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Local inspection of refractive index and thickness of thick transparent layers using spectral reflectance measurements in low coherence scanning interferometry

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A R T I C L E I N F O

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A B S T R A C T :

For a long time, obtaining the optical and morphological properties of a transparent sample with high accuracy without degrading the layer has been challenging. To achieve these expectations, contactless techniques are used and have not only been proven well-suitable but have also brought optical methods to the forefront. Over recent years white light scanning interferometry has been increasingly used for studying and characterizing transparent materials with thicknesses ranging from a few hundred nanometers to several micrometers. Then, multiple techniques have been developed to retrieve the transparent layer properties from interferometric data. The more recent techniques, based on the use of an error function which defines the best fit between the experimental and theoretical data, allow the determination of the thickness of very thin films ($< 1\ \mu m$). We show here that a method based on this principle can be applied to thicker layers ($> 1\ \mu m$) for simultaneously measuring their optical and morphological properties, provided that a crucial step is carefully considered during the data acquisition process. This enables the simultaneous measurements of both the thickness and the refractive index (dispersion) without any prior assumptions about one of the two parameters. We demonstrate the proposed method by accurate measurements on a few micrometers thick PMMA layer as well as on a SnO_2 layer, which is a much more dispersive sample.

1. Introduction

The possibility of determining the optical and morphological properties of an unknown transparent sample without any information about its composition has always been an important challenge in a wide range of domains and in particular in that of materials. Coherence scanning interferometry is already a well-established method for measuring surface roughness and structure in 3D on different kinds of materials [1]. Indeed, this far field imaging method enables submicron spatial resolution and high speed non-destructive analysis of large sample areas [2]. As regards transparent materials, the use of white light-based interferometric techniques has been demonstrated for providing local information concerning the thickness or refractive index of the sample. The oldest known method consists in recording the interference signal of the layer and then looking at the optical path separating the interferograms from the front and rear interfaces of the layer at a specific point [3]. The technique mentioned has nevertheless a major drawback since it becomes unusable for very thin films. As a matter of fact the extremely low thickness leads to a single global signal corresponding to a mix between the fringes from the top and bottom surfaces and thus prevents the accurate separation of each envelope peak. To deal with this problem, innovative solutions have been developed based on the processing of interferometric data. These methods use the analysis of interference fringes in the spectral domain and combine experimental measurements with theoretical models in order to recover the thickness of the transparent thin film [4]. The idea is to bring the model (describing the interferometric spectral response of the layer) to converge towards the experimental data by optimizing the value of the parameter sought. The fitting model corresponds for most of the time to the phase [5] or magnitude [6] of the Fourier transform of the interference signal since they contain the information on both the thickness and index of the film. Work has been carried out to determine

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which of these parameters leads to the most sensitive measurement [7].

Usually, knowing either the thickness or the optical index, the two techniques presented enable one of the two previous parameters to be obtained since the optical path traveled by the light over one round trip within the layer is related to both. In consequence, it is necessary to know one of the two parameters in order to find the value of the other. Determining both parameters at the same time and from the same measurement remains a challenge. Li et al. [8] have nevertheless demonstrated this possibility using the processing of the interferometric signal in the spectral domain and by measuring three thin materials with thicknesses ranging from 100 nm to 300 nm. The simultaneous measurement of the thickness and the refractive index was validated through comparison with the results obtained from ellipsometry. Up until now limited to very thin films, mainly because of the high signal quality and contrast in such films, it is shown in this work that a similar spectral method can also be applied to thicker samples provided that more precautions are taken during the acquisition process in order to keep an interference signal of high quality. Even though the technique mentioned first, which relies on the measurement of the distance separating the interferograms, could also be applied in the case of thick layers, it remains far less accurate compared to the proposed technique and does not allow the measurement of the thickness and the optical index independently from each other if one of them is unknown. Furthermore, it is obviously impossible to extract the dispersion of the material.

2. Theory

The method proposed here is based on the spectral analysis of the interference fringes and uses the magnitude of the signal Fourier transform (FT). Similarly to what has been performed in Ref. [4], the first step is to develop the model used to describe the theoretical spectral behavior of the transparent layer. In the case of very thin films, with a thickness lower than the coherence length of the source, the multiple reflections of the light within the layer have to be taken into account and the magnitude of the FT corresponds then to the well-known total reflection coefficient [9]. For thick layers with an optical thickness (product of the real thickness and the optical index) exceeding the coherence length of the source, being ~2 μm in our case, a new model must be established. Indeed, the 2nd order reflections, i.e. the light coming back from the sample after propagating more than one round trip in the layer, must not be considered because it possesses an optical path much higher than that being reflected only once. This light interferes for a different position of the sample and is then either attenuated by the coherence zone of the interferometric system [10] or merely suppressed during the signal processing (windowing).

The theoretical development of the interference signal of a transparent layer, neglecting the 2nd order reflections, followed by a Fourier transform calculation, leads to the expression of the spectral reflectance of the layer that can be written as:

$$|R_{\mathrm{mod}}(\lambda)| = r_{01}^2 + r_{12}^2(1 - r_{01}^2)^2 + 2r_{01}r_{12}(1 - r_{01}^2)\cos\left(\frac{4\pi}{\lambda}en + \phi_{01} - \phi_{12}\right) \quad (1)$$

The spectral reflectance $|R_{\mathrm{mod}}|$ denotes the model that will be used to recover the properties of the layer, with e and n respectively being its thickness and refractive index. r_{ij} and ϕ_{ij} refer respectively to the magnitude and phase of the Fresnel reflection coefficient of the interface ij (01: air/layer, 12: layer/substrate). It can be noted that the previous expression assumes that no absorption occurs during the light propagation. This hypothesis is validated for the samples studied here. To compute the Fresnel coefficient, the complex refractive index of the silicon substrate is extracted from Ref. [11].

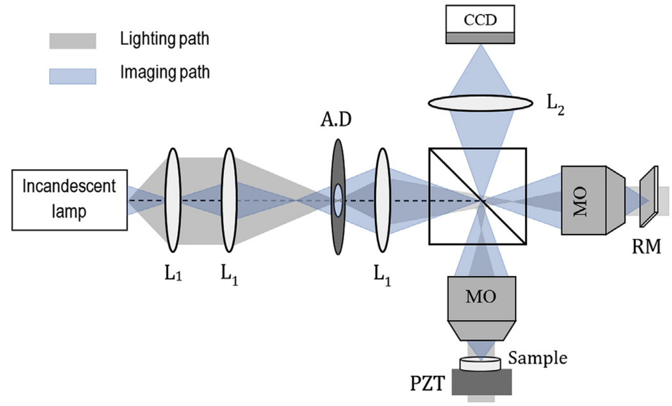

Fig. 1. Schematic diagram of the optical system. L1, aspheric lenses; L2, imaging lens f = 200 mm; A.D, aperture diaphragm; MO, 50x microscope objectives; RM, reference mirror; PZT, piezoelectric device for Z-scanning.

3. Experimental details

3.1. Optical set-up

The experimental optical set-up used to carry out the experiments is an adapted Leitz-Linnik interference microscope (Fig. 1).

The source is an incandescent lamp with an 800 nm central wavelength and a 290 nm bandwidth. The illumination arm is built so as to obtain a Köhler illuminator providing a very homogeneous illumination of both the sample and the reference mirror. The aperture diaphragm enables the spatial coherence of the illumination to be controlled by adjusting the maximum angle of the incident light. After propagation of the light in both arms and reflection on the sample and the mirror, each reflected wave is focused onto the camera by the imaging lens. The resulting image is made of the superposition of the image of the sample, the image of the reference mirror and an interference pattern made of black and white fringes that depends on the difference of optical length between each arms. By scanning these fringes within the depth of the sample, one can obtain information about the sample composition. The purpose is then to build a stack of interferometric images (corresponding at each specific position of the sample along Z) by simultaneously moving the sample with the piezoelectric device and recording the resulting image (Fig. 2).

The interference signal from which the spectral reflectance of the layer is extracted is then obtained by looking at the intensity profile at one specific point in the stack. Because the interference fringes are extracted from 3 × 3 pixel binning in the image stack, the local measurement of the thickness and refractive index is very well spatially resolved: the analysis is made on an area equal to the surface of the diffraction spot in our case which is about 2.27 μm^2. The whole post-processing only consists in the windowing of the fringes signal, the use of a zero-padding loop to increase the spectral accuracy and the application of the fast Fourier transform algorithm to recover the

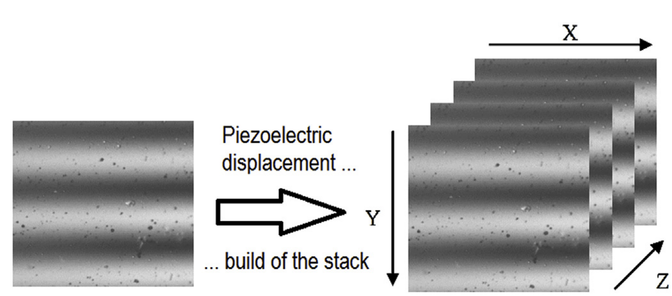

Fig. 2. Interferometric image acquired by the camera and construction of the XYZ image stack.