CHALLENGES IN INTERFEROMETRIC MEASUREMENTS OF MEMS AND SEMICONDUCTOR DEVICES

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Introduction

Measuring MEMS and structures of semiconductor devices poses unique challenges to interferometry because these devices are very complex with multiple planes having different roughnesses, their surfaces are often protected by transparent layers like polysilicon, and whole devices are frequently protected by cover glass. The structures of these devices also often have many narrow and deep gaps called trenches that are difficult to measure precisely, thus usually necessitating a destructive method to determine the depth of the trenches, such as cross sectioning and measuring via scanning electron microscope.

However, interference microscopes are ideally suited for these kinds of measurements since they have nanometer to subnanometer vertical resolution with up to 8 millimeters maximum vertical range. Standard objectives allow up to 100X magnification while long-working-distance objectives, including ones compensated for measurements through glass, provide measurement capability at up to 40X magnification even parts are mounted beneath a protective cover glass or in an environmental chamber. Lateral resolution ranges from a few microns to about 500 nanometers, depending on the objective, with fields of view from 10mm to about 50um. Measurements typically take under a few seconds since they are based on full field measurement rather than point-by-point surface scanning.

Trenches measurement

White light interferometry[1] (WLI) provides a common tool in interference microscopy for micro-roughness and profile measurements of surfaces with discontinuities larger than 160nm. The analysis of fringes is based on the principle of low coherence peak sensing where the peak is created at the position of the object's surface. While well known is the fact that light incident on surfaces with sub-wavelength structure undergoes strong diffraction, little attention is paid to the fact that strong diffraction effects are also present when light is incident on objects with structures on the order of microns. These diffraction effects create additional coherence peaks that do not correspond to the surface topology; these additional coherence levels must be properly interpreted by WLI algorithms.

These additional coherence peaks were observed for a silicon surface with etched trenches not only 1.2 microns wide but also 5 and 10 microns wide – dimensions larger than in sub-wavelength structures but not large enough for fringes to represent geometrical structure of the object. The depth of the analyzed trenches was on the order 20 – 40 microns. The experimental data obtained with the Veeco optical profiler NT 8000 was compared with simulated results obtained from rigorous coupled-wave analysis[2] (RCWA) and Hopkins image-formation theory. We have found very good agreement between experimental and simulation results for a trench 5 microns wide and about 23 microns deep[3], and the experimental and simulated fringes are shown in Figure 1. In both cases the fringes in the void area of the trench at its top surface level are visible and are called induced coherence levels. They can significantly limit the range of measurements if interpreted as fringes corresponding to geometrical surface.

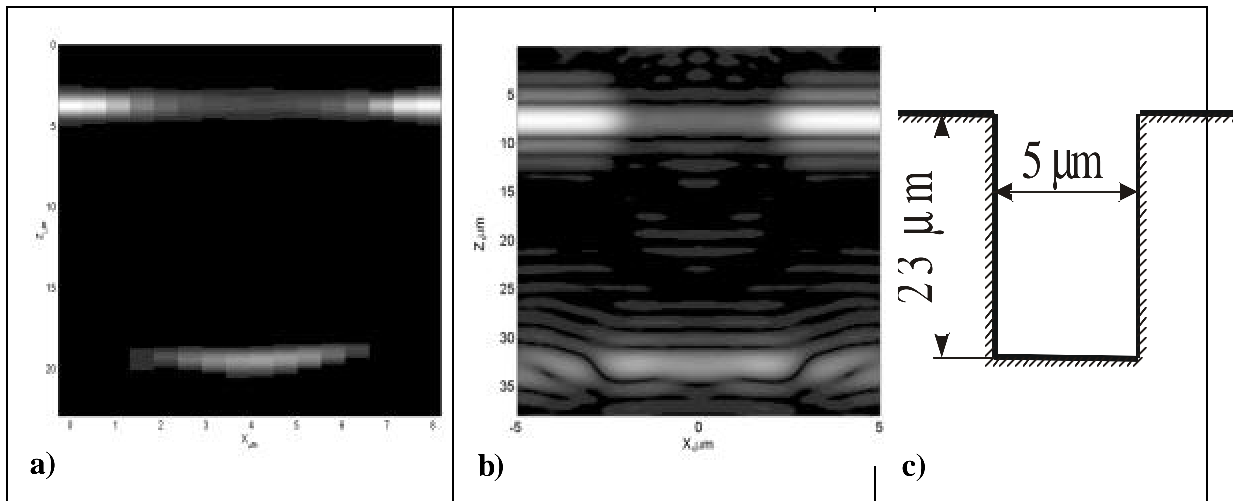

Figure 1. Fringe contrast images from experimental (a) and simulated (b) data for trench 5 microns wide and about 23 microns deep (c). For this structure an additional coherence level is observed above the bottom of the trench in the form of an extension of the coherence level representing incorrectly the top surface of the trench.

The amplitude of the coherence peaks varies the trench width and depth and is influenced by changes in the optical system such as the numerical aperture (NA), magnification, polarization and wavelength spectra. For example, for an objective with a given numerical aperture the amplitude of the additional coherence level increases with the decreasing trench width. The amplitude of the fringes at the bottom of trench decreases making the amplitude of the fringes representing the real surface much weaker than the additional coherence levels created from strong complex diffraction effects. The additional coherence levels can be a problem in i.e. MEMS measurement if not interpreted correctly. With special software we can measure the depth of a 1.2 micron wide and 40 micron deep trench.

Film thickness measurement

There is another group of objects for which white light fringes are not a straightforward representation of object's profile or rather interface. This is the case when an object is covered with a transparent film and the object's surface profile is of interest and not necessarily the top surface of film. For transparent coatings with thicknesses above several microns, two sets of white light fringes are created due to the top and bottom coating interfaces. The maximum of the second set of fringes is created at the distance corresponding to the optical coating thickness for white light. For this, the effective group index of refraction of the coating must be determined experimentally for each of the profiler's objectives to include the effects of the illuminating and imaging numerical apertures and the spectral properties of the source and system. The dispersion of the material, especially when using large NA objectives, quickly reduces the visibility of second set of fringes. Thus, the range of measurable thicknesses can be extended if a narrower bandwidth filter and/or a lower numerical objective is used, up to a maximum of several hundred micrometers thickness. The shift of fringe sets due to reflection of different interfaces can be also accounted for in high precision measurements.

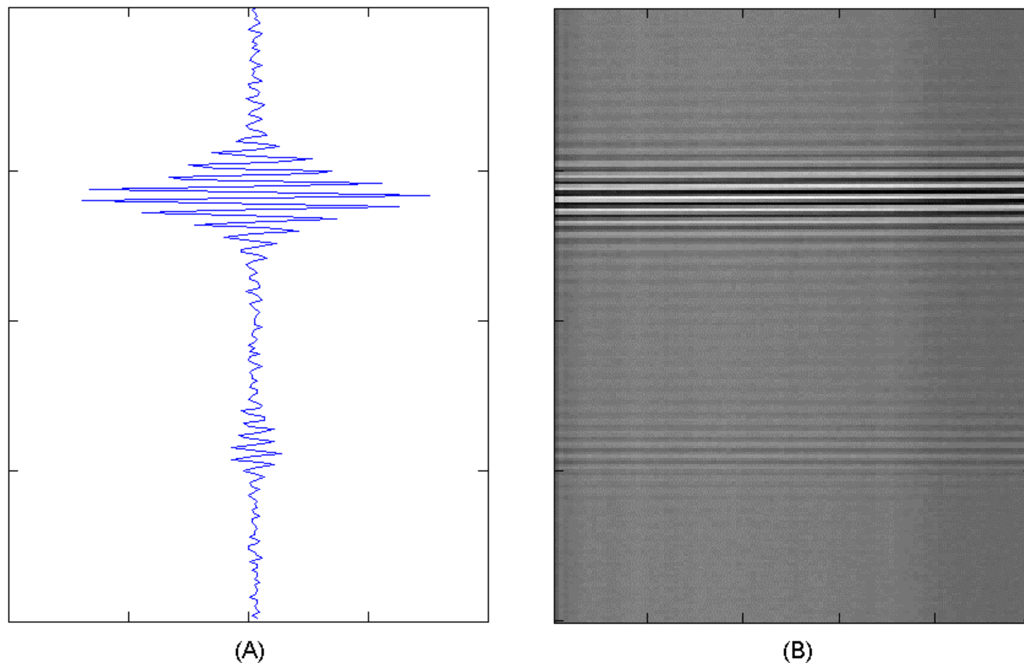

Figure 2. Two sets of white light fringes as seen by a single pixel (a) and the row of pixels (b) for a transparent film. The second set of fringes is created below the true interface between substrate and film due to group index of refraction of film larger than one.

Calibrating effective group index of refraction directly on the system accounts both for the film's group index of refraction and also for the fact that the film is illuminated by multiple beams at a wide range of angles determined by the numerical aperture of the objective. One method of calibration uses a known film thickness sample manufactured from the same material as the test object. Since the thickness of the sample is known, the program determines the proper value for the effective group index of refraction so as to achieve the correct film thickness value.

A different calibration method uses a specially prepared sample or part of the sample under test; this method is often used when the film creates a step to a bare substrate. If it can be assumed that the substrate is a flat surface on each side of the step, the value of the effective group index of refraction can be obtained in one vertical scan. In this case, the film step height, calculated from the top surface of the film to the bare surface (fringes from the film/substrate interface are disregarded), is equalized to the optical thickness of the film determined by the positions of two sets of fringes at the air/film and film/substrate interfaces. The effective group index of refraction can then be calculated.

Using these techniques we have measured many samples like photoresist thickness on MEMS, epoxy-acrylic thickness on flex circuits, polymers, Lithium Tantalate (LiTaO3) films of 5-25 micron thickness on silicon and quartz wafers. The repeatability of an average film thickness measurement is on the order of single nanometers. The typical range of measurable film thicknesses is from 3 to 150 microns depending on the objective and the dispersion of the film. This measurement allows for detection of flows on the surface and interface of the film.

6. Special analysis of sample structure

In the semiconductor and MEMS industries, film thickness varies over different structures on the substrate; thus, often a single technique for film thickness measurement cannot be applied to the whole field of view. In this case a special software approach[4], through which ideal surface templates are generated for each structure from the design files or prior measurements, can be applied in different regions. These templates may contain multiple sub-regions, or data islands, each of which can be characterized in a different manner. Surface measurements from a white light interference microscope are matched with the ideal object template using a variety of techniques and threshold criteria. The template-based technique is tolerant of errors from both rotation and translation and allows for accurate characterization of each data island and its relative positions.

The software has also a capability of presenting data consisting of any combination of sets of fringes (only first, only second, distance between first and second, first only but second if two sets of fringes exist with extension to multiple sets of fringes) allowing for flexibility in the object's structure display without the necessity of using a template-based technique. Thus, for example a surface profile can be easily displayed if any unwanted fringes due to local or locally varying thickness coatings are present or unwanted fringes are created due to the surface microstructure.

Software can store, display and analyze not only the measured height map but also the intensity map as seen through the conventional microscope; thus, the discoloration effect on paints and coatings can also be documented.

Summary:
Transparent layers and trenches often add to measurement challenges. Interference fringes formed by the unique characteristics of these objects require special analysis to obtain the correct profile of the object's surfaces and sub-surfaces. With developed special software and calibration routines, we can measure the topography of the top surface of a transparent layer, the thickness of the layer up to 150 micrometers and the topography of the sub-surface – the interface between substrate and layer in one measurement scan. With special software we also can measure the depth of trenches with very high depth to width aspect ratio. The ratio can be as large as 15:1 and trenches as narrow as 1.2 microns in width. The measurement of narrow trenches (10 microns and less) is especially challenging since additional fringes induced by diffraction may appear in the gap of the trenches and require a special interpretation.

1. M. Fleischer, R. Windecker, H. J. Tiziani, "Theoretical limits of scanning white-light interferometry signal evaluation algorithms," Applied Optics, **40**, 2815 (2001).
2. A..Tavrov, M. Totzeck, N. Kerwien, H.J. Tiziani, "Rigorous coupled-wave analysis calculus of sub micrometer interference pattern and resolving edge position versus signal-to-noise ratio," Opt. Eng. **41**(8) 1886-1892 (2002).
3. A. Tavrov, J. Schmit, W. Osten, N. Kerwien, H.J. Tiziani "Induced coherence effects" submitted to Applied Optics.
4. E. Novak, M. Krell, T. Browne, „Templete based software for accurate MEMS characterization," SPIE Proceedings 4980, 75-80 (2003).