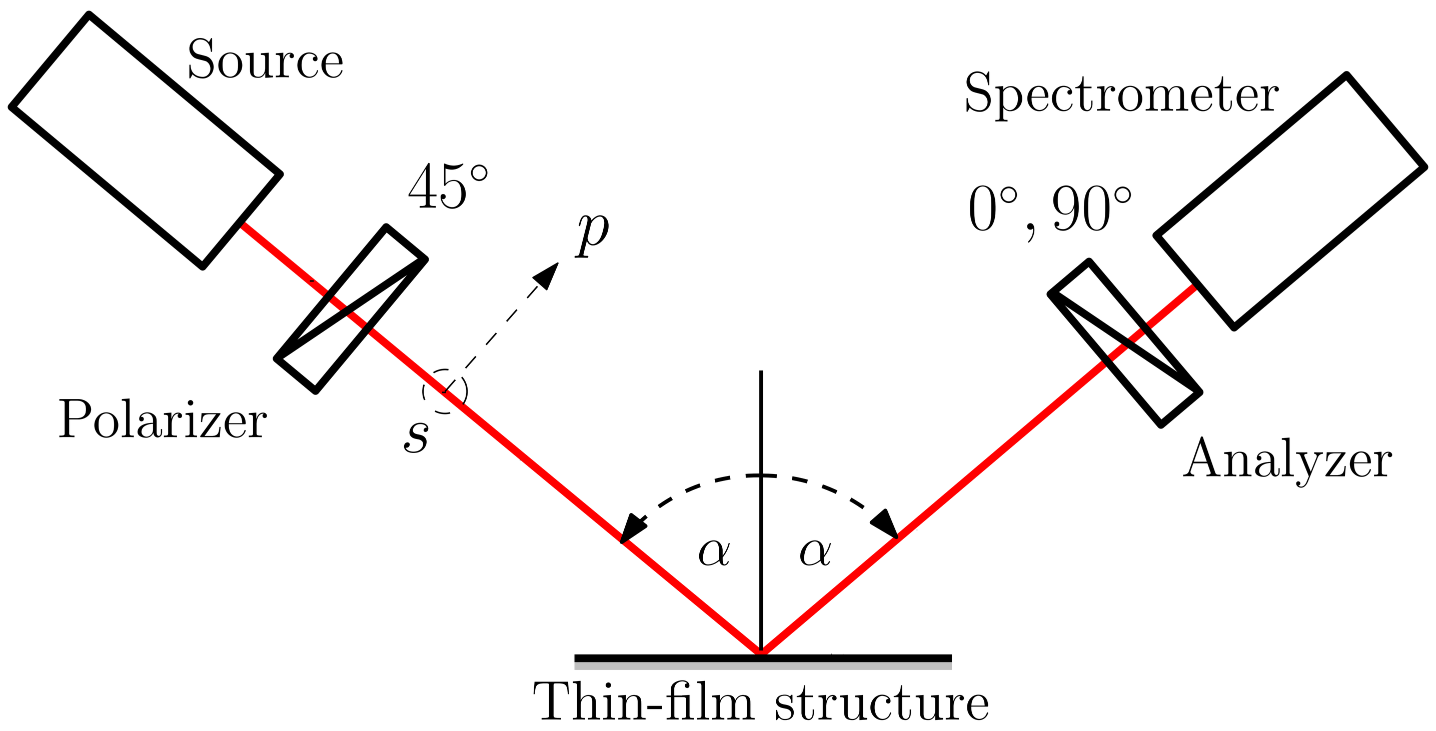


Figure 1: *Experimental setup with a polarimetry configuration to measure the reflectance ratio $\Re^e(\lambda)$.*

3. Theoretical background

The spectral reflectances of p- and s-polarized components and the theoretical reflectance ratio $\Re(\lambda) = R_p(\lambda)/R_s(\lambda)$ of the thin-film structure as well, can be expressed using:

$$R_{p,s}(\lambda) = \frac{R_{1p,s}(\lambda) + R_{2p,s}(\lambda) + 2[R_{1p,s}(\lambda)R_{2p,s}(\lambda)]^{1/2}\cos[2\beta(\lambda) + \phi_{p,s}(\lambda)]}{1 + R_{1p,s}(\lambda)R_{2p,s}(\lambda) + 2[R_{1p,s}(\lambda)R_{2p,s}(\lambda)]^{1/2}\cos[2\beta(\lambda) + \phi_{p,s}(\lambda)]}. \quad (2)$$

The equation contains the relationship between the thin-film thickness and the tangent wavelengths $\lambda_{\tan,m}$ of the reflectance ratio spectrum [1]:

$$d = \frac{\lambda_{\tan,m}}{4\pi[n_1^2(\lambda_{\tan,m}) - \sin^2\alpha]^{1/2}}[(2m+1)\pi - \phi_s(\lambda_{\tan,m})]. \quad (3)$$

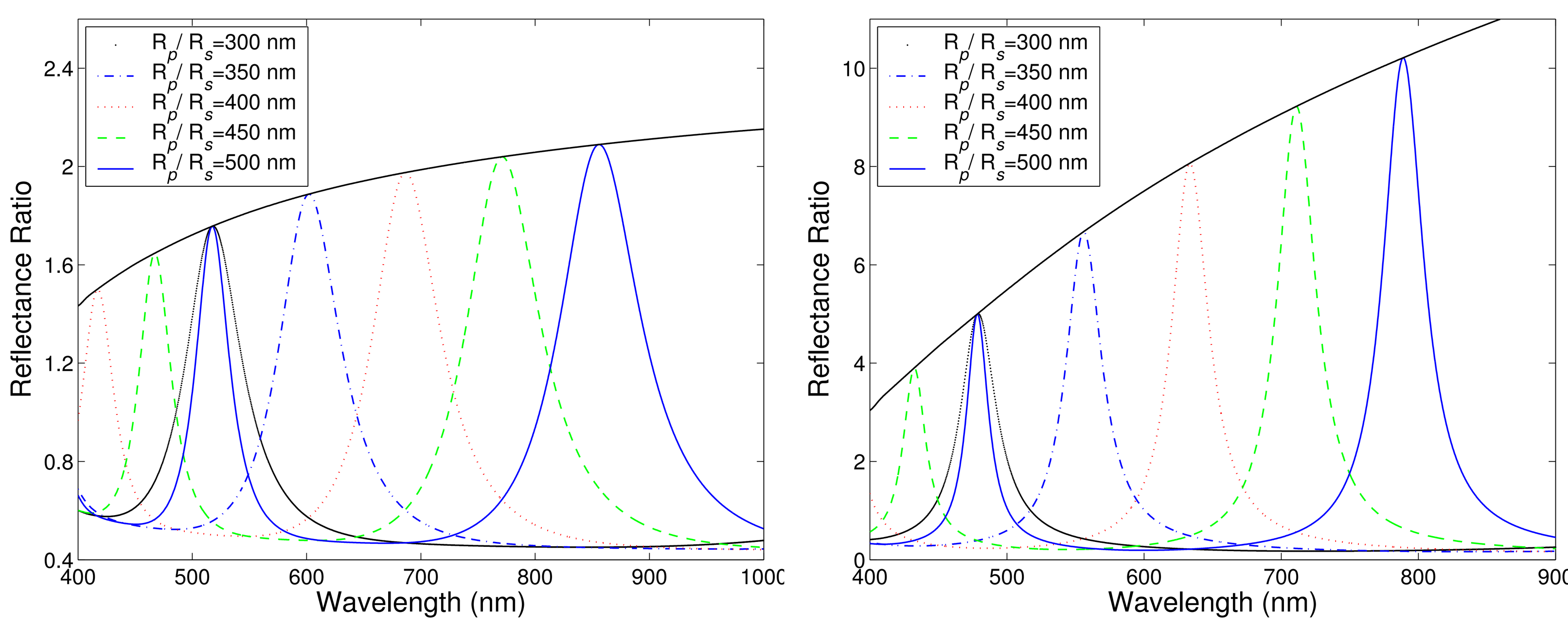
where m is an integer.

4. Numerical simulations

Using Eq. (2), we constructed the theoretical spectral reflectance ratio $\Re(\lambda)$ as a function of wavelength λ for a SiO_2 thin film on a Si substrate (see Fig. 2) and the data taken from [2, 3]. We constructed the approximate function $d = f(\lambda_{\max,m})$ derived from Eq. (3), where $\lambda_{\max,m}$ is the wavelength of the maximum, which is close to $\lambda_{\tan,m}$ for a weakly absorbing substrate [1]. This dependence is illustrated in Fig. 4 for three angles of the incidence $\alpha = 30°, 45°$, and $60°$. According to Fig. 4, it is evident that the functions are linear (the correlation coefficients of the linear fits are 1) and can be expressed as:

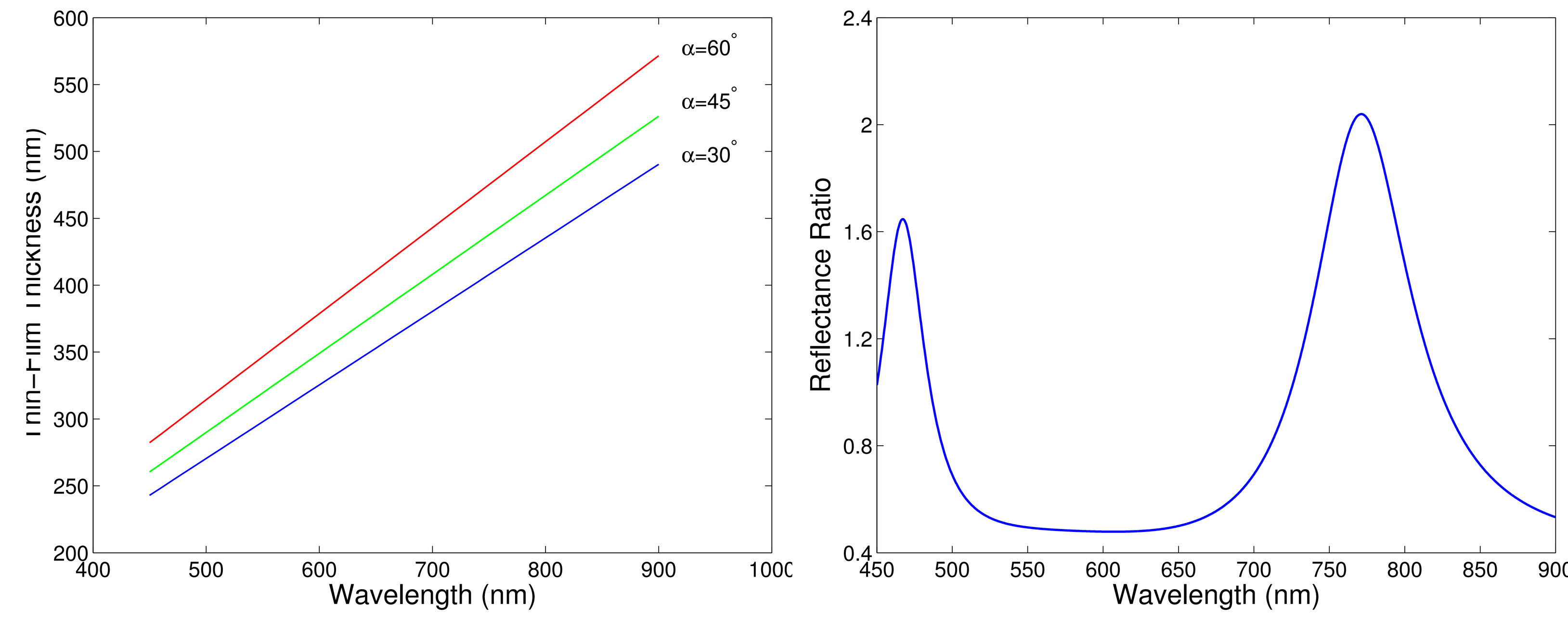
$$d = A + B\lambda_{\max,m}, \quad (4)$$

where the characteristic parameters A and B are listed in Table 1.



(a) (b)

Figure 2: *Theoretical wavelength dependences of the reflectance ratio $\Re(\lambda)$ for the SiO_2 thin film of the thicknesses d=300, 350, 400, 450, and 500 nm on a Si substrate (a) $\alpha = 45°$, (b) $\alpha = 60°$.*



(a) (b)

Figure 3: *(a) Approximative linear dependences of the thin film thickness on the wavelength of a maximum of the reflectance ratio $\Re(\lambda)$ for $\alpha = 30°, 45°$, and $60°$ and the SiO_2 thin film on a Si substrate. (b) Theoretical reflectance ratio $\Re(\lambda)$ for the angle of incidence $\alpha = 45°$ and the SiO_2 thin film of thickness d=450 nm on the Si substrate ($\lambda_{\max,1}$ =771.31 nm).*

Table 1: *Parameters A and B for the angles of incidence α and the SiO_2 thin film on a Si substrate with the wavelengths $\lambda_{\max,m}$ and the thicknesses d corresponding to Eq. (4).*

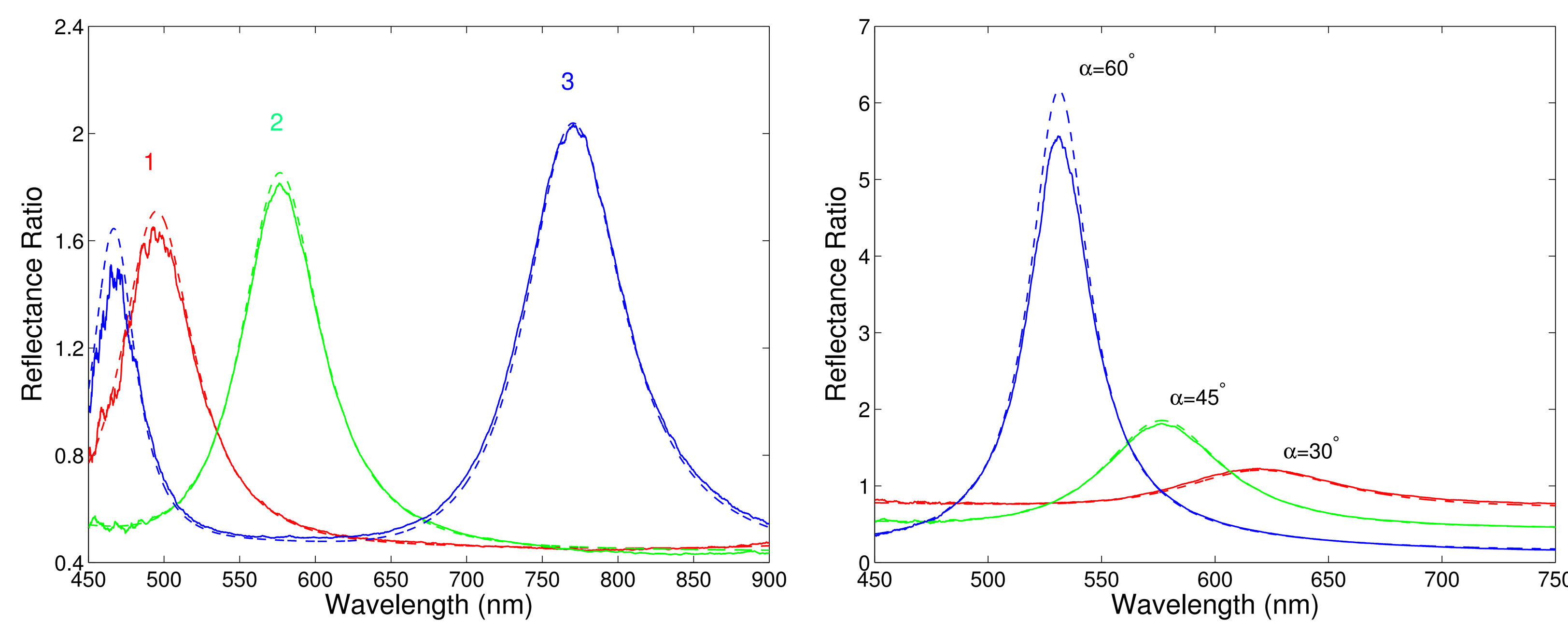
α (°)	A (nm)	δA (nm)	B	δB	$\lambda_{\max,1}$ (nm)	d (nm)
30	-4.5045	±0.0119	0.54988	±0.00002	827.01	450.3
45	-5.5590	±0.0146	0.59098	±0.00002	771.31	450.3
60	-7.1025	±0.0185	0.64297	±0.00003	711.23	450.2

5. Experimental results and discussion

The wavelength dependence of the reflectance ratio $\Re^e(\lambda)$ was measured for three samples of SiO_2 thin films on a Si substrate (see Fig. 4) by the three-step procedure presented above (angles of the incidence $\alpha = 30°, 45°$, and $60°$). The thicknesses d and d_{fit} of the SiO_2 thin films determined from the maxima and the measured reflectance ratios, respectively, are listed for $\alpha = 45°$ in Table 2. The results agree very well with those obtained by a technique of spectral reflectometry [4]. Moreover, the dashed curves in Fig. 4 (the theoretical reflectance ratios) demonstrates a good agreement between the theory and experiment.

Table 2: *Oxidation times T, angle of incidence α, thicknesses d [4], wavelengths $\lambda_{\max,m}$, thicknesses d and d_{fit} of the SiO_2 thin films.*

Sample	T (min)	d (nm) [4]	α (°)	$\lambda_{\max,1}$ (nm)	d (nm)	d_{fit} (nm)
1	122	285.3	45	496.82	288.1	286.3
2	212	337.4	45	577.49	335.7	334.8
3	392	450.6	45	771.29	450.3	449.5



(a) (b)

Figure 4: *(a) Measured reflectance ratio $\Re^e(\lambda)$ for the angle of incidence $\alpha = 45°$ and the third sample compared with a fit (dashed). (b) Measured and theoretical (dashed) wavelength dependences of the reflectance ratio $\Re^e(\lambda)$ for $\alpha = 30°, 45°$, and $60°$ and sample 2 of the SiO_2 thin film on a Si substrate.*

6. Acknowledgments

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References

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