Nanoscale Measurements With a Through-Focus Scanning Optical Microscope

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Introduction

In the current world of nanotechnology, fast and reliable measurement of nanoscale features is extremely useful. It is further advantageous if the analytical tools used are cost-effective and have high throughput, such as optics-based tools. In conventional optical microscopy, it is usually deemed necessary to acquire images at the "best-focus" position for meaningful analysis. However, the out-of-focus images do contain useful information regarding the target. On the basis of this, we introduce a new method for nanoscale dimensional analysis with nanometer sensitivity using a conventional optical microscope. The method is called the through-focus scanning optical microscope (TSOM- pronounced "tee-som") imaging method.[1-5] The TSOM method is applicable to 3D targets, enabling the method to be used for a wide range of target geometries.

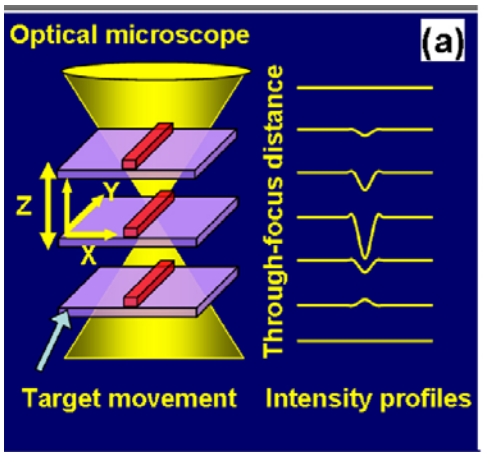
The TSOM Image Construction

In Figure 1, we demonstrate the method used to construct the TSOM images, using an isolated line as a target. Optical images are acquired as the target is scanned through the focus of the microscope (along the Z-axis) as shown in Figure 1(a). Each scan position results in a slightly different 2D intensity image. The acquired optical images are stacked at their corresponding scan positions, creating a 3D TSOM image, where the X and the Y axes represent the spatial position of the target and the Z axis is the focus position. In this 3D space, each location has a value corresponding to its optical intensity. The optical intensities in a plane (for example, the XZ plane) passing through the location of interest on the target (through the center of the line, for example) can be assembled and conveniently plotted as a 2D image resulting in a TSOM image as shown in Figure 1(b), where the X (horizontal), Y (vertical) and Z (color scale) axes represent the spatial position on the target, the focus position and the optical intensity respectively.

Applications of the TSOM Method

At present we are exploring two applications of the TSOM method. They are: (1) to identify which dimensional parameter is

changing (e.g., a change in height versus width) and to estimate the magnitude of these changes; and (2) to determine the absolute dimensions of a target. The first application is best examined by looking at the difference between two sets of TSOM images, which results in a differential image, unique to that pair of targets. Although optical simulations are not necessary for this first type of application, they greatly enhance the rigor of the method. The presence of optical aberra-



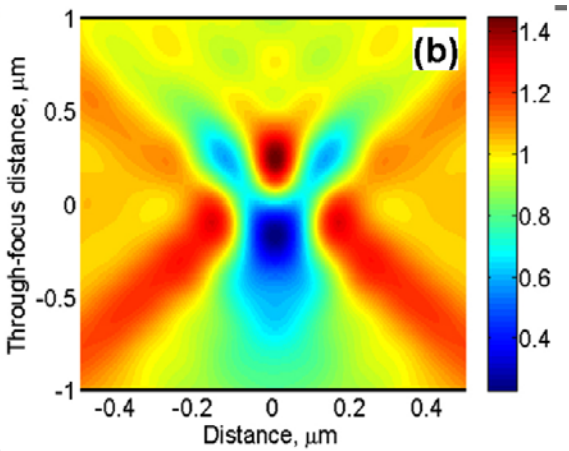


Figure 1. Method to construct a TSOM image. (a) Schematic showing the image-acquisition process by through-focus scanning of an isolated line. The schematic of the cross-sectional image-intensity profiles at the various scan positions is shown on the right side. (b) Simulated two-dimensional TSOM image (*X-Z* plane) of the isolated line. [Line width = 40nm, line height = 80nm, sidewall angle = 90°, λ = 193nm, illumination NA = 0.4, imaging NA = 0.95, Si line on Si substrate]

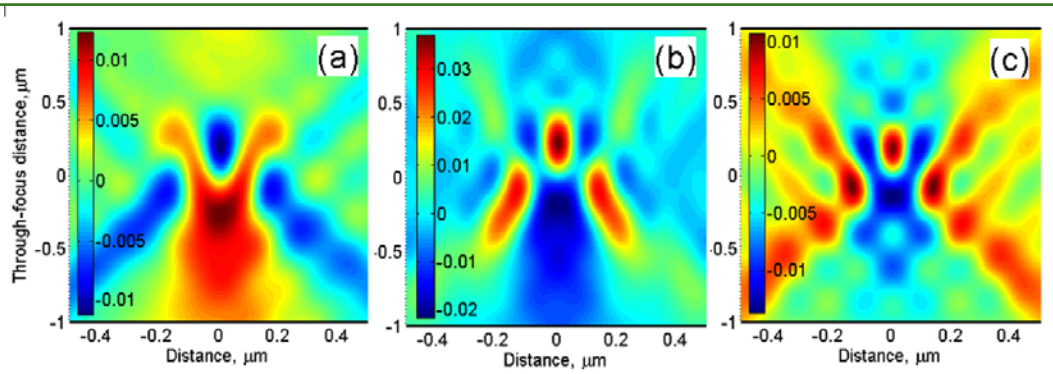


Figure 2. Simulated differential TSOM images obtained for the 2D isolated line target shown in Figure 1(b) for (a) 2.0nm difference in the line width (42nm and 40nm), (b) 2.0nm difference in the line height (82nm and 80nm), and (c) 2.0° difference in the sidewall angle (90° and 88°).

tions appears to have a negligible effect on this type of analysis. The second type of application requires accurate optical simulations with satisfactory experiment-to-simulation agreement. In the following paragraphs, we discuss in detail these two applications using the TSOM images.

Dimensional changes produce corresponding changes in the TSOM images. Although nanoscale dimensional changes produce differences in the corresponding TSOM images that may not be easy to identify, the differential TSOM image highlights the dimensional differences. For example, an isolated 2D line produces distinct differential TSOM images for line width, line height and sidewall angle differences as shown in Figures 2(a), 2(b) and 2(c), respectively. In this example, the differential TSOM images facilitate identification of the dimensions that are different between these nanoscale targets.

Although the differential TSOM images are distinct for different dimensional differences, they appear qualitatively similar for varying magnitude differences of the same dimension. Once the varying parameter (e.g., line width) is identified, one approach to quantify the difference in this parameter is to evaluate the "mean square difference" (MSD) of the differential image intensity, which is defined as:

$$MSD = \frac{1}{n}\sum_{i=1}^{n}(TSOM\ image1 - TSOM\ image2)^2$$

where n is the total number of pixels in the image.

For example, 1.0nm and 2.0nm differences in the line widths of an isolated line produce MSD values of 0.58 x 10^{-6} and 2.45x 10^{-6}, respectively (mean line width = 40nm, line height = 100nm, λ = 546nm, NA = 0.8, illumination NA = 0.4, Si line on Si substrate). Similarly, differences in line height and sidewall angle produce MSD values in direct relationship to the magnitude of the dimensional differences. The theoretical analysis shows that the differential TSOM images highlight the dimensional differences and the MSD indicates the magnitude of the difference.

Experimental Verification

As a first demonstration of this technique, we compare simulation data to experimental results for 2D line grating targets. Using an atomic force microscope (AFM) for reference metrology, we measured dimensions of a grating target. Using these as input parameters to the model, we then obtained the simulated TSOM images. Figures 3(a) and 3(b) are experimental and simulation TSOM images, respectively, for the selected grating target. Figures 3(c) and 3(d) are the experimental and the simulated differential TSOM images for a 3.0nm difference in the line width. Agreement between the experiment and the simulation is satisfactory in this initial comparison.

If we assume the TSOM images to be unique for a given target under a given experimental condition, we can then compare the experimental TSOM images with that of a library of simulated TSOM images. The reported measurement would be the dimensions of the best match between the experimental images and the simulated images. Using an AFM for reference metrology, we experimentally measured a grating bottom line width, line height, sidewall angle, and pitch as 140nm, 230nm, 87° and 601nm, respectively. Comparing the TSOM image from the experimentally measured target with the library gave the best line width match as 126nm. It is expected that better optical

measurement accuracy will be achieved with improved optical models, and optical system characterization and normalization, facilitating improved simulation to experiment matching.[6]

Under certain circumstances, a direct observation of the TSOM images is helpful. For example, the TSOM images can highlight the presence of defects and the type of defect in a dense grating. As a demonstration, we present four experimental TSOM images for four dense gratings fabricated with intentional defects, as shown in Figure 4(a) to 4(d). The four types of defects produce distinctly different TSOM images, firstly indicating the presence of defects and secondly pointing to the type of defect. In contrast, the absence of defects would produce featureless TSOM images for these dense targets. This type of analysis is also applicable for single, isolated defects or several random defects present in a dense grating.

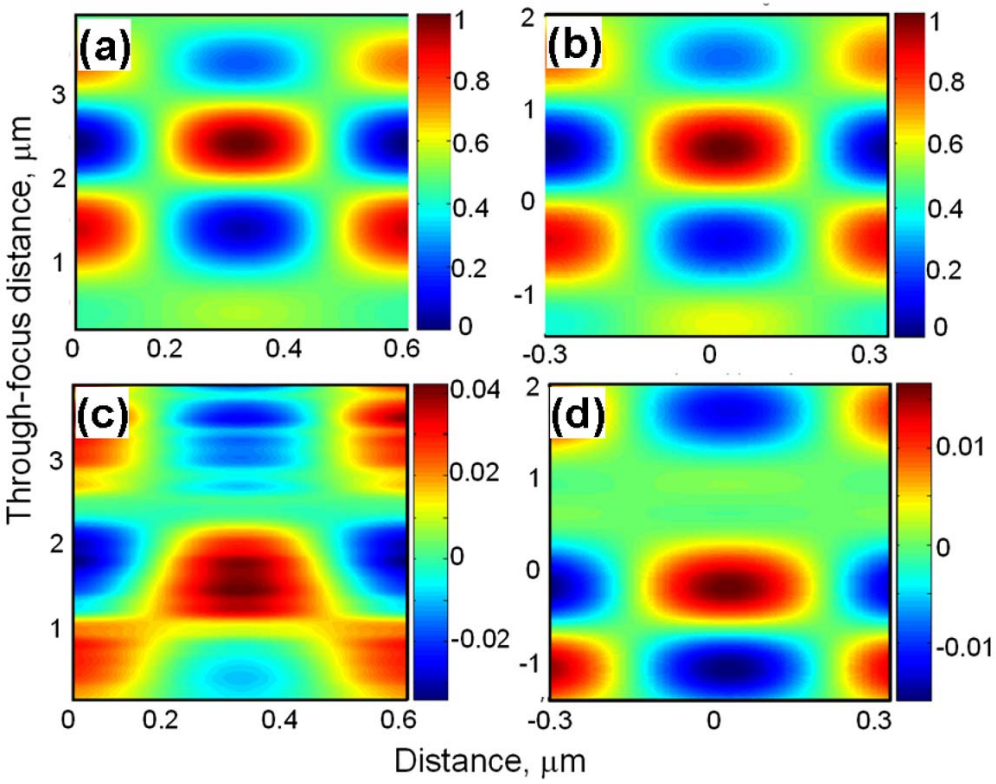


Figure 3. Experimental TSOM image for a 2D line grating target with 149nm line width. (b) Simulated TSOM image obtained for the same target shown in (a). (c) The experimental *differential* TSOM image for 3.0nm difference in the 2D grating target line width (149nm and 146nm). (d) The simulated differential TSOM image for the same 3.0nm difference in the line width. [Si line on Si substrate. λ = 546nm, line height = 230nm, sidewall angle = 87°, pitch = 60nm, illumination NA = 0.36, imaging NA = 0.8]

Concluding Remarks

We have presented a novel optical technique to construct TSOM images, using a conventional optical microscope. The TSOM images exhibit nanoscale dimensional sensitivity and parametric signature differences. The technique facilitates identification of the dimension that is different between two nano-sized targets, has sensitivity to the magnitude of the difference and can potentially derive the absolute target dimensions using a library matching method. In the current world of nanotechnology, this method has application to a wide range of target geometries including particles, lines, and 2D and 3D structures and materials. In addition, it eliminates the requirement to precisely set the target at the best focus position. Since optical microscopes are widely available, the TSOM method can be used readily and economically. This methodology has potential utility for a range of measurement problems in nanotechnology, biotechnology and semiconductor manufacturing. The primary limitations of this method are the requirement for accurate simulations, and satisfactory experiment-to-simulation agreement (for the second type of application).

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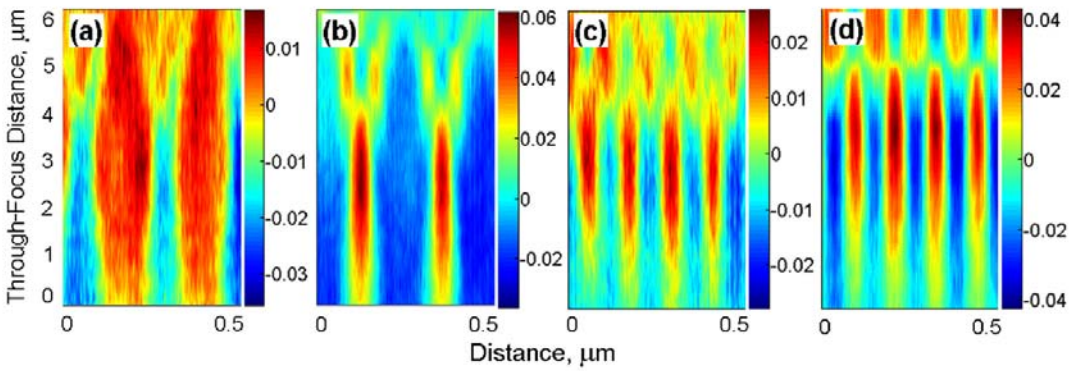

Figure 4. Experimental TSOM images for dense line gratings fabricated with intentional defects. Every tenth line is (a) smaller, or (b) larger by 10nm; or every fifth line is (c) smaller, or (d) larger by 10nm. [λ = 546nm, nominal line width = 90nm, nominal pitch = 270nm, illumination NA = 0.36, imaging NA = 0.8]

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