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Thin film thickness measurements using Scanning White Light Interferometry

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ABSTRACT

Scanning White Light Interferometry is a well-established technique for providing accurate surface roughness measurements and three dimensional topographical images. Here we report on the use of a variant of Scanning White Light Interferometry called coherence correlation interferometry which is now capable of providing accurate thickness measurements from transparent and semi-transparent thin films with thickness below 1 μm. This capability will have many important applications which include measurements on optical coatings, displays, semiconductor devices, transparent conducting oxides and thin film photovoltaics. In this paper we report measurements of thin film thickness made using coherence correlation interferometry on a variety of materials including metal-oxides (Nb_2O_5 and ZrO_2), a metal-nitride (SiN_x:H), a carbon-nitride (SiC_xN_y:H) and indium tin oxide, a transparent conducting oxide. The measurements are compared with those obtained using spectroscopic ellipsometry and in all cases excellent correlation is obtained between the techniques. A key advantage of this capability is the combination of thin film thickness and surface roughness and other three-dimensional metrology measurements from the same sample area.

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1. Introduction

Thin film thickness measurements with sub-nanometre accuracy are important in a range of applications such as thin film optical coatings, displays, semiconductor devices, thin film photovoltaics, thin film transparent conducting oxides …. For example, the precise thickness of a single layer anti-reflection coating determines its anti-reflective quality and spectral response. The precise thickness of a transparent conducting oxide will determine its transmittance and sheet resistance. Spectroscopic ellipsometry is usually used to make these measurements.

Likewise, surface roughness and other surface metrology measurements such as feature width, form, volume and angle on thin films are also important. In optical coatings, surface roughness causes scattering and haze. In display or photovoltaic devices, roughness of the transparent conducting oxide contact can lead to shunting of the devices. These metrology measurements are made using a variety of techniques including stylus profilometry, Atomic Force Microscopy, Scanning Electron Microscopy and Scanning White Light Interferometry (SWLI).

Here we report on the use of a variant of SWLI called coherence correlation interferometry (CCI) [1] which is now capable of combining sub-nanometre thin film thickness measurements with quantitative three-dimensional metrology and imaging from the same thin film sample area. The technique provides these measurements quickly and accurately and now has a potentially important role not just in research and development but also in quality control in a manufacturing environment. The SWLI technique has previously been used routinely for thick film thickness measurements where the film is typically >1 μm. Although it has been recognised that combining thin film thickness measurements with surface metrology is a powerful capability, this has previously involved hardware modifications such as the addition of a polariser, a change of lens and also requires modelling software [2]. In this paper, we report on the use of a thin film measurement capability made possible by the development of the 'helical complex field' (HCF) function [3–6].

The HCF function equates to a topographically defined helix modulated by the electrical field reflectance of the film. As such, it provides a 'signature' of the thin film structure so that through optimization, the thin film structure may be determined on a local scale. In order to use the HCF function approach, it is necessary to provide an "a priori" knowledge of the dispersive film index. These values of refractive index (n) and the extinction coefficient (k) can be measured using ellipsometry or assumed from published bulk values. A "pattern" measurement can be performed for an accurate characterization of thickness uniformity. Although both ellipsometry and CCI rely on n and k to describe the dielectric function, the derivations are different since ellipsometry uses polarisation and CCI uses interference for the thickness measurement.

A variety of thin films have been investigated including metal-oxides, niobium pentoxide (Nb_2O_5) and zirconium oxide (ZrO_2), a metal-nitride (SiN_x:H), carbon-nitride (SiC_xN_y:H) and indium tin oxide (ITO) a transparent conducting oxide. The thin film thickness measurements

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are compared with those obtained using spectroscopic ellipsometry and corresponding surface roughness measurements from the same sample areas are also presented.

2. Coherence correlation interferometry (CCI)

Coherence correlation interferometry (CCI) is a Scanning White Light Interferometry technique which uses light interference patterns (set of interference fringes) from a white light source (xenon). Two beams are produced by splitting the main beam from the source; one is reflected by a reference mirror, while the other one scans the surface. The light is reflected locally by the surface and the reflected beam is correlated to the reference one and an interference pattern is created. The signal is detected by a high resolution digital CCD camera. Three-dimensional topographical maps are created by measuring the position of the lens which is moved in the vertical direction to obtain the maximum constructive interference. Use of white light allows only one peak as maximum. Each pixel acts as single interferometer, combining them together allows the accurate measurement of a relatively large surface area. The accuracy of the measurement is highly dependent on the efficacy of the coherence correlation algorithm used.

One of the main advantages of the technique is that it is non-contacting and there is no risk of damaging the surface with a stylus. It also provides information in three dimensions which provides a more complete surface representation than two dimensions. Furthermore the measurements are taken over a relatively large and hence representative area of the surface. The scan area is defined by the magnification of the lens used and it ranges between 165 μm × 165 μm for a 100× objective lens to 6.6 mm × 6.6 mm for a 2.5× objective lens. The area can be further extended using "stitching mode" to combine images. It has the capability of obtaining measurements with sub-nanometre interferometric resolution with a vertical range limited at 100 μm by the vertical traverse available to the lens. The technique provides sub-micron lateral resolution depending on the wavelength of light and the numerical aperture (NA) of the objective. The technique provides two and three-dimensional images of the surface together with a range of quantitative analysis routines for roughness, waviness and form. Measurements include root mean square roughness (Sq), average roughness (Sa), maximum peak height (St), step height, groove width and depth, etc.

3. Thick and thin film thickness measurement analysis

Interference occurs when two light waves interfere; the resultant wave has an amplitude dependent on their phase difference. If the phase difference is 2mπ (where m is any integer), constructive interference occurs and the intensity is at a maximum. For the phase difference of (2 m + 1)π destructive interference occurs and the intensity is minimal. For the analysis of relatively *thick* films, typically greater than 1 μm, the interaction of the incident white light and the thin film surface and its interface results in the local formation of two distinct interference bunches. It is possible to locate the positions of the two envelope maxima and thereby determine the thick film thickness using refractive index information.

In the case of a transparent thin film, due to the proximity of the surface and the thin film interface, the interference bunches associated with the surface and the thin film overlap. The overlap of the interference bunches makes the film thickness measurement impossible using the traditional approach used for thick films which requires their separation. In this regime, it is necessary to operate with another approach using the 'helical complex field' (HCF) function.

The HCF function is based on a 'reference' material (defined by the input of n and k values) and the measured thin film. The net field reflectance of the 'reference' material $\overline{r_{eff}}(\upsilon)$ is multiplied by the ratio of the positive arm sidebands (SB^+) of the Fourier transform of the interference intensities of the film and the 'reference' material. $\overline{z_{xy}}$ is the average difference between the two beams, $\overline{z_k}$ is the average net path length shift of the sample of the kth step, the $I_{\mathrm{thin}}(\overline{z_k})$ is the interference intensity. The resulting HCF function is spatially defined as a distorted helix, which is modulated by the electrical field of reflectance of the film.

$$\mathrm{HCF}(\upsilon) = \overline{r_{eff}}(\upsilon)\frac{F^-\left(I_{\mathrm{thin}}(\overline{z_k})\right)_{SB^+}}{F^-\left(I_{ref}(\overline{z_k})\right)_{SB^+}} = a_{\mathrm{HCF}}(\upsilon)e^{i\varphi_{\mathrm{HCF}}(\upsilon)}$$

This equation is the synthesized HCF function, which is referred to the dispersive index (n and k values). These values have to be inserted in the material data base prior to the measurement. They can be extracted from ellipsometry results or assumed from bulk values available in the literature; n and k are considered for a certain number of wavelength values mainly across the visible spectrum (350 nm–850 nm) and they refer to I_{ref} value in the HCF equation.

$F^-\left(I_{\mathrm{thin}}(\overline{z_k})\right)_{SB^+}$ refers to the measured thin film, while $F^-\left(I_{ref}(\overline{z_k})\right)_{SB^+}$ depends on the input of the 'reference' material. The resulting function is expressed as helix function ($e^{i\varphi_{\mathrm{HCF}}(\upsilon)}$) distorted by the term $a_{\mathrm{HCF}}(\upsilon)$. The synthesized HCF function is then compared to the defined function. $r(\upsilon)e^{i\varphi(\upsilon)}$ is the electrical field reflectance and Δz_{HCF} is the difference between the position of the reference and the closest step of the scan.

$$HCF_{\mathrm{fit}}(\upsilon) = \overline{r(\upsilon)e^{i\varphi(\upsilon)}}e^{i4\pi\upsilon\Delta z_{\mathrm{HCF}}}$$

$HCF_{\mathrm{fit}}(\upsilon)$ is used to fit $\mathrm{HCF}(\upsilon)$ as shown. The lower the fitting number, the more accurate is the thickness measurement.

$$\mathrm{HCF}(\upsilon) \cong \mathrm{HCF}_{\mathrm{fit}}(\upsilon) = a_{\mathrm{HCF}}(\upsilon)e^{i\varphi_{\mathrm{HCF}(\upsilon)}} \cong \overline{r(\upsilon)e^{i\varphi(\upsilon)}}e^{i4\pi\upsilon\Delta z_{\mathrm{HCF}}}$$

Fitting figures reveal the validity of the measurement. An example is shown in Fig. 1. The continuous line represents $\mathrm{HCF}_{\mathrm{fit}}(\upsilon)$, the fitting function while the dotted line is $\mathrm{HCF}(\upsilon)$, the synthesised function. The HCF approach can be broken down into three different parts, which identify the fitting figure for the CCI thin film measurement; the real part of the HCF is in red, the imaginary part of HCF is in blue and the reflectance is in green. The values are taken on the sampling profile from 0.8 mm to −0.8 mm across the field of view, against the wavelength of light in μm. Fig. 1 shows a good fitting of 0.198 for a 68.8 nm thin film of silicon carbon-nitride deposited on polished silicon. Better fittings were obtained for the thin films presented in this study, such as 0.018 for 67.6 nm thick silicon nitride coated on polished silicon,

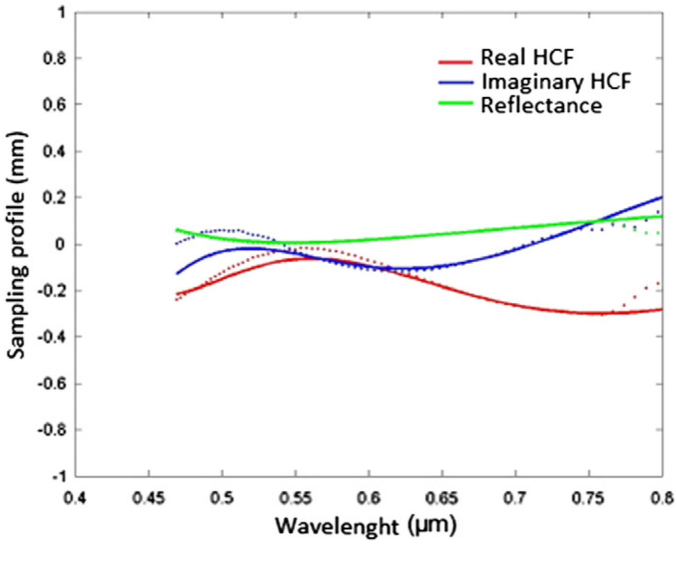

Fig. 1. Example of fitting figure (fit 0.198) of HCF function for 68.8 nm thick silicon carbon-nitride deposited on polished silicon.

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