Transparent film profiling and analysis by interference microscopy

Peter J. de Groot and Xavier Colonna de Lega
Zygo Corporation
Laurel Brook Road, Middlefield, CT 06455

ABSTRACT

A white-light interferometer with new signal analysis techniques provides 3D top surface and thickness profiles of transparent films. With an additional change from conventional object imaging to pupil-plane imaging, the same instrument platform provides detailed properties of multilayer film stacks, including material optical properties. These capabilities complement conventional surface-topography measurements on the same platform, resulting in a highly flexible tool.

Keywords: White light, thin films, interferometry, microscopy

1. INTRODUCTION

Perhaps the first metrology application of interferometry was for transparent film thickness measurement, when Newton and Hooke produced colors with an air film between lenses and flat plates. The colors appeared as concentric rings, with equal thickness the same color. The same principle was applied throughout the last century, sometimes using a printed look-up table of perceived hues and corresponding film thicknesses.

More recently, films measurement has become an important topic in automated interference microscopy, in part because of the expansion of high-value, high-volume technology products that involve microscopic thin-film structures.

Transparent films present a challenge to established interferometric techniques such as scanning-white light interferometry (SWLI). As recently as 5 years ago, most commercial SWLI microscopes for 3D surface profiling were limited to opaque surfaces. This has changed, to the point where interference microscopy today is in many cases displacing traditional ellipsometers and reflectometers for specific film structure analysis tasks.

Here we review three different white-light interference microscopy techniques for transparent film metrology:

- 3D Top surface profiling over unknown thin films greater than 500nm thick;
- Full 3D film-thickness and interface profiling using signal modeling;
- Detailed multiple-angle, multiple-wavelength ellipsometric film-stack analysis, including multi-layer thickness and index information, using a interference microscopy in the pupil plane.

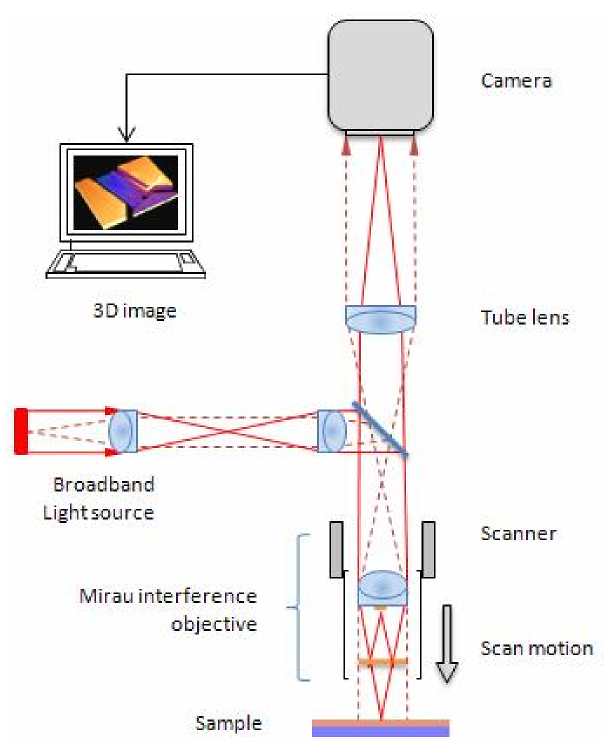


Figure 1: Scanning white light interferometer for 3D surface measurements. In this paper, all results are for a 0.8-NA objective, a 110-nm spectral bandwidth and 570-nm center wavelength.

Interferometry XIV: Applications, edited by Erik L. Novak, Wolfgang Osten, Christophe Gorecki,
Proc. of SPIE Vol. 7064, 70640I, (2008) · 0277-786X/08/$18 · doi: 10.1117/12.794936

2. TOP-SURFACE TOPOGRAPHY OVER TRANSPARENT FILMS

Optical instruments such as the SWLI system of Figure 1 have a sometimes unwanted sensitivity to transparent films and underlying patterns visible through the films. In many cases, we only want to see the top-surface profile, similar to what a stylus or AFM tool provides, and the film stack and embedded patterns are of secondary interest.

Figure 2 shows white-light interference fringes modulated by a contrast envelope. In the presence of a transparent film, the signal changes to a complex mixture of overlapping signals. If the film is sufficiently thick, the signals generated by the film interfaces are separable and can be associated with the upper and lower surface profiles [1][2][3].

In the case of Figure 3, the overlap is such that it is difficult to cleanly separate the contributions. It can be shown that in spite of this overlap, the leading edge of the signal in Figure 3 still relates most strongly to the top-surface reflection. We have developed a technique for interpreting signals when the desired information relates only to this top-surface profile. The first step is to synthesize a model of the top-surface portion of the signal, by extracting or *slicing* an example signal acquired from an opaque surface, leaving only the leading edge (Figure 4). For each pixel, we locate the position within the experimental signal that provides the best match to this *TopSlice* model signal (Figure 5).

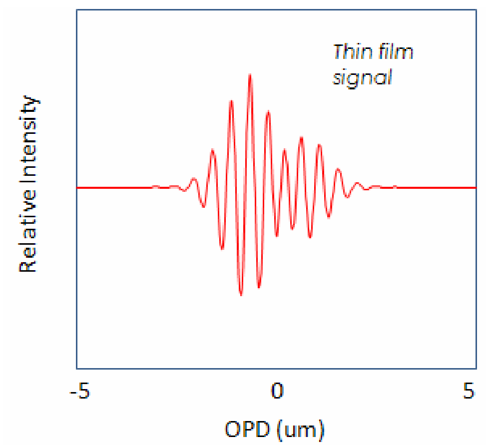


Figure 2: SWLI signal generate by the instrument shown in Figure 1

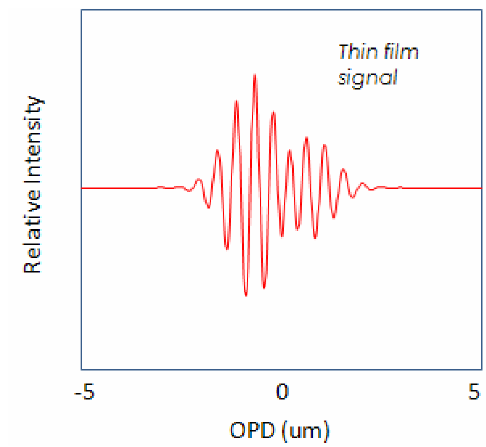


Figure 3: SWLI signal for a thin-film surface structure.

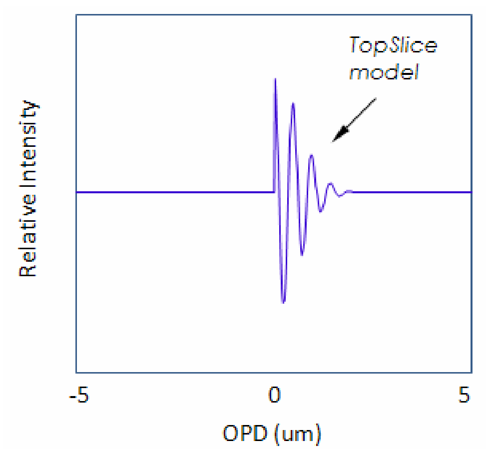


Figure 4: Creating a TopSlice model signal from the original opaque-surface SWLI signal in Figure 2.

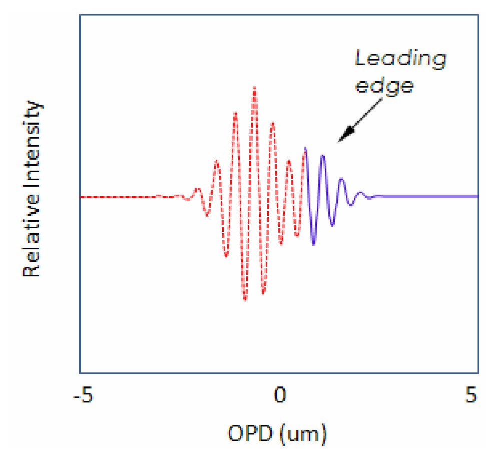


Figure 5: Locating the leading edge of the thin-film signal in Figure 3 using the TopSlice model signal with an adjustable amplitude and phase.

Matching the TopSlice model to the experimental signal involves a sliding-window least-squares analysis [4]. Software shifts the model signal from one scan position to the next, and the quality of fit to the experimental signal is evaluated using the phase and amplitude as free parameters. The best-fit scan position provides an initial estimate of surface height, with the phase used as a refinement to achieve <1nm repeatability.

Simulations and experimental work show that the TopSlice method is effective for films having an optical thickness (thickness times index of refraction) greater than 1/4 the coherence length, defined as the square of the center wavelength divided by the source bandwidth. For a visible-wavelength system having 570nm center wavelength and 110nm bandwidth, the minimum thickness for a 1.46-index SiO_2 film is 500nm. Experiments with broadband light sources and high-NA objectives show that the technique is extendible to 200nm.

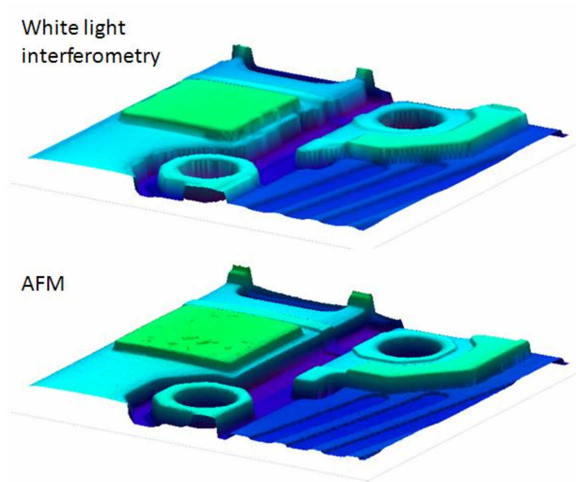


Figure 6: Comparison of interferometry with AFM measurements of the top surface of a thin-film transistor. The images are 40 microns square.

Figure 6 compares a 3D top-surface interferometry image with atomic force microscopy (AFM) for a flat-panel display pixel. This sample has transparent films in several areas, with a minimum thickness of 600nm. A nice feature of this approach is that it does not require any advance knowledge of the material properties of film or embedded features.

3. 3D FILM THICKNESS PROFILES USING MODEL-BASED SWLI

To go beyond the simple top-surface profile, we can take advantage of the information encoded in the distorted shape of the white-light interference signal. Provided that we know the optical properties of our instrument well enough, an effective approach is to model the expected response of the instrument to a range of possible film parameters, creating a *library* of model signals that we compare in their entirety with the experimental signal to find the best match.

A model-based approach has the advantage of simultaneously provides a direct 3D measurement of film thickness as well as the upper and lower interface profiles simultaneously. Figure 7 illustrates an example 2D cross section of photoresist over copper, comparing the direct measurement of film thickness using model-based SWLI and an AFM measurement of the difference in surface height between the resist and the surrounding flat area. Measurements such as these are of interest e.g. to the displays and semiconductor industries, for control of resist patterning, dielectric trench fill, and chemical-mechanical polishing [5].

Most researchers working in the area of model-based SWLI for 3D thickness imaging have opted for a frequency-domain analysis to identify film characteristics [6][7][8][9]. The graphs in Figure 8 illustrate a comparison of calculated and measured signals in both the frequency and scan (time) domains. Figure 9 summarizes the result of a library search for two example films, illustrating film thickness identification by a least-squares calculation of fit quality in the frequency domain.

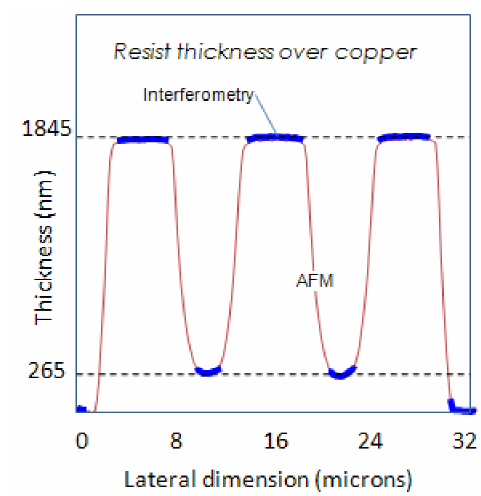


Figure 7: Comparison of interferometry with AFM measurements of the thickness of patterned photoresist. The AFM result derives from a top-surface measurement relative to the surrounding uncoated area. Correlation is <10nm.

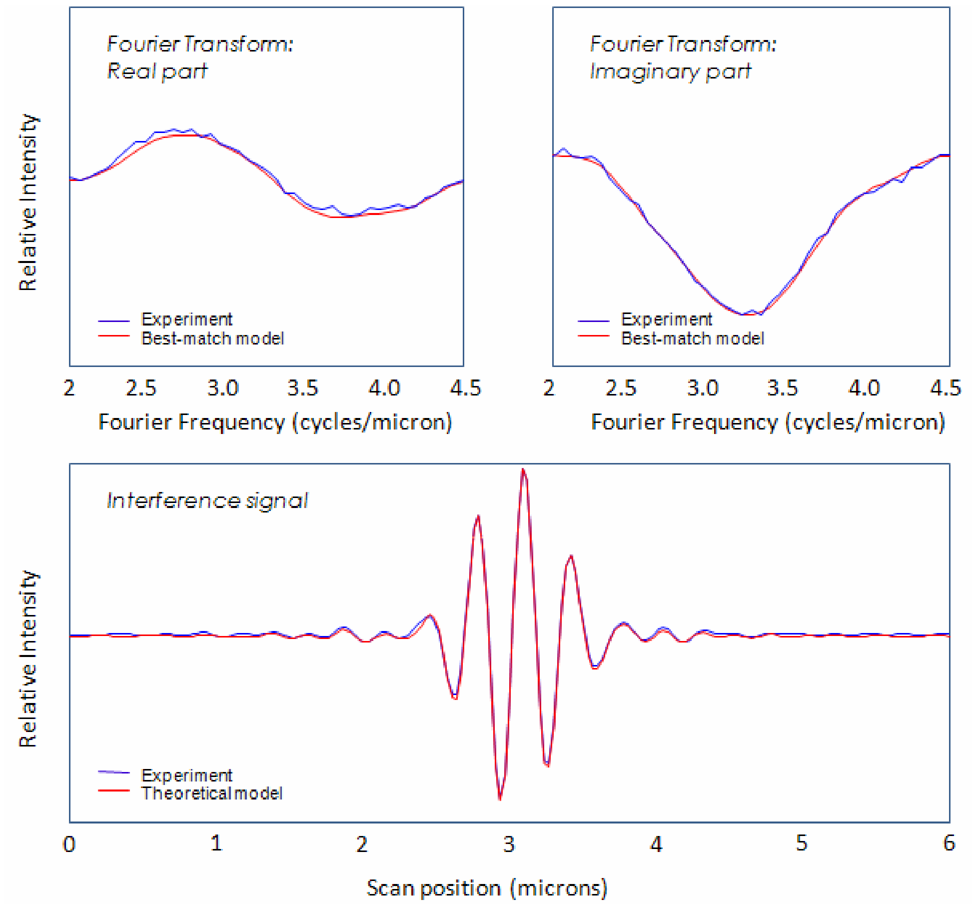


Figure 8: Frequency-domain (Top 2 graphs) and time-domain (lower graph) representations of a SWLI signal from a 185-nm SiO2 film on Si, comparing the experimental signal with the best-fit from the model signal library.

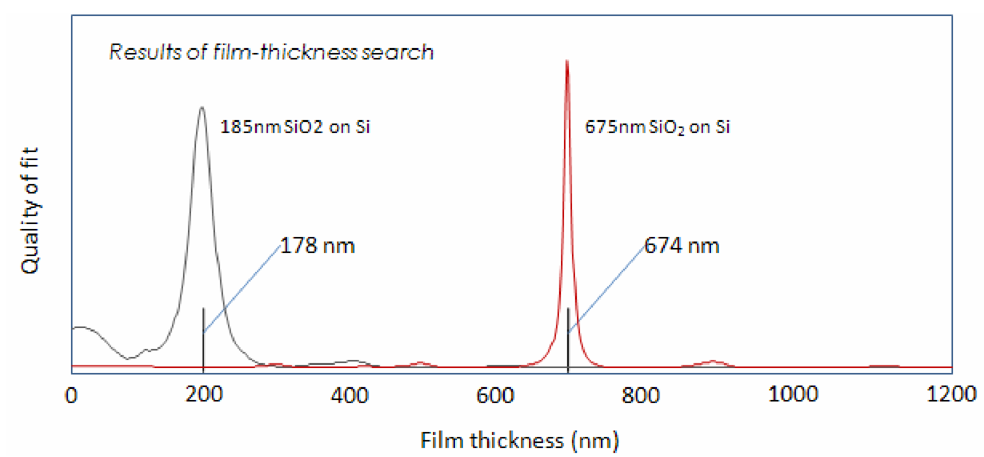


Figure 9: Results of a search through a range of 0-1200nm film thicknesses to find a match of theoretical to experimental signals for two different SiO_2 on Si film thickness standards: 185nm and 675nm. The vertical axis quantifies the quality of fit, with higher values corresponding to a better frequency-domain match of theory to experiment.

4. PUPIL-PLANE SWLI

The 3D films profiling described above is a natural extension of the surface topography measurement of conventional interference microscopy for simple film structures. For more complex multilayer structures, or for films having unknown optical properties, a useful trade is to exchange 3D profiling for a detailed analysis at a single point on the object surface, as shown conceptually in Figure 10.

The trade involves a change in hardware, replacing the tube lens of Figure 1 with a pupil-plane relay lens as shown in Figure 11. The addition of a polarizer in the interference objective converts the SWLI instrument into a multiple-angle, multiple-wavelength ellipsometer [10][11]. Multiple angles and polarization states follow from the pupil-plane geometry, while a Fourier analysis of the white-light interference signal dissects the optical properties of the surface according to wavelength.

The pupil-plane geometry provides far greater flexibility, detail and accuracy than could be expected from an imaging-mode analysis alone. Figure 12 (next page) illustrates this for a 3-layer structure of mixed dielectric and metal films. A three-parameter Cauchy model describes the optical properties of the dioxide layers, and the copper is assumed to conform to tabulated index values. The data regression optimizes three material parameters and three unknown thicknesses. The results were confirmed using a traditional variable angle spectroscopic ellipsometer.

Figure 13 (next page) shows the center-to-edge variation in film thickness of a nominally 80-nm silicon nitride film as a function of measurement site. Metrology of the <2.5nm range in film thickness, when combined with surface topography mode, allows for control of etch and polishing operations in semiconductor processing.

5. SUMMARY

Interference microscopy, traditionally limited to surface topography measurements of opaque structures, has made the transition to a much more flexible technique that not only accommodates transparent films, but provides a films analysis capability that complements conventional ellipsometry and reflectometry. The three techniques described illustrate this transition.

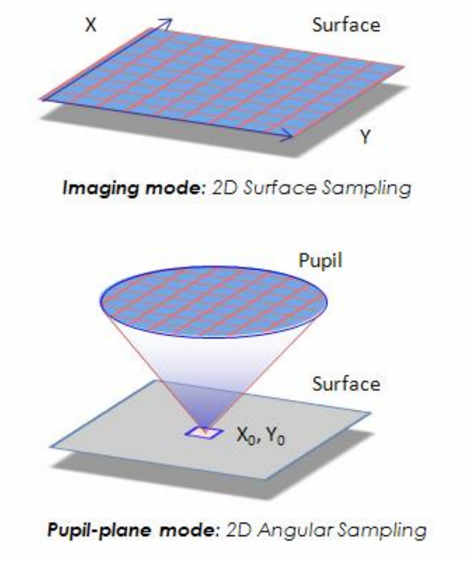


Figure 10: Concept illustration of the transition from SWLI imaging mode to pupil-plane mode.

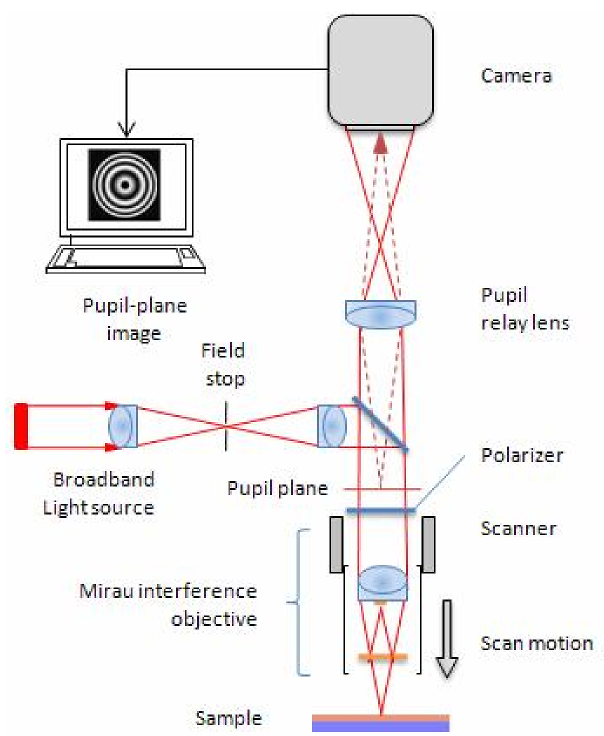
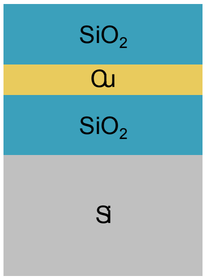


Figure 11: Scanning white light interferometer in pupil-plane mode for detailed film structure analysis.



PUPS	Ellipsometry
207 nm	211 nm
18.4 nm	17.6 nm
354 nm	360 nm

Figure 12: Comparison of pupil-plane SWLI (PUPS) analysis and a traditional spectral ellipsometric measurement of a three-layer film.

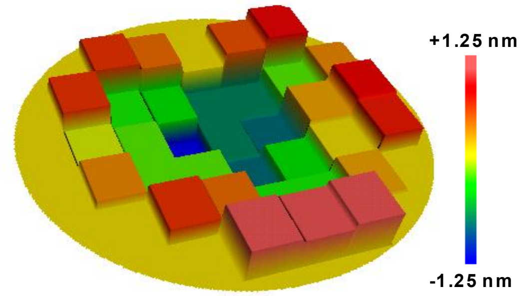


Figure 13: Variation in thickness of a nominally 80-nm thick Si_3N_4 film on a silicon wafer by measurement site, using the pupil-plane technique.

In the TopSlice technique, the interferometry signal is manipulated in a general way so that the instrument can continue to operate as a 3D surface topography tool in the presence of unknown surface films. For a standard SWLI instrument, the minimum film thickness is approximately 500nm, extendible to 200nm with new light sources.

In the modeling approach, full 3D profiling of film thickness as well as topography follow from matching theoretical response to measured signals on a pixel-by-pixel basis. This technique has no theoretical lower thickness limit, and potentially provides additional information about film properties and optically unresolved features.

In the pupil-plane method, the instrument makes the final transition to a fully-functional films analysis system. This technique closes the gap between interference microscopy and conventional ellipsometry for many applications of interest, including in particular, those applications that benefit from a dual-use configuration that provides both materials characterization and 3D surface topography in one tool.

REFERENCES

[1] Lee and Strand, "Profilometry with a coherence scanning microscope," Appl. Opt. 29, 3784 (1990).

[2] P. A. Flournoy, R. W. McClure, and G. Wyntjes, "White-light interferometric thickness gauge," Appl. Opt. 11, 1907 (1972).

[3] A. Bosseboeuf and S. Petigrand, “Application of microscopic interferometry techniques in the MEMS field” Proc. SPIE 5145, 1 (2003).

[4] P. de Groot, “Method and system for analyzing low-coherence interferometry signals for information about thin film structures,” US Patent 7,321,431 (2008).

[5] X. Colonna de Lega, and P. de Groot, "Optical Topography Measurement of Patterned Wafers," AIP ULSI Conference Proceedings 788, 432 (2005).

[6] P. de Groot, "Method and apparatus for surface topography measurement by spatial-frequency analysis of interferograms" US Patent No. 5,398,113 (March 14, 1995).

[7] S.-W. Kim and G.-H. Kim, “Thickness-profile measurement of transparent thin-film layers by white-light scanning interferometry,” Appl. Opt. 38, 5968 (1999).

[8] D. Mansfield, “The distorted helix : thin film extraction from scanning white light interferometry,” Proc. SPIE 6186, paper 23 (2006).

[9] D. S. Wan, “Measurement of thin films using Fourier amplitude,” US Patent Application 200710139656 (2007)

[10] X. Colonna de Lega and P. de Groot, “Interferometer with multiple modes of operation for determining characteristics of an object surface,” US Patent Application 20060158658 (2006).

[11] X. Colonna de Lega and P. de Groot, “Characterization of materials and film stacks for accurate surface topography measurement using a white-light optical profiler,” Proc. SPIE 6995 paper 1 (2008).