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Ellipsometry of single-layer antireflection coatings on transparent substrates

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ABSTRACT

The complex reflection coefficients of *p*- and *s*-polarized light and ellipsometric parameters of a transparent substrate of refractive index n_2, which is coated by a transparent thin film whose refractive index $n_1 = \sqrt{n_2}$ satisfies the anti-reflection condition at normal incidence, are considered as functions of film thickness *d* and angle of incidence ϕ. A unique coated surface, with $n_1 = \sqrt{n_2}$ and film thickness *d* equal to half of the film-thickness period D_ϕ at angle ϕ and wavelength λ, reflects light of the same wavelength *without* change of polarization *for all incident polarization states.* (The reflection Jones matrix of such coated surface is the 2×2 identity matrix pre-multiplied by a scalar, hence $\tan\Psi = 1, \Delta = 0$.) To monitor the deposition of an antireflection coating, the normalized Stokes parameters of obliquely reflected light (e.g. at$\phi = 70^\circ$) are measured until predetermined target values of those parameters are detected. This provides a more accurate means of film thickness control than is possible using a micro-balance technique or an intensity reflectance method.

1. Introduction

Antireflection coatings (ARCs) are widely used on ophthalmic eye glasses, lenses of imaging systems, and other optical elements. ARCs are also important for increasing the efficiency of photovoltaic solar cells and photodetectors used in optical communication systems. Consequently, the optical characterization of such coatings is of interest.

Whereas the present work is focused on transparent substrates, the results are nearly equally applicable to substrates such as Si for which $k << n$, where n and k are the real and imaginary parts of the complex refractive index. (For Si, $0.002 \leq k/n \leq 0.094$ and $n > 3.6$, in the 390–760 nm visible spectral range [1].)

For a transparent substrate of refractive index n_2, the refractive index n_1 and thickness d of a transparent single-layer ARC for zero reflection at normal incidence are given by $n_1 = \sqrt{n_2}$ and $d = \lambda/(4n_1)$, respectively, where $\lambda$is the wavelength of light in air or vacuum ($n_0 = 1$) [2,3].

Here we examine the reflection properties of such coatings and the potential of *in-situ* (in-vacuum) monitoring of their deposition via measurements of the Stokes parameters of obliquely reflected light at sufficiently high angle of incidence (e.g.$\phi = 70^\circ$).

We first consider optical coatings that *only* satisfy the AR *refractive-index* condition $n_1 = \sqrt{n_2}$. For a given angle of incidence ϕ, the complex reflection coefficients R_p and R_s for incident *p*- and *s*-polarized light (Section 2) and their ratio $\rho = R_p/R_s = \tan\psi \exp(j\Delta)$ (Section 3) are periodic functions of the normalized film thickness $\varsigma = d/D_\phi$, with first period $0 \leq \varsigma \leq 1$, and

$$D_\phi = (\lambda/2)(n_1{}^2 - \sin^2\phi)^{-1/2}, \tag{1}$$

is the *metric* film-thickness period at given λ and ϕ.

As a concrete example, we consider an IR-transparent Si substrate ($n_2 = 3.478$ [4]), which is coated by a single layer of SiON of the proper stoichiometry ($n_1 = \sqrt{n_2} = 1.865$[5]), at the optical communications wavelength $\lambda = 1{,}55\ \mu$m.

An important conclusion of Section 3 is that a coating with $n_1 = \sqrt{n_2}$ and normalized film thickness $\varsigma = 1/2$ at given λ and ϕ is characterized by $\rho = 1$, $\psi = 45^\circ$, $\Delta = 0$. Such a coated surface reflects light *without* change of polarization *for all incident polarization states.* This condition can be verified experimentally by placing the coated reflector between linear polarizer and analyser in the incident and reflected beams, respectively, at azimuth angles P and $A = P \pm 90^\circ$ measured from the plane of incidence (p direction), and detecting a null *independent* of P. High precision of null detection is achieved by introducing small ac Faraday rotation before the analyser and using a lock-in amplifier to zero the first harmonic of the detected signal at the modulation frequency [6].

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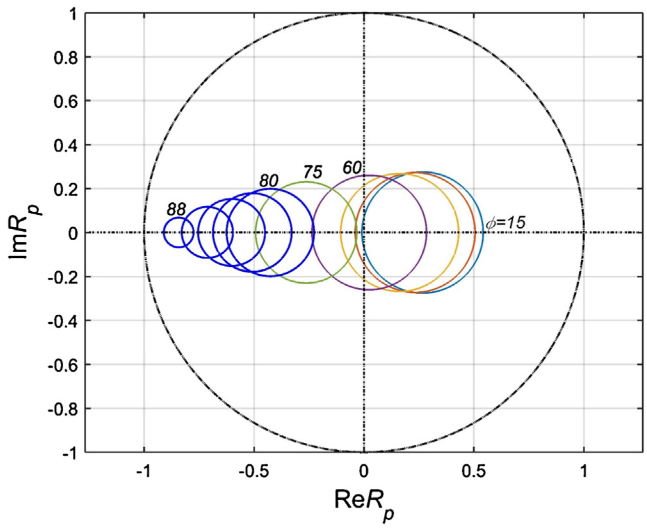

Fig. 1. CAI-VT contours of R_p for the SiON-Si film-substrate system ($n_1 = 1.865$, $n_2 = 3.478$) at $\lambda = 1.55\mu m$ and ϕ from 15° to 75° in steps of 15°, and 80° to 88° in steps of 2°.

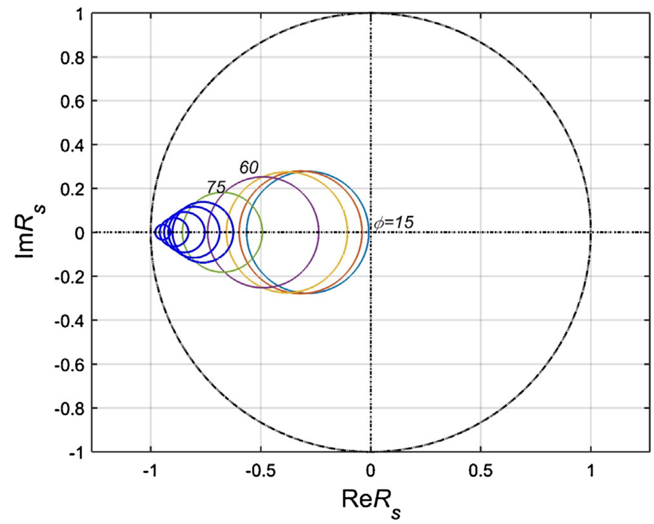

Fig. 2. CAI-VT contours of R_s for the same conditions as in Fig. 1.

In Section 4 the response of an ARC for incident *p*- and *s*-polarized light is considered as a function of ϕ from $\phi = 0$ to $\phi = 90°$. An ARC of quarter-wave thickness ($\varsigma = 1/2$) at normal incidence is *no longer* of quarter-wave thickness ($\varsigma < 1/2$) at oblique incidence.

To monitor the deposition of an ARC, incident linearly polarized light, e.g. at azimuth angle $P = 30°$, is reflected at oblique incidence. (The choice of $P = 30°$ is intended to compensate for the lower reflectance of the *p* polarization with respect to that of the *s* polarization.) The desired ARC is achieved when certain predetermined target values of the normalized Stokes parameters [6] s_1, s_2, s_3 of reflected light are detected by a Stokes-vector polarimeter, as further elaborated in Section 4. Finally, Section 5 gives a brief summary of this work.

Detailed equations that govern the reflection of *p*- and *s*-polarized light by thin-film-coated surfaces are available elsewhere (e.g. [6]) and are not repeated here.

2. Complex reflection coefficients R_p and R_s of transparent film on transparent substrate with refractive indices $n_1 = \sqrt{n_2}$

The complex reflection coefficients R_p and R_s of a film-substrate system for incident *p*- and *s*-polarized light are related to the complex exponential function $X = \exp(-j2\pi\varsigma)$ of normalized film thickness ς by a bilinear transformation (BT), $R_\nu = (r_{01\nu} + r_{12\nu}X)/(1 + r_{01\nu}r_{12\nu}X)$, $\nu = p, s$ [7], whose coefficients are determined by the Fresnel reflection coefficients ($r_{ij\nu}$, $\nu = p, s$) at the ambient-film (01) and film-substrate (12) interfaces.

For one full film-thickness period, $0 \le \varsigma \le 1$, the locus of X is the unit circle in the complex plane and its multiple images via the BT at different values of ϕ yield the families of constant-angle-of-incidence, variable-thickness (CAI-VT) contours or circles of R_p and R_s shown in Figs. 1 and 2, respectively. Figs. 1 and 2 represent the specific case of a Si substrate ($n_2 = 3.478$) and a thin-film coating of SiON ($n_1 = \sqrt{n_2} = 1.865$) at wavelength $\lambda = 1.55\mu m$. The circles are generated at discrete values of ϕ from 15° to 75° in equal steps of 15° and ϕ from 80° to 88° in equal steps of 2°. The outermost circle in Figs. 1 and 2 is the unit circle of *X*.

Two circles, not shown in Fig. 1, pass through the origin ($R_p = 0$) : one at $\phi = 0$, which represents the AR condition at normal incidence, and the other at $\phi = \phi_B = \arctan(3.478) = 73.959°$, which represents zero reflection of *p*-polarized light at the Brewster angle of the air-Si interface. At grazing incidence, $\phi = 90°$, the circle collapses to a single point at $R_p = -1$. All circles of R_p f or $\phi > \phi_B$ lie entirely in the left half plane.

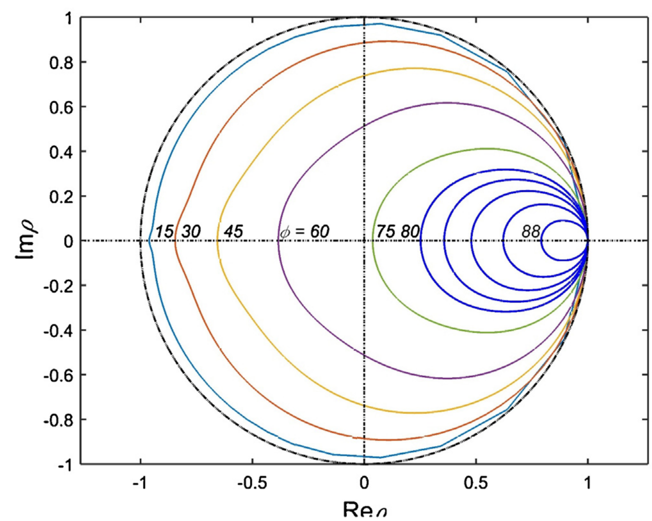

Fig. 3. CAI-VT contours of $\rho = R_p/R_s$ for the same conditions as in Figs. 1 and 2.

Compared to Fig. 1 for R_p, the family of circles of R_s in Fig. 2 are squeezed along the negative real axis. Again, the limiting circle at $\phi = 90°$ is the single point at $R_s = -1$.

3. Ratio of complex reflection coefficients $\rho = R_p/R_s$ and ellipsometric parameters of transparent film on transparent substrate with refractive indices $n_1 = \sqrt{n_2}$

Fig. 3 shows a family of CAI-VT contours of the ellipsometric function [6] $\rho = R_p/R_s$, at ϕ=15° to 75° in steps of 15° and ϕ=80° to 88° in steps of 2°, for a transparent SiON thin film ($n_1 = 1.865$) on a transparent Si substrate ($n_2 = 3.478$) that satisfy the AR condition $n_1 = \sqrt{n_2}$ at wavelength $\lambda = 1.55\mu m$. The outermost contour in Fig. 3 is the unit circle of *X*.

In Fig. 3 all contours pass through the common point $\rho = 1$ at $\varsigma = 0.5$ independent of ϕ. Therefore, for a transparent coating with $n_1 = \sqrt{n_2}$ and quarter-wave optical thickness ($\varsigma = 0.5$) at oblique incidence, the *complex* reflection coefficients R_p and R_s of the film-substrate system are *identical*, hence the state of polarization of