Invited Paper

Model-based white light interference microscopy for metrology of transparent film stacks and optically-unresolved structures

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1 Introduction

Surface form and roughness evaluation by interferometry is a highly-evolved practical science, encompassing a wide range of tools from the laser Fizeau to the interference microscope sketched below as Fig. 1.

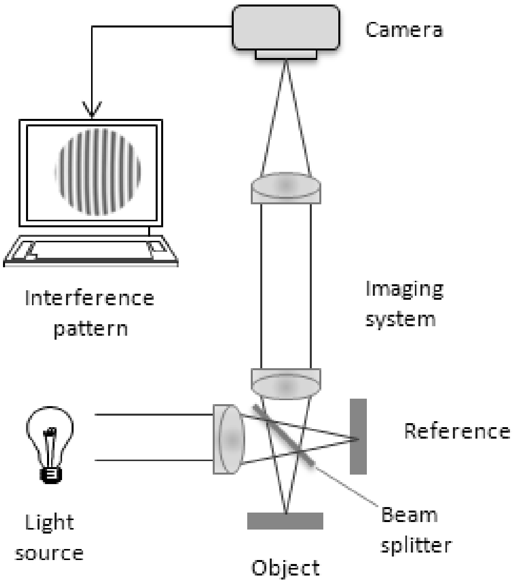

Fig. 1. A Michelson-type interference microscope for 3D surface profiling.

The present work considers the current revolution in white-light interference microscopy, in which the fairly simple pairing of interference phase to surface height has given way to more complex and powerful techniques that extract *surface structure* details, such as transparent film characteristics and the shape of optically-unresolved surface features. These new capabilities rely on a *model-based* interpretation of the interference signals, using methods and optical geometries that are still in rapid development.

2 Model-based analysis

Let us begin with the signal shown in Fig. 2, with its characteristic interference fringes and white-light contrast envelope. A significant industry has developed around the idea that the phase of the interference fringes varies linearly with the surface height, at a rate inversely proportional to the wavelength. In spite of advances in enabling technologies for interferometry, the principles of 3D surface metrology today are about the same as they have been for 100 years, relying on this linear phase-height relationship with perhaps an equally simplified, generic formula for the fringe contrast envelope.

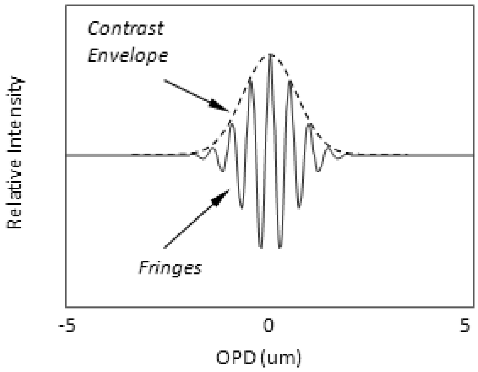

Fig. 2. A white-light interferometry signal as a function of optical path difference (OPD).

From the earliest days of commercial white-light interferometry in the 1990’s, it has been understood that there is more about the surface structure that could be extracted from the signal if we use a more detailed model of the interference effect [1]. The signal in Fig. 3, for example, looks very different from the simple model represented by Fig. 2. The differences relate to surface structure—in the case of Fig. 3, a transparent thin film of silicon dioxide on a silicon substrate. This signal is not so easy to interpret as the one in Fig. 2, particularly as the film gets thinner and the overlapping signals coalesce.

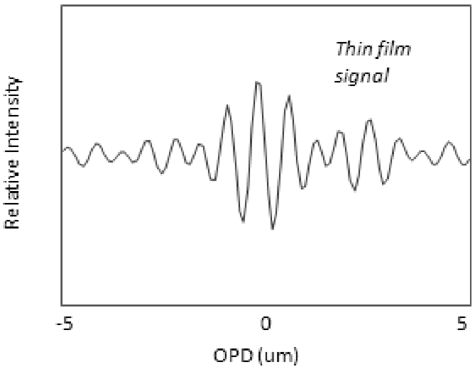

Fig. 3. Signal for an object having a transparent film coating of approximately 1 micron thickness.

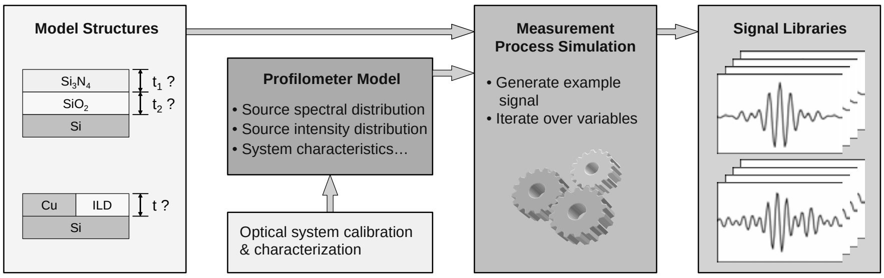

Fig. 4. Schematic flowchart of model-based interferometry. A comparison of the experimental signal with the signal library entries leads to the determination of a surface structure characteristic such as film thickness.

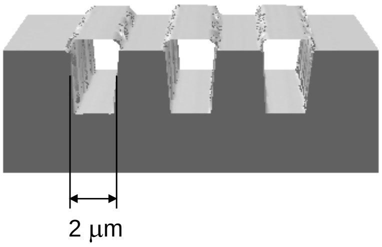

Fig. 5. Example model-based white light interference 3D profiling of film thickness measured with a 100X objective, showing simultaneously the top surface and underlying substrate profiles of a sample related to semiconductor processing. Here the Si substrate has trenches that are 480 nm deep, filled with SiO_2 that protrudes 70 nm above the surface of the wafer. From ref. [2]

The essence of a model-based approach is to begin with a more complete and accurate model of the interferometer and how the light interacts with the object surface [3]. Next, we solve the *inverse problem* to discover parameters such as film thickness by comparing of experimental and theoretical signals (or the Fourier Transforms) over a range of possible surface structures [2][4].

The first and most well-documented application of model-based white light interferometry has been 3D profiling of transparent film thickness and topography, as illustrated in Fig. 5. This is a capability difficult to match in any other tool—reflectometry may provide film thickness profiles but not topography, while tactile gages provide topography over films but without film thickness. Here we have both, in a non-contact, high-speed instrument with high data density.

3 Pupil-plane interferometry

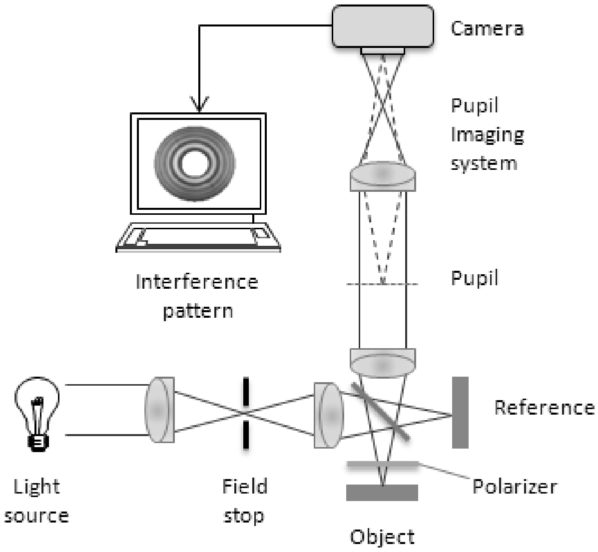

Fig. 6. White-light nterferometer for detailed surface structure analysis at a single point on the object surface.

For a higher-performance, advanced films capability (AFC), we adopt the geometry of Fig. 6, which shares some features with traditional conoscopy [5], microellipsometry [6] and monochrome interferometric techniques [7]. A field stop reduces the view to a single, 10-micron diameter spot on the object surface, and a special lens relays the pupil image to the camera in place of the object image [8][9]. The addition of a polarizer enables complex surface reflectivity analysis as a function of polarization and angle of incidence. Fourier analysis of the white-light interferometer signals adds the dimension of wavelength, as shown in the data example of Fig. 7. A model-based interpretation of these multiple-wavelength, multiple-angle ellipsometric data provides the desired information about surface structure.

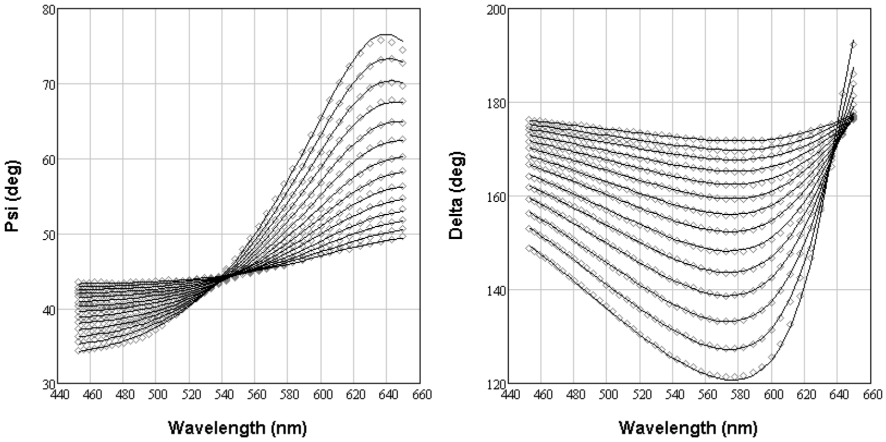

Fig. 7. Plot of ellipsometric parameters Delta and Psi measured as a function of wavelength and angle of incidence for a two-layer film stack of 56 nm Diamond Like Carbon (DLC) on 5 nm alumina over a metal alloy, using the AFC interferometer of Fig. 6. Markers represent experimental data points computed from a single measurement. Lines correspond to Delta and Psi computed using an optimized model of the film stack. Each line maps to a different angle of incidence, covering a 20° to 46° range. See Ref.[10].

Because the geometry of Fig. 6 relies on a platform that is very close to the conventional 3D imager of Fig. 1, it is straightforward to switch between the two modes using a simple exchange of imaging lens. We have reported several applications of this combination instrument in Ref. [10]and related papers.

4 Sub-wavelength surface structures

Transparent films are not the only surface structure characteristics that can influence white-light interference effects. Features ten times smaller than the source wavelength can leave a record of their presence in the interference signal shape that can be related to parameters such as width, height, edge shape and other optically-unresolved critical dimensions.

We use rigorous coupled wave analysis (RCWA) to model these effects and determine their influence on the interferometer signals. In collaboration with the Institut für Technische Optik at the University of Stuttgart, we employ a version of RCWA developed for high-NA white light interferometry [11]. RCWA is most effective with regular patterns or grating-like structures. The compromise is that we do not directly image individual sub-wavelength features, but rather to infer critical dimensions from the aggregate interaction of white light with these grating structures specifically designed for this purpose.

A first approach involves measurements of trench depth using a simple 3D step-height measurement using an interference microscope in imaging mode. For the example shown in Fig. 8, the unresolved grating manifests itself as an overall change in measured profile, which can be compared to theoretical expectations to determine the substrate etch depth. For simple structures with only one or two variable parameters, this method is a rapid and effective means of parameter control with a repeatability for individual measurements of 0.1nm rms and a validated correlation to AFM measurements, as detailed in Ref.[12].

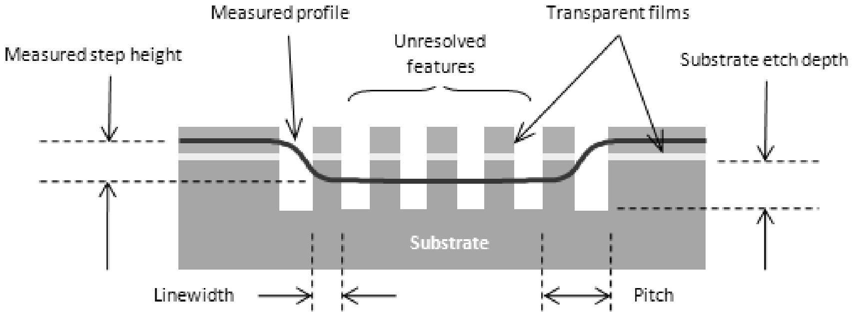

Fig. 8. Optical step-height measurement on a surface structure that includes transparent film layers with optically unresolved features. The measured profile does not resolve the features but is influenced by linewidth and etch depth.

For more complex structures or a multi-parameter analysis, we again call upon the pupil-plane geometry of Fig. 1. This is a more sensitive method with correspondingly greater complexity in the analysis, comparable to classical scatterometry but using an interferometer in place of the traditional reflectometer or ellipsometer. We call our technique Interferometric Critical Dimension analysis or ICD [8][9].

Fig. 9 shows a cross section of a periodic, 160-nm pitch structure that was measured using the ICD approach at a mean wavelength of 500nm. Seven parameters define the structure shape, including film thickness, side-wall angle (SWA), lateral width or critical dimension (CD), and height. Comparison with theoretical modeling using 4 wavelengths, 4 angles of incidence between 30° and 50°, and the complete 0 to 2π azimuth range available to the pupil-plane geometry provides simultaneous measurement of all of these sub-wavelength feature parameters in a few seconds. The cross section determined experimentally by ICD shown to the left in Fig. 9 is in good agreement with the scanning-electron microscope (SEM) cross section image shown on the right. The 3 sigma reproducibility for the 7 parameters over 3 days range between 0.25nm and 0.75 nm for dimensions and 0.25° and 0.35° for angles.

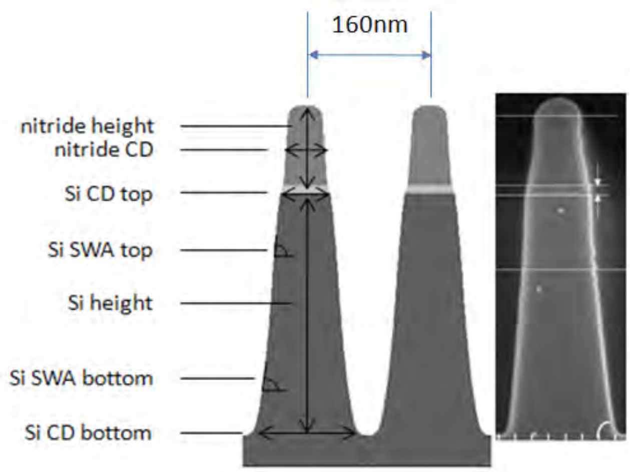

Fig. 9. Seven-parameter critical-dimension analysis (ICD) of an optically-unresolved, sub-wavelength grating-like structure using pupil-plane white-light interferometry.

5 Summary and conclusion

The field of application for white-light and related coherence-based interferometric techniques significantly increases with model-based methods; particularly when these techniques are combined with variations in optical geometry such as the pupil-plane geometry (Fig. 6) of our AFC and ICD instruments. Interference microscopes are now capable not only of high-quality 3D topography measurements, but detailed parameter analysis of transparent films and sub-wavelength structures relevant to state-of-the art, high-technology devices and systems.

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