

Measurement of complex refractive index using microellipsometry and its relevance to surface measurement using coherence scanning interferometry

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Abstract

Coherence scanning interferometry (CSI) is an increasingly popular method to provide high resolution measurements of surfaces. In essence sub-nanometre axial resolution is achieved by measuring the phase of the field scattered from the surface of interest. The phase is not simply a function of surface height, however, it depends on the complex refractive index of the surface material. The phase contribution due to materials properties is small and approximately constant across the field of view for the case of homogenous surfaces. It can lead to significant measurement errors, however, when composite microstructures of conducting and non-conducting media are examined.

This paper discusses the measurement of complex refractive index using a single-point microellipsometer based on a Michelson interferometer. It shows how the optical properties of the substrate are related to the phase of the scattered components at different spatial frequencies. A whole-field implementation of the method using CSI is then discussed.

Keywords: Coherence scanning interferometry, surface measurement, microellipsometer, complex refractive index.

1. Introduction

Coherence scanning interferometry (CSI) provides measurements of surface topography with sub-micrometre lateral resolution and sub-nanometre axial resolution that is achieved by measuring the phase of the field scattered from the surface of interest. It is well known, however, that the phase of the scattered components is not simply a function of height but depends on the angle of incidence and the optical properties of the surface. When homogenous materials are measured this is not a problem since the effect leads to a uniform phase offset and results in a small axial displacement of the measured surface. Composite surfaces of conducting and non-conducting media, such as metal tracks deposited on a glass substrate, do present a problem since an additional phase change, $\Delta\phi$, will be interpreted as a change in surface height. At a wavelength of 633 nm, for example, reflection at normal incidence results in phase changes of 14.6°, 28.1° and 35.7°, for aluminium, silver and gold respectively and corresponds to surface height errors of approximately 12 nm to 30 nm.

Traditionally, ellipsometry has been used to determine the optical properties of bulk materials and thin films from measurements of the polarisation state of light reflected at varying angles of incidence [1]. Essentially the same information can be retrieved from the back-focal plane of a large aperture objective lens when the object of interest is probed by a scanning beam in an arrangement similar to a confocal microscope. This method of microellipsometry was first examined by See *et al.* [2] and later by Feke *et al.* [3] using phase shifting interferometry. In this paper we consider a modified microellipsometry set-up using carrier fringe encoding (digital holography) to measure the phase changes due to reflection for different polarisation states and angles of

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incidence. We then compare these measurements to theory and discuss how the same basic method can be implemented in CSI.

2. Microellipsometry

The microellipsometer that we have used is shown in fig. 1. A polariser (P) and half-wave plate ($\lambda/2$) are used to control the intensity and plane of polarization of a He-Ne laser. The beam is expanded (BE), collimated (L) and directed along the paths of a Michelson interferometer by the wedge beam-splitter (BS).

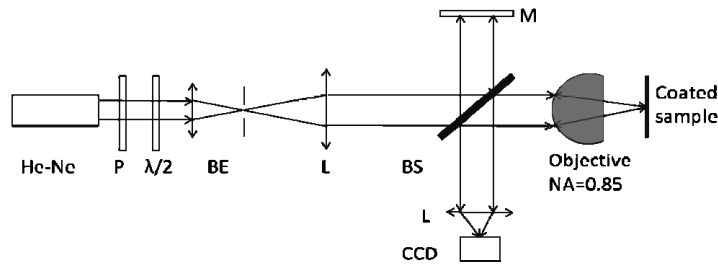


Fig. 1 Microellipsometric set-up

In the object path, the sample is placed in the front focal plane of the objective lens ($NA = 0.85$) where the beam is focused. In this way, the objective re-collimates the reflection field and this is mixed with the wavefront returned from a tilted mirror (M) that is placed in the reference arm of the interferometer such that the resulting interference is modulated by carrier fringes. This is recorded by a CCD camera (240 by 320 pixels) that is focused on to the back focal plane of the objective. The phase and amplitude of the reflected field in this plane can be retrieved unambiguously by demodulating the interferogram using a bandpass filter centred on the carrier frequency in the usual way [4].

In order to remove the effect of aberrations, two recordings are made with orthogonal plane polarised beams in the back focal plane of the objective. The phase difference between the resulting demodulated fields is then calculated. Fig. 2(a) shows the intensity distribution recorded by the CCD that was measured in the back focal plane after reflection from a gold sample. The slightly curved fringes are principally caused by spherical aberration. Fig. 2(b) shows the phase difference between the demodulated fields corresponding to orthogonal polarisation states. A transverse modulation with a period of two cycles per revolution is increasingly evident as the radial co-ordinate increases.

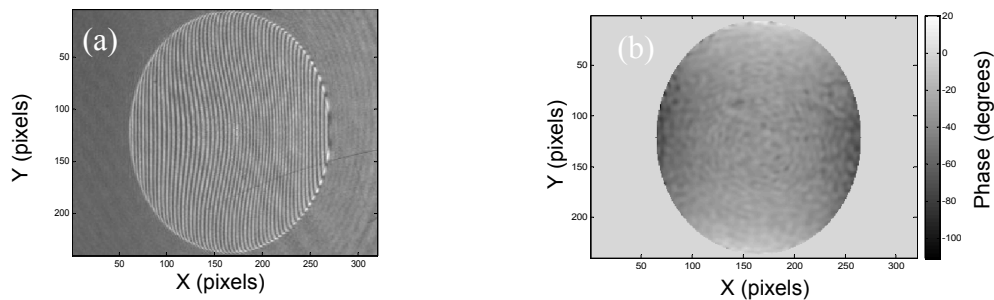


Fig. 2 a) Interferogram with carrier fringes; b) demodulated phase; both for gold sample

The result can be explained by noting that each point in the back focal plane of the objective corresponds to a plane wave component in the sample illumination. With reference to fig. 3, each of these components can be further decomposed into s- and p-components that are polarised in and out of the plane of incidence respectively.

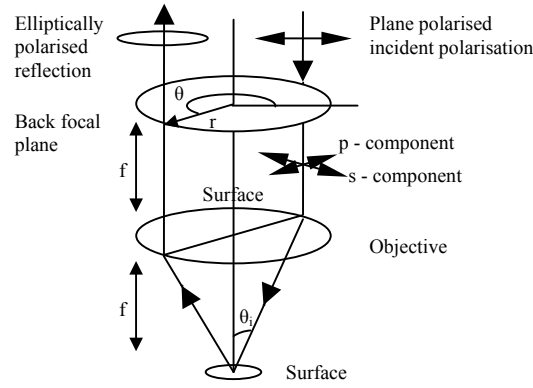


Fig. 3 Geometry of the s- and p-components

For the case of incident light of amplitude, A_0 , plane polarised in the $\theta = 0^\circ$ direction, the s- and p-components, of the reflected fields $E_s(r, \theta)$ and $E_p(r, \theta)$, in the back focal plane of the objective can be written,

$$\begin{aligned} E_p(r, \theta) &= r_p A_0 \cos \theta \\ E_s(r, \theta) &= -r_s A_0 \sin \theta \end{aligned} \quad (1)$$

where, r_s and r_p are the amplitude reflection coefficients given by the Fresnel equations,

$$\begin{aligned} r_p &= \tan(\theta_i - \sin^{-1}(n_i \sin(\theta_i)) / n_t) / \tan(\theta_i + \sin^{-1}(n_i \sin(\theta_i)) / n_t) \\ r_s &= -\sin(\theta_i - \sin^{-1}(n_i \sin(\theta_i)) / n_t) / \sin(\theta_i + \sin^{-1}(n_i \sin(\theta_i)) / n_t) \end{aligned} \quad (2)$$

and the angle of incidence, $\theta_i = \tan^{-1}(r/f)$. Since interference only occurs between similarly polarised beams, the measured reflected field corresponds to the polarisation component that is parallel to the reference field. For the case of incident radiation polarised in the plane $\theta = 0^\circ$, noting that the s- and p-components of the reference field are 180° out of phase, the field, $E_0(r, \theta)$, that is measured after demodulation can be written,

$$E_0(r, \theta) = A_0 (r_p \cos^2 \theta - r_s \sin^2 \theta) \quad (3)$$

Similarly the field, $E_{90}(r, \theta)$, for the case of incident radiation polarised in the plane $\theta = 90^\circ$ can be written,

$$E_{90}(r, \theta) = A_{90} (r_p \sin^2 \theta - r_s \cos^2 \theta) \quad (4)$$

From eqn. 3 and eqn. 4, we obtain an expression that relate $E_0(r, \theta)$ and $E_{90}(r, \theta)$ to the well-known ellipsometric parameters ψ and Δ ,

$$\frac{E_0(r, \theta) \cos^2 \theta + E_{90}(r, \theta) \sin^2 \theta}{E_0(r, \theta) \sin^2 \theta + E_{90}(r, \theta) \cos^2 \theta} = \tan \psi \exp(-i\Delta) \quad (5)$$

where, it is assumed that $A_0 \approx A_{90}$.

By converting the ratio of the electric fields to polar coordinates, fitting a second order polynomial to the radial dependence and filtering at a transverse frequency of two cycles per revolution, we obtain amplitude and phase maps of the ratio of electric fields over the entire azimuth i.e. over 360° in the back focal plane. For each sample, the phase of $E(r, \theta)$ at the extreme of the aperture (i.e. at the full NA) is reproduced in fig. 4(a) and can be compared with the values of the phase derived from measurements of the refractive index from the ellipsometer,

(make J.A. Woollam Co., Inc., Model No. M2000DI) at the full NA in fig. 4(b). It can be seen that the phase values that we have measured follow the correct trend but are consistently smaller than those predicted by theory. Since, r_s and r_p , increases sharply with NA it is thought that the full NA of the objective may not have been properly filled. It is found that the experimental results fit well with the theory at NA = 0.76.

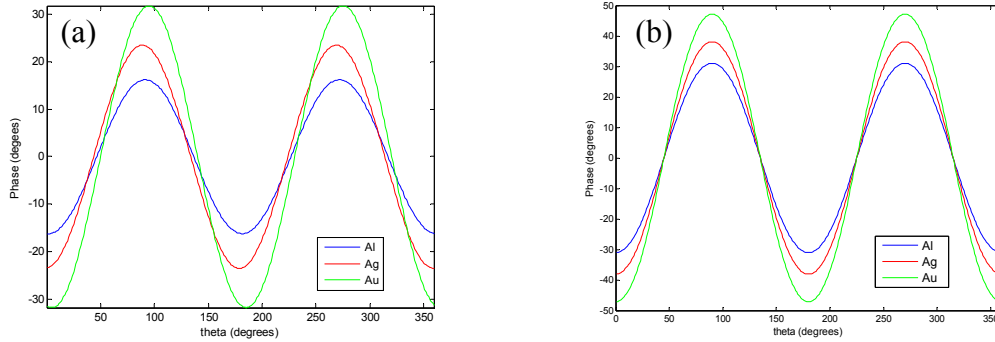


Fig. 4 Phase difference at the extreme of the aperture for NA = 0.85
a) Experimental graph from microellipsometry; b) Theoretical graph

From eqn. 5 the ratio of $E_0(r, \theta)$ and $E_{90}(r, \theta)$, at $\theta = 0^\circ$ gives ellipsometric parameters, ψ and Δ , and these can be related to the complex refractive index of the sample [1]. The values of the real and imaginary parts of the refractive index measured by microellipsometry are compared with those measured with the ellipsometer in Table 1. Good agreement can be seen for the imaginary part but some discrepancy is observed in the real part. We believe that this is due to the intensity variation in the reference beams of orthogonal polarizations, which affects the real part of the refractive index more than the imaginary part.

Table 1. Comparison of complex refractive index values by microellipsometry and ellipsometry

Sample surface materials	$\tan \psi$ (calculated)	Δ in degrees (calculated)	Refractive index measured by micro-ellipsometry for 633 nm (NA=0.85)	Refractive index by ellipsometry measured for 633 nm (NA=0.85)
Au	1.09	29.87	$0.56 + 3.24j$	$0.27 + 3.01j$
Ag	1.19	22.53	$1.70 + 3.72j$	$0.09 + 3.88j$
Al	1.17	18.36	$2.22 + 4.43j$	$0.74 + 4.76j$

It is clear that measurement of the refractive index can be used to calculate the phase change, $\Delta\phi$, that is observed when CSI instrumentation is used to measure the topography of metallic surfaces. Next, we move on to consider ways in which the method can be extended to whole-field measurement in a modified CSI arrangement.

3. CSI Implementation

The advantage of microellipsometry over its traditional counterpart is a capability to provide high resolution maps of optical parameters from composite surfaces. It is clear from the above results, however, that the transverse modulation at large angles of incidence is of chief concern and this could equally well be estimated from the change in phase at a single point in the back focal plane that occurs when the plane of polarisation of the illumination is rotated by 90° . A configuration capable of this reduced measurement task is illustrated in fig. 5(a). The configuration retains the focused illumination that defines the point of interest on the sample but only the phase of a single, oblique plane wave component of the scattered field is measured. Exactly the same information can be retrieved, however, if the sample is *illuminated* by an oblique plane wave and the phase and amplitude of

the scattered field is *measured* in the back focal plane as illustrated in fig. 5(b). This reverse configuration has the advantage that the point of interest can be selected by multiplying the measurements by an appropriate phase mask and integrating. The reverse configuration is, therefore, a whole-field implementation of microellipsometry.

In a recent publication [5], we have shown that CSI can be considered to be a holographic method that records an image (interferogram) that is a combination of holographic recordings made with plane wave illumination at different angles of incidence and different wavelengths. Unfortunately, it is not generally possible to separate individual holographic recordings from a CSI interferogram unless either the spatial frequency content of the illumination or the measured field is modified. A straightforward modification to conventional CSI that can be directly compared to the microellipsometry discussed previously is, therefore, to restrict the illumination to oblique plane waves.

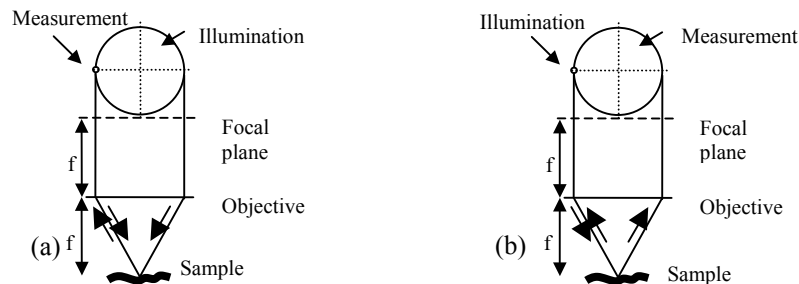


Fig. 5 Simplified configurations; a) single-point b) whole-field

In this way, a CSI instrument would scan the sample through focus using a conventional Mirau objective but would otherwise resemble the configuration shown schematically in fig. 5(b). Using the analysis methods that we have described elsewhere [5], it can be shown that this configuration provides separable holographic recordings of the scattered field at different wavelengths. By recording two interferograms with orthogonal polarisation the optical properties of the sample surface could be imaged at different points and at different wavelengths.

Conclusions

In this paper we have discussed how CSI measurements are affected by the optical properties of materials and have described a microellipsometer that can be used to measure the complex refractive index. The similarities between microellipsometry and CSI have been outlined and a CSI set-up to measure complex refractive index has been proposed. We are currently building a CSI system with this capability to measure the surface topography of composite surfaces or varying complex refractive index.

Acknowledgements

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References

- [1] M. Born and E. Wolf, Principles of Optics, Cambridge University Press, 1999.
- [2] C.W. See, M.G. Somekh, R.D. Holmes, Scanning optical microellipsometer for pure surface profiling, Appl. Opt. 35 (1996) 6663-6668.
- [3] G.D. Feke, D.P. Snow, R.D. Grober, P.J. de Groot, L. Deck, Interferometric back focal plane microellipsometry, Appl. Opt. 37 (1998) 1796-1802.
- [4] U. Schnars and W. Jueptner, Digital Holography, Springer, 2005.
- [5] J.M. Coupland and J. Lobera, Holography, tomography and 3D microscopy as linear filtering operations, Meas. Sci. Technol. 19 (2008)