WHITE-LIGHT INTERFEROMETRIC METHOD TO MEASURE THICKNESS OF THIN FILMS

MERANIE HRÚBOK TENKÝCH FILMOV POMOCOU INTERFEROMETRICKEJ METÓDY V BIELOM SVETLE

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Abstract

In this paper, we present a white-light spectral interferometric technique for measuring the thin-film thickness by means of a slightly dispersive Michelson interferometer with a thin-film structure as a mirror. A new method of phase retrieval from the spectral signal is utilized, which is based on the use of a windowed Fourier transform in the wavelength domain. Two spectral interferograms are recorded to measure the spectral interference signal from which we retrieved the spectral phase including the effect of both a cube beam splitter and the phase change on refection from the thin-film structure. Knowing the effective thickness, dispersion of the beam splitter made of BK7 optical glass and the spectral phase, we can determine by simple procedure wavelength dependences of both OPD and nonlinear-like phase. The spectral functions are used to determine the thin-film thickness of a silicon dioxide on a silicon substrate. The results are compared with method based on fitting of the recorded spectral interferogram and they serve as an illustration of the feasibility of the new technique in measuring the thin-film thickness.

V tejto práci je prezentovaná metóda interferometrie v bielom svetle pre meranie hrúbok tenkých filmov pomocou slabo disperzného Michelsonovho interferometra, v ktorom tenký film nahrádza jedno zrkadlo. Je použitá nová metóda rekonštrukcie spektrálnej fázy, ktorá využíva Fourierovu transformáciu vo vlnovej oblasti. Pri spracovaní spektrálneho interferenčného signálu sú zahrnuté taktiež efekty deliča zväzkov, ako aj zmeny fázy pri reflexii na tenkom filme. Zo znalostí efektivnej hrúbky a disperzie deliča a ďalej spektrálnej fázy je možné určiť jednoducho OPD ako aj tzv. nelineárnu fázu. Tieto speltrálne funkcie sú použité pre určenie hrúbky SiO_2 *na kremíkovej podložke. Výsledky sú porovnané s metódou, ktorá fituje celý interferogram a ilustrujú vhodnosť tejto novej metódy na meranir tenkých filmov.*

Key words

White-light spectral interferometry, thin-film thickness, phase retrieval, windowed Fourier transform, nonlinear-like phase, silicon dioxide

Spektrální interferometrie v bílém světle, tloušťka tenké vrstvy, rekonstrukce fáze, okénková Fourierova transformace, nelineární fáze, oxid křemičitý.

Introduction

Physical thickness and wavelength dependences of optical constants [1] belong to the most important parameters and functions characterizing the thin-film structures. There are many optical methods [2], based on ellipsometric [3], reflectometric [4] or interferometric measurements how to determine these parameters and characteristics. Ellipsometric measurements performed at a single wavelength and a fixed angle of incidence provide the film thickness and optical constants. Measurements by spectroscopic ellipsometry and normal incidence spectroscopic reflectometry provide the results over a wide wavelength range with greater precision and accuracy. The optical method most commonly employed for micrometer-scale thickness measurements include Fourier transform infrared and white-light interferometry. Recently, a new technique of dispersive white-light spectral interferometry has emerged as a useful tool for measuring the thickness of thin films [5-7] and for distance measurement [8].

Theoretical and experimental background

Consider a slightly dispersive Michelson interferometer as shown in Fig. 1 with a cube beam splitter of the effective thickness t_{ef} and one of the mirrors represented by a thin-film structure on a substrate, which is characterized by a complex reflection coefficient [1, 2]:

$$r(\lambda) = \sqrt{R(\lambda)}\exp[i\delta_r(\lambda)], \tag{1}$$

where $R(\lambda)$ and $\delta_r(\lambda)$ are wavelength-dependent reflectance and phase change on reflection, respectively.

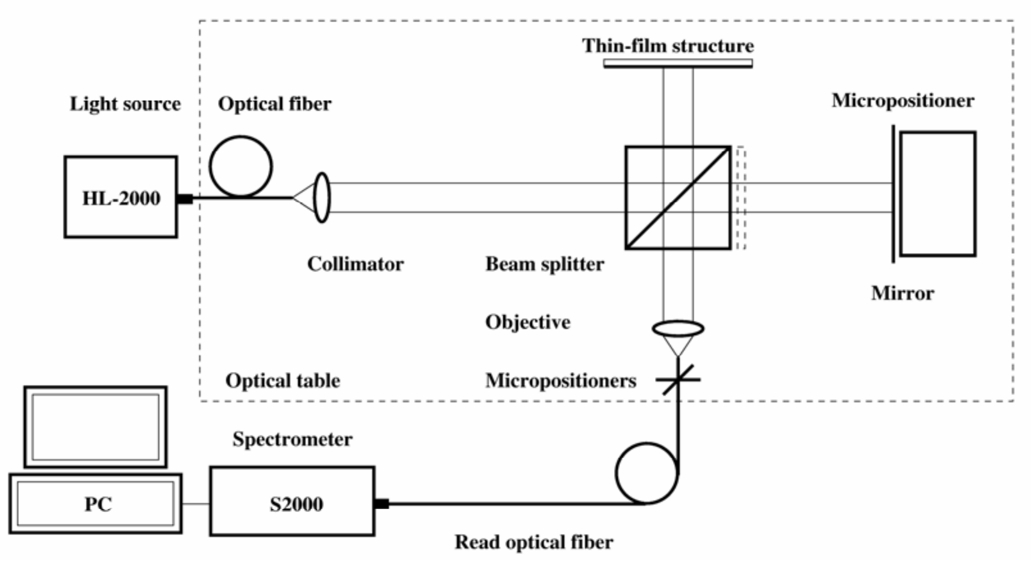

Fig. 1. *Experimental set-up with a Michelson interferometer to measure of the thin-film structure thickness on a substrate*

Suppose next that spectral intensity (interferogram) $I(\lambda)$ recorded at the output of the interferometer by a fiber-optic spectrometer of a Gaussian response function can be expressed as [4, 5]:

$$I(\lambda) = I^{(0)}(\lambda)\{1 + V(\lambda)\exp\{-\pi^2/2)[\Delta^g(\lambda)\Delta\lambda_R / \lambda^2\,]^2\}\cos[(2\pi/\lambda)\Delta(\lambda)]\}\,, \tag{2}$$

where $I^{(0)}(\lambda)$ is the reference spectral intensity, $V(\lambda)$ is a visibility term, $\Delta(\lambda)$ and $\Delta^g(\lambda)$ are the wavelength-dependent optical path difference (OPD) and group OPD between interfering beams, respectively, and $\Delta\lambda_R$ is the width of the spectrometer response function.

The wavelength-dependent OPD $\Delta(\lambda)$ between two beams in the Michelson interferometer is given by:

$$\Delta(\lambda) = 2L + 2n(\lambda)t_{ef} - \lambda\delta_r(\lambda)/(2\pi), \tag{3}$$

where $2L$ is the difference of path lengths between the interfering beams in the air whose dispersion is neglected, t_{ef} is the effective thickness of the beam splitter and $n(\lambda)$ is the wavelength-dependent refractive index of the beam splitter material. The corresponding group OPD $\Delta^g(\lambda)$ satisfies over the wavelength range slightly broader than that of the visible spectrum the approximation:

$$\Delta^g(\lambda) \cong 2L + 2N(\lambda)t_{ef}\,, \tag{4}$$

where $N(\lambda)$ is the wavelength-dependent group refractive index, which is related to the refractive index $n(\lambda)$ via the equation:

$$N(\lambda) = n(\lambda) - \lambda\frac{dn(\lambda)}{d\lambda}\,. \tag{5}$$

When light is incident on the surface of the thin-film structure on a substrate, multiple reflections take place and the complex reflection coefficient can be determined according to well-known relations [1]. The phase change $\beta(\lambda)$, that the reflected wave experiences as it traverses once from one boundary to the other, is given at normal incidence by:

$$\beta(\lambda) = (2\pi/\lambda)n_1(\lambda)d\,, \tag{6}$$

where $n_1(\lambda)$ is the wavelength-dependent refractive index of the thin-film structure and d is its thickness. The phase change $\delta_r(\lambda)$ can be expressed as the sum of two contributions:

$$\delta_r(\lambda) = 2\beta(\lambda) + \varphi_{nl}(\lambda)\,, \tag{7}$$

where $\varphi_{nl}(\lambda)$ is the so-called nonlinear phase function, which is wavelength-dependent and which is due to the multiple reflections within the thin-film structure.

The spectral interference signal is defined as:

$$S(\lambda) = I(\lambda)/I^{(0)}(\lambda) - 1\,. \tag{8}$$

Eq. (8) can be rewritten as [6]:

$$S(\lambda) = a(\lambda)\cos[\Phi(\lambda)]\,, \tag{9}$$

where $a(\lambda)$ is the overall visibility function (envelope function) and $\Phi(\lambda)$ is the unwrapped phase function. This function is known with ambiguity of $m2\pi$, where m is an integer. The OPD $\Delta(\lambda)$ between interfering beams we can written as:

$$\Delta(\lambda) = [\Phi(\lambda)/(2\pi) + m]\lambda\,. \tag{10}$$

When we know $\Phi(\lambda)$, t_{ef} and $n(\lambda)$, we can determine the interference order m and thus the absolute spectral phase difference $\varphi(\lambda)$ or OPD $\Delta(\lambda) = (\lambda/2\pi)\varphi(\lambda)$. Interference order m has to be chosen so that linear dependence between OPD $\Delta(\lambda)$ and $n(\lambda)$ of the beam splitter material is satisfied. Knowing OPD $\Delta(\lambda)$, we can construct for a chosen mirror position $L = L_0$ the so-called nonlinear-like phase function $\delta(\lambda)$, which is wavelength-dependent and which satisfies the relation [6, 7]:

$$\delta(\lambda) = (2\pi/\lambda)[2L_0 + 2n(\lambda)t_{ef} - \Delta(\lambda)]\,. \tag{11}$$

Experimental setup

The experimental setup used in the application of spectral-domain white-light interferometry to measure thickness of a thin-film structure is shown in Fig. 1. It consists of a white-light source: a halogen lamp HL-2000 (Ocean Optics, Inc.) with launching optics, an optical fiber and a collimating lens, a bulk-optic Michelson interferometer with a cube beam splitter made of BK7 optical glass, a thin-film structure on a substrate, a metallic mirror connected to a micropositioner, a microscope objective, micropositioners, a read optical fiber, a miniature fiber-optic spectrometer S2000 (Ocean optics, Inc.), an A/D converter and a personal computer. The effective thickness of the beam splitter was determined by a spectral interferometric technique utilizing a Michelson interferometer with two identical metallic mirrors.

A uniform SiO_2 thin film on a silicon wafer, representing the thin-film structure, was prepared by dry oxidation process described by the so-called Deal-Growe model [9] for four annealing times in a furnace at 1200°C. Single-crystal silicon wafers with subsequent parameters: diameter (100 ± 0.5) mm, orientation (111), B doped type P, were prepared by ON Semiconductor, Czech Republic.

Results and discussion

First, we report on the method how to determine the thin-film thickness d by fitting the recorded spectral interferogram to the theoretical one [5]. To perform the fit we need to know the reference spectral intensity as shown in Fig. 2(a) by the blue line and the recorded interferogram represented by the dots. Fig. 2(b) demonstrates very good agreement between theory (red line is obtained by the Levenberg-Marquardt least-squares algorithm [5] which is used as the fitting procedure) and experiment for the selected thin film thickness.

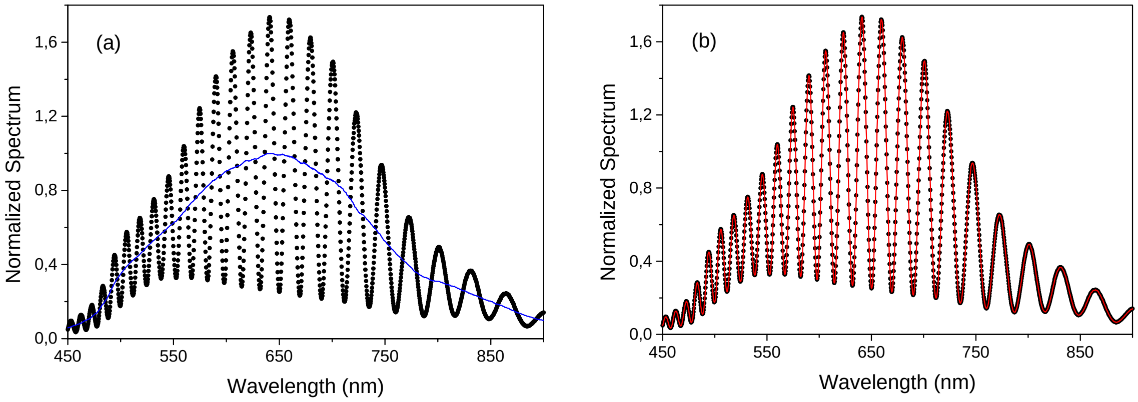

Fig. 2. *(a) Example of the recorded spectral interferogram (dots) and the reference spectrum (blue line). (b) Comparison of recorded (dots) and calculated (red line) interferograms.*

We recorded another interferograms for different OPDs adjusted in the interferometer with a 10 μm step and processed them by the above presented fitting algorithm. We obtained the thin-film thickness d with an average value of 449.7 nm and a standard deviation of 1.9 nm.

Second, a new method of phase retrieval [7, 10] from the spectral signal is utilized, which is based on the use of a windowed Fourier transform [11] in the wavelength domain. This method is based on the idea to find new functions that contain information about thin-film structure. Fig. 3(a) shows by the solid line the spectral signal [6, 7] corresponding to the reference spectrum and the recorded interferogram both shown Fig. 2(a). The retrieved phase $\Phi(\lambda)$ is used to construct a signal $\cos[\Phi(\lambda)]$ shown in Fig. 3(a) by the red line and demonstrates good phase reconstruction of the spectral signal. The absolute phase $\varphi(\lambda)$ is obtained by a procedure [4] utilizing the linear dependence of the OPD $\Delta(\lambda)$ on the refractive index $n(\lambda)$ of the beam splitter glass BK7 as shown in Fig. 3(b).

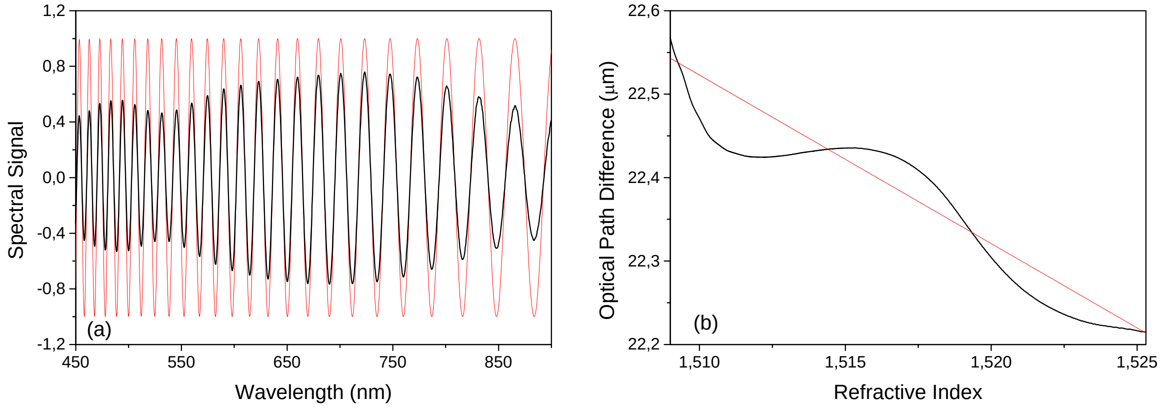

Fig. 3. *(a) Comparison of the measured spectral signal with the modeled one (red) that uses the retrieved spectral phase. (b) The absolute OPD as a function of the refractive index of BK7 glass with a linear fit (red line).*

The retrieved OPD $\Delta(\lambda) = (\lambda/2\pi)\varphi(\lambda)$ is fitted to the theoretical OPD by using the Levenberg-Marquardt least-squares algorithm [6, 7] to obtain the thin film thickness. The results of the procedure are shown in Fig. 4(a) and the corresponding thickness is d = 451.2 nm. The retrieved OPD $\Delta(\lambda)$ is also used to determine the nonlinear-like phase function $\delta(\lambda)$ which is given by Eq. (11). We used the Levenberg-Marquardt least-squares algorithm [6, 7] to fit the retrieved nonlinear-like phase function to the theoretical one. The results of the procedure are shown in Fig. 4(b) and the corresponding thickness is d = 451.7 nm.

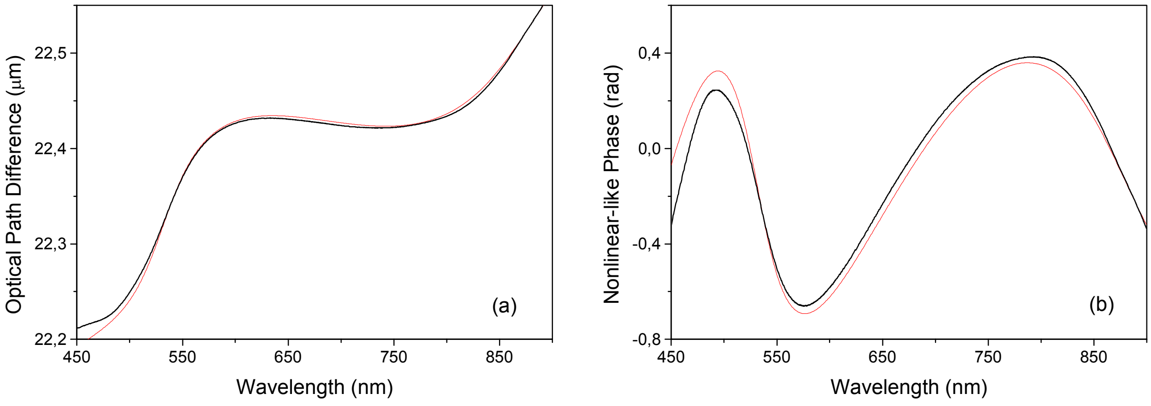

Fig. 4. *(a) The absolute OPD as a function of wavelength together with the corresponding fit (red curve). (b) The nonlinear-line phase as a function of wavelength together with the corresponding fit (red curve).*

In comparison with Fig. 4(a) there is the apparent effect of magnifying the discrepancy between the theoretical and experimental functions but the nonlinear-like phase is more important for thin-film structure description.

Fig 5(a), (b) demonstrate very good agreement between theory and experiment for four samples.

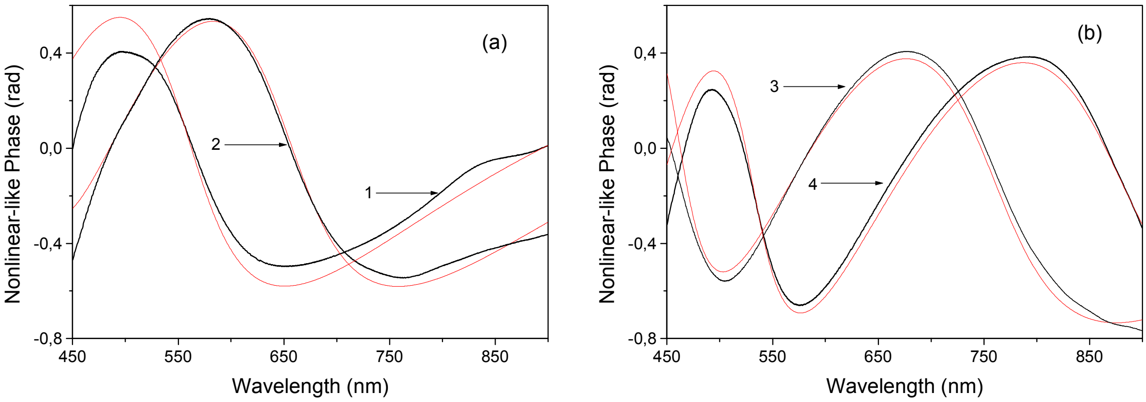

Fig. 5 (a), (b). *The retrieved nonlinear-like phase as a function of wavelength with the corresponding fit (red curve) for four samples*

We can summarize the obtained results and conclude that there is very good correlation between experiment and theory by all of used methods (see Table 1).

Table 1. The oxidation time T and the thicknesses d_{OPD}, d_{NLP}, and d_{FCS} of the SiO_2 thin films

Sample No.	T (min)	d_{OPD} (nm)	R_{OPD}	d_{NLP} (nm)	R_{NLP}	d_{FCS} (nm)
1	122	285.4	0.99699	286.7	0.94591	283.2±2.8
2	212	336.4	0.99947	336.6	0.99479	335.0±1.3
3	326	391.4	0.99911	390.3	0.99142	393.5±2.9
4	392	451.2	0.99832	451.7	0.98433	449.7±1.9

The errors in determining the thickness d_{OPD} and d_{NLP} of the SiO_2 thin films, which are characterized by the correlation coefficients R_{OPD} and R_{NLP}, can be attributed to the systematic errors due to the theoretical model adopted. Table 1 also shows the results of additional measurements of the thickness d_{FCS} by fitting of the recorded channelled spectrum (FCS) to the theoretical one [1]. In order to determine the thickness of the SiO_2 thin films precisely, one has to know the exact optical constants for both the SiO_2 thin film and Si substrate [2]. Moreover, it should be stressed that the precision of the interferometric method could be improved provided that the interferograms are recorded in a broader spectral range. The nonlinear-like phase function can be used for another applications, for example for research of the mirror protective coatings.

Conclusion

Presented paper refers to the white-light spectral interferometric methods using slightly dispersive Michelson interferometer with a thin-film structure as a mirror for measuring of the thin-film structures. First, we remind the method how to determine the thin-film thickness by fitting the recorded spectral interferogram to the theoretical one. Second, we present a new method that is based on the phase retrieval from the spectral signal and is used to determinate new functions containing information about thin-film structure. This method utilizes the white-light spectral interferometric technique for determination of the absolute spectral phase difference or OPD between the beams in interferometer combined with the windowed Fourier transform in the wavelength domain. The obtained results illustrate very good agreement between experiment and theory for all used methods.

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