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Three-dimensional Nanometrology with TSOM Optical Method

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Abstract— **Through-focus scanning optical microscopy (TSOM) is a new metrology method that achieves 3D nanoscale measurement sensitivity using conventional optical microscopes; measurement sensitivities are comparable to what is typical when using scatterometry, scanning electron microscopy (SEM), and atomic force microscopy (AFM). TSOM can be used in both reflection and transmission modes and is applicable to a variety of target materials and shapes. Nanometrology applications that have been demonstrated by experiments or simulations include defect analysis, inspection and process control; critical dimension, photomask, overlay, nanoparticle, thin film, and 3D interconnect metrologies; and nanoscale movements of parts in micro and nano-electro mechanical systems. Industries that could benefit include semiconductor, data storage, photonics, biotechnology, and nanomanufacturing. TSOM is relatively simple and inexpensive, has a high throughput, and provides nanoscale sensitivity for 3D measurements with potentially significant savings and yield improvements in manufacturing.**

Keywords— **three-dimensional metrology, TSOM, nanometrology, through-focus, optical microscope**

1. INTRODUCTION

The demand on tools to make 3D measurements at the nanoscale is very high as dimensional information at the nanoscale is required to enable progress in nanotechnology and nanoscience [1,2]. Several tools, such as the atomic force microscope (AFM), scanning tunneling microscope (STM), and scanning electron microscope (SEM) are routinely used to provide measurements at this scale. However, with the commercialization of nanotechnology, fast and reliable nanoscale feature measurements will become increasingly important [1,2]. Optics-based tools can be advantageous because they have a relatively low cost of ownership with high throughout, and are usually completely non-contaminating and non-destructive.

It is often a misconception that optical microscopes are not well suited for dimensional measurements of features that are smaller than half the wavelength of illumination (200 nm sized features in the visible region) due to diffraction [3]. Of course, optical microscopes have been used for years to measure photomask linewidth features well below half the illumination wavelength. Certainly, diffraction-dominated images make meaningful analysis of the targets difficult. However, this limitation can be circumvented by (i) considering the image as a dataset (or signal) that represents the target, (ii) using a set of through-focus images instead of one “best focus” image, and (iii) making use of highly developed optical models [4-6].

In conventional optical microscopy, images are acquired at the "best focus" position based on the belief that the most faithful representation of the target is rendered only at the best focus position. However, the out-of-focus images do contain additional useful information about the target. This information can be obtained using an appropriate data acquisition and analysis method. Based on this and on the observation of a distinct signature for different parametric variations, we introduced a new method for nanoscale dimensional analysis with nanometer sensitivity for three-dimensional, nano-sized targets using a conventional brightfield optical microscope [7-15]: through-focus scanning optical microscopy (TSOM). TSOM is applicable to three-dimensional targets (where a single “best focus” may be impossible to define), thus enabling it to be used for a wide range of target geometries and application areas. Here we present a brief summary on the TSOM method. The TSOM method was recognized and presented with an R&D 100 Award in 2010 [16].

2. TSOM IMAGE CONSTRUCTION

The TSOM method requires a conventional brightfield optical microscope with a digital camera to capture images, and a motorized stage to move the target through the focus. Fig. 1 demonstrates the method to construct TSOM images using an isolated line as a target. Simulated optical images are used here to illustrate the method. Optical images are acquired as the target is scanned through the focus

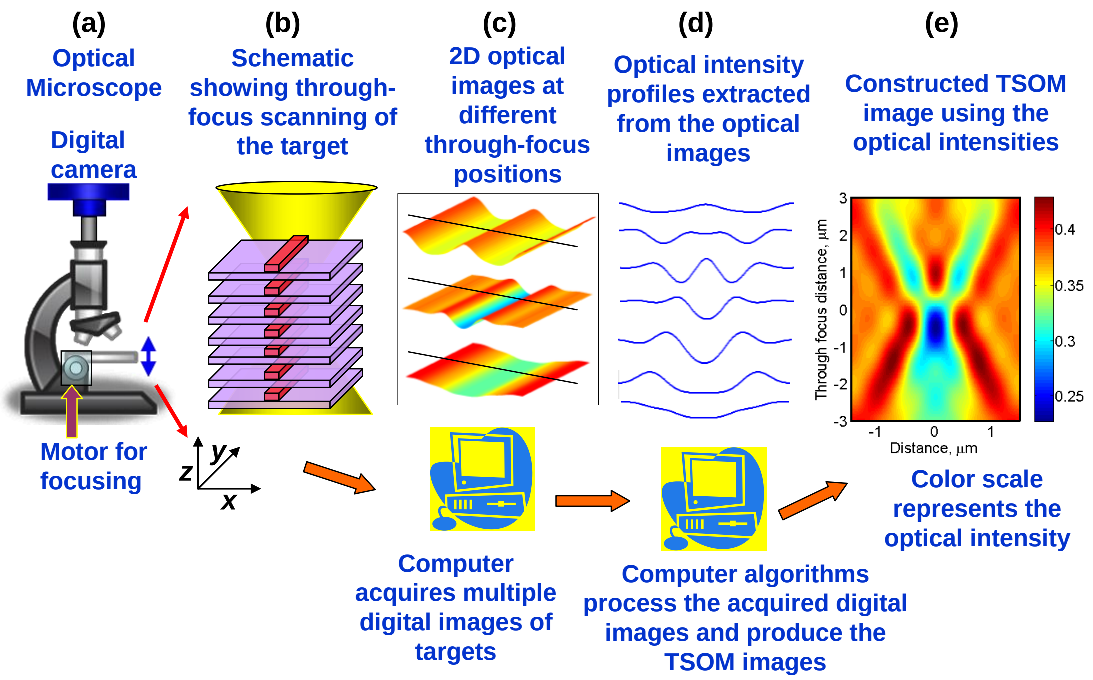

Figure 1. Method to construct TSOM images using a conventional optical microscope.

of the microscope (along the z-axis) as shown in Figs. 1(a) & 1(b). Each scan position results in a slightly different two-dimensional intensity image (Fig. 1(c)). The acquired optical images are stacked at their corresponding scan positions, creating a three-dimensional TSOM image, where the x and the y-axes represent the spatial position on the target and the z-axis the scanned focus position. In this 3D space, each location has a value corresponding to its optical intensity. The optical intensities in a plane (e.g., the xz plane) passing through the location of interest on the target (e.g., through the center of the line) can be conveniently plotted as a 2D image, resulting in a 2D-TSOM image as shown in Fig. 1(e), where the x axis represents the spatial position on the target (in x), the y axis represents the focus position, and the color scale represents the optical intensity. Note that the intensity (color) axis is typically rescaled for each image. For 3D targets, appropriate 2D-TSOM images are selected for dimensional analysis. In this paper, we use "TSOM image" to refer to these 2D-TSOM cross-sectional images.

3. CHARACTERISTICS OF TSOM IMAGES

The TSOM images have several characteristics useful for nano-scale dimensional analysis as given below. A detailed explanation of these characteristics can be found elsewhere [13-15]. A differential TSOM image is the difference between two TSOM images and highlights nano-scale differences.

1. TSOM images change with target.
2. Differential TSOM images appear to be distinct for different dimensional changes.
3. Differential TSOM images are qualitatively similar for differences in the same dimension.
4. Integrated optical intensity of a differential TSOM image indicates the magnitude of the dimensional difference.
5. TSOM images appear to be unique.
6. TSOM images are robust to optical aberrations and process variation.

An example for characteristic 2 of the TSOM images is shown here. Fig. 2 presents TSOM images for two targets with a 1.0 nm difference in the linewidth. Visual inspection of the two TSOM images would indicate that they are similar. In the same way, the TSOM images for a small difference in the line height or sidewall angle also appear similar. However, a simple subtraction of any two TSOM images distinctly highlights the difference between them. This difference can be highlighted using a differential TSOM image. This is illustrated in Fig. 3 for four different dimensional differences. They are a 1 nm difference in the line height, a 1 nm difference in the linewidth, a 1 nm difference in both the linewidth and the line height, and a 1 degree difference in the sidewall angle. The differential TSOM images for the four types of dimensional differences appear distinctly different.

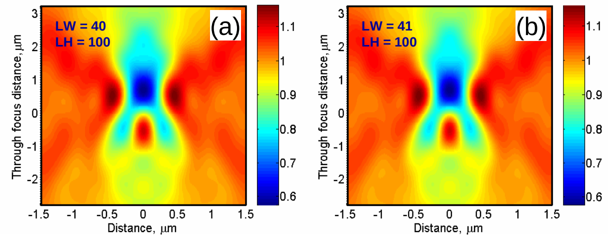

Figure 2. Simulated TSOM images for two isolated line targets. LW = Linewidth in nm, LH = Line height in nm, λ = 546 nm, Si line on Si substrate.

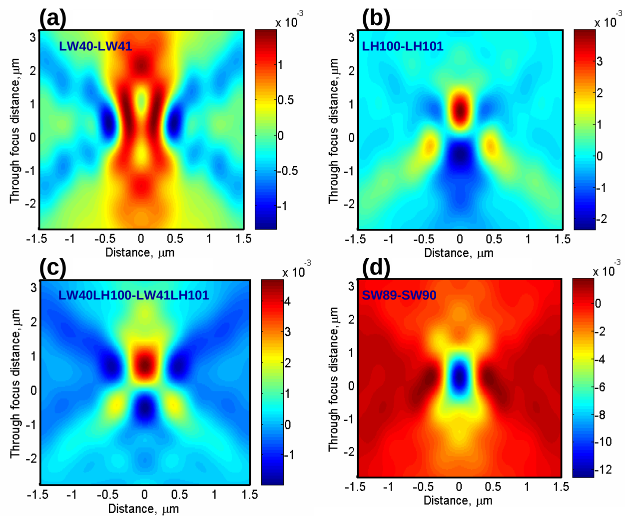

Figure 3. Simulated differential TSOM images obtained for the isolated lines shown in figure 4. (a) 1.0 nm change in the linewidth (b) 1.0 nm change in the line height (c) 1.0 nm change in both the line height and the linewidth, and (d) one degree change in the sidewall angle (LW = Linewidth in nm, LH = Line height in nm).

4. TWO TYPES OF APPLICATIONS

Currently, based on the characteristics of the TSOM images, we propose two applications of the TSOM method:

(i) To determine differences in dimensions, and
(ii) To determine the absolute dimensions of a target

The first type of application, sensitivity to dimensional change, requires a minimum of two targets. For these sensitivity measurements, although simulations are not necessary, they can greatly enhance the understanding of the dimensional sensitivity behaviour pattern of the method.

In the second type of application, an acquired TSOM image is compared with either a simulated or experimentally created library. The best matched TSOM image in the library provides the physical dimensions of the target. Creating a library experimentally requires a set of reference calibration samples (accurately measured with other reference techniques) that span the range of anticipated values for the parameters to be measured by TSOM. Determining the physical dimensions using a simulated library, on the other hand, requires accurate simulations, validated by satisfactory experiment-to-simulation agreement during the development phase.

5. MEASUREMENT TO SIMULATION COMPARISON

To validate the simulations, data were collected to produce an experimental TSOM image. For this experiment, a Si line grating was chosen and the target and through-focus images were acquired at 100 nm through-focus step increments. Using reference metrology tools such as scanning electron microscopy (SEM) and atomic force microscopy (AFM), the target bottom linewidth, line height, and pitch were measured as 152 nm, 230 nm, and 601 nm, respectively. These were used as input parameters to the model to simulate the TSOM image. The experimental and simulated TSOM images are presented in Fig. 4, demonstrating good qualitative experiment to simulation agreement.

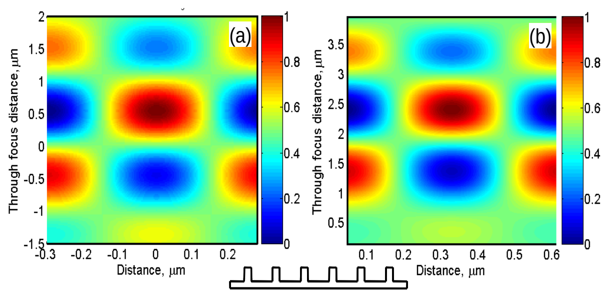

Figure 4. Comparison of (a) simulation and (b) experimental TSOM images for a line grating. Linewidth = 152 nm, Line height = 230 nm, Pitch = 601 nm, λ = 546 nm, Si line on Si substrate. Only one pitch period is shown in the figure.

The measured differential TSOM image, which includes noise and other experimental imperfections, was compared with the simulation analysis. We chose two line gratings (pitch = 601 nm) with 146 nm and 149 nm linewidths (about 3 nm difference). Using λ = 546 nm light, we obtained two experimental TSOM images to yield one differential TSOM image. To obtain the experimental differential TSOM image, we normalize the intensities of the experimental TSOM images such that the maximum intensity in the image is equal to one and the minimum intensity equals to zero. The two normalized TSOM images are then cross-correlated to get the best match. At this point, differential TSOM images are obtained. We applied the same normalization procedure to the simulation results to maintain consistency with the experiment. Differential TSOM images from the simulations and the experiments are shown in Fig. 5. Although agreement is not ideal, the images have substantial qualitative similarities.

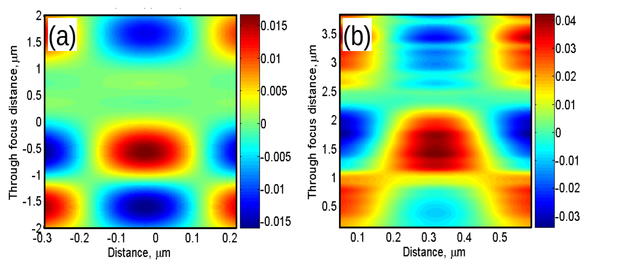

Figure 5. Comparison of (a) simulation and (b) experimental differential TSOM images. The differential images were obtained for the two targets with linewidths of 146 nm and 149 nm. Line height = 230 nm, Pitch = 601 nm, λ = 546 nm, Si line on Si substrate.

6. SOME EXAMPLE APPLICATIONS

A. Experimental Linewidth Determination Using Simulated Library

The utility of the TSOM image approach in metrology is based on an assumption that any given target produces a unique TSOM image under a given experimental condition. This was used to experimentally measure the linewidth of a line grating. The results are still preliminary. We evaluated the dimensions of the selected target, including the linewidth, using an AFM as the reference metrology tool. The AFM-measured linewidth was 145 nm for the selected target. However, we assumed the linewidth to be unknown. Using the measured dimensions, we simulated a small library of TSOM images, varying only the linewidth from 140 nm to 160 nm with a step increment of 0.5 nm, keeping the line height (230 nm), the pitch (601 nm), and the sidewall angle (which is curved) constant. The library matching of the experimental TSOM image was carried out by evaluating the mean square difference (MSD) [10,13,14] values from the differential TSOM images. The differential TSOM images between the experimental and the simulated TSOM images were obtained after they were aligned to get the best correlation. A plot of the MSD values evaluated as a function of the linewidth in the library is shown in Fig. 6. The inset shows a magnified view of the minimum of the curve. This gives the best linewidth match as 153 nm. The TSOM image-based linewidth value differs with the AFM measured linewidth of 145 nm. The discrepancy between the AFM and the optical technique requires further study beyond the scope of this paper. However, this example demonstrates the potential utility of the TSOM method for absolute dimensional measurements.

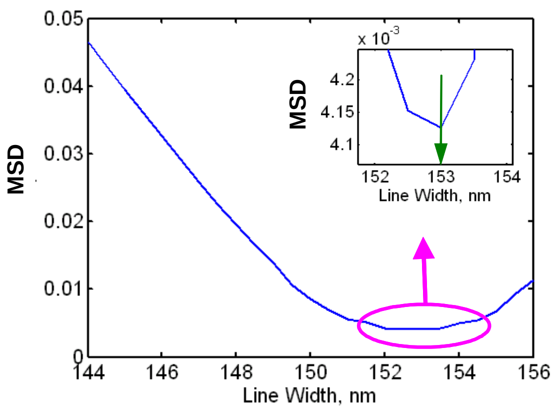

Figure 6. A plot of the MSD values evaluated comparing the experimental 'unknown' target with the library of simulations. The inset shows the magnified portion of the highlighted curve.

B. Dimensional Analysis of Nanodots (Nanoparticles, Quantum Dots) Using Experimental Library

We conducted an experiment to determine the size of nanodots using a measured library. For this purpose, approximately square Si nanodots on a Si substrate were fabricated with nominal sizes ranging from 40 nm to 150 nm and a fixed height of about 70 nm. The SEM lateral dimension reference measurements were always larger than the nominal designed dimensions. Even though the nanodots are not exactly the same as nanoparticles, the measurement procedure remains the same. Lateral dimensions of the nanodots were measured using an SEM, which has a nominal measurement uncertainty of about 5 %. Following the SEM measurements, the TSOM images were acquired for the selected nanodots using polarized illumination at a wavelength of 546 nm. A typical background intensity-normalized to zero TSOM image for TE polarization is shown in Fig. 7(a). Using the

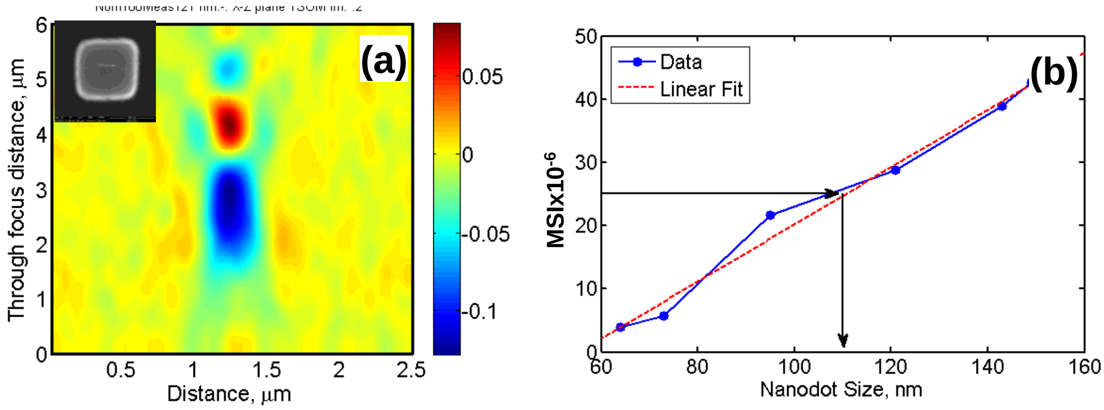

Figure 7. (a) SEM image of a 121 nm nanodot and its experimental intensity-normalized TSOM image (λ = 546 nm, TE Polarization, Si nanodot on Si substrate). (b) Experimental mean square intensities of the normalized TSOM images of the selected square nanodots showing a linear trend with size. Arrow marks indicate the experimental size determination of a nanodot of unknown size using the library/calibration curve.

experimental TSOM images thus created, integrated mean square intensities (MSIs) for the selected nanodots were evaluated and plotted as a function of the SEM-measured nanodot size as shown in Fig. 7(b). Under the current experimental conditions, the curve nominally follows a linear trend. This is treated as the library or the calibration curve for dimensional analysis of nanodots of unknown size. An "unknown-size" nanodot was measured from this calibration curve using the integrated mean square intensity of its TSOM image, producing a measured size of 108 nm. This "unknown-size" nanodot had previously been measured with SEM producing an measured size of 103 nm. Considering this an initial attempt, the agreement is good.

C. Critical Dimension (CD) Analysis of Dense Line Gratings

Although dense, uniform line gratings with pitch below one-half the wavelength of the illumination result in an uninteresting featureless TSOM image when the grating fills the field of view, CD analysis with TSOM is still possible if the edge of the grating is analyzed as shown in Fig. 8(a-c). It is recognized that the dimensions of the lines at the edge of a grating are usually different from the lines in the middle of the grating, however, this does demonstrate a way to use the TSOM method to access some potentially useful dimensional analysis information, even for dense gratings. The experimental differential TSOM image for an AFM-measured 3.2 nm difference in the linewidths shows a good signal (see Fig. 8(c)). Consequently, we proposed a much smaller size line grating as shown in Fig. 8(d) for dimensional analysis. The simulated differential TSOM image for a nanometer difference in the linewidths shows a good signal (Fig. 8(f)), indicating that the smaller sized gratings are equally effective for dimensional analysis using the TSOM method. Advantages include the ability to use much smaller sized gratings, which use less valuable area, and the ability to extend the use of visible wavelength illumination and optics for measuring dense gratings with linewidths potentially down to as small as 16 nm (with 1:2 pitch), as listed in the International Technology Roadmap for Semiconductors out to 2025. Further experimental verification work is needed to come to a definite conclusion.

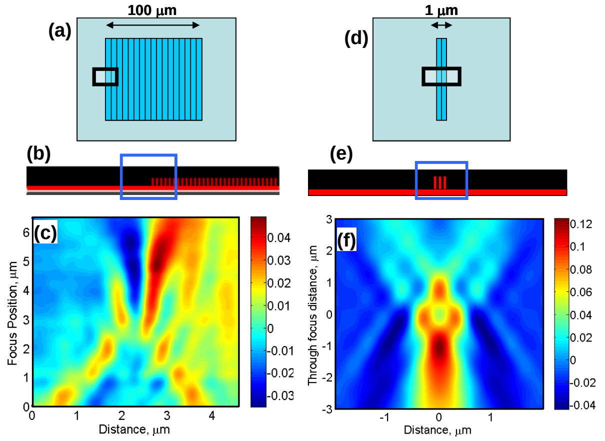

Figure 8. (a) and (b) Location of TSOM analysis for large dense gratings shown in two views. (c) Experimental differential TSOM image at the edge for 3.2 nm difference in the CD using λ = 546 nm (AFM measured CDs are 118.5 nm and 115.2 nm, Pitch = 300 nm and Line height = 230 nm, (d) and (e) Proposed smaller area line gratings shown in two views, and (f) Simulated differential TSOM image for one nanometer difference in the line width using λ = 546 nm (Linewidths = 17 nm and 16 nm, Pitch = 48 nm (1:2) and Line height = 60 nm)

D. Defect Analysis

Under certain circumstances, the use of the direct (not differential) TSOM image is helpful. For example, TSOM images can highlight the presence of defects and the types of defects in a dense grating, if for example the defect is a periodic variation in linewidth. Experimental TSOM images for two dense gratings fabricated with intentional defects are shown in Fig 9. The two types of defects with periodic 10 nm differences in the linewidths produce distinctly different TSOM images, indicating the presence of the defects and pointing to the type. In contrast, the absence of any defects would produce featureless TSOM images for these dense targets.

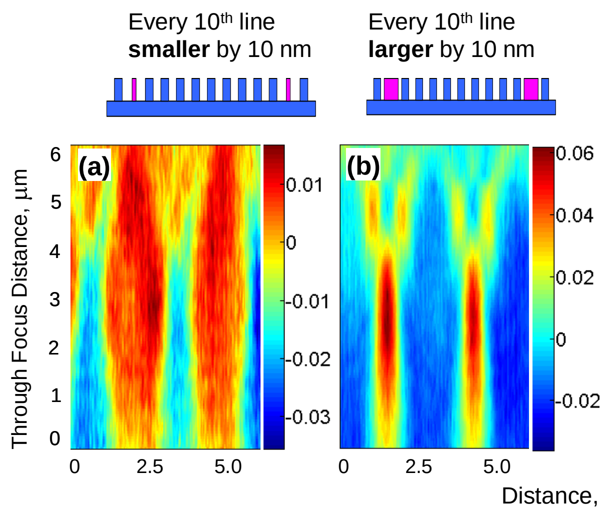

Figure 9. Experimental TSOM images for dense line gratings fabricated with intentional defects. λ = 546 nm, nominal line width = 100 nm, nominal pitch = 300 nm.

Defect analysis is also possible using differential TSOM images for defects in a 3D random structure as shown in Fig. 10.

7. SUMMARY

This paper presents a novel through-focus scanning optical microscopy (TSOM) method that potentially transforms a conventional optical microscope into a 3D metrology tool with nanometer measurement sensitivity, comparable to typical scatterometry, SEM, and AFM. It achieves this by using the additional information contained in a set of through-focus optical images rather than just a single image at the best focus position. The TSOM images are formed by stacking the through-focus optical image intensity profiles such that the x-axis represents the lateral distance on the target, the y-axis represents the through-focus position and the intensity of the image, and the z-axis represents the optical intensity. We have proposed two main applications of the TSOM images: (i) to determine a change in the relative dimensions and (ii) to determine the actual dimensions of a target. We presented several examples using optical simulations and experimental results.

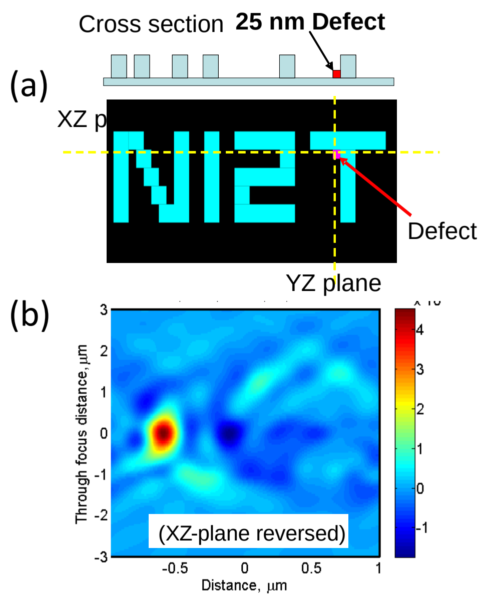

Figure 10. Determination of the presence of defects in a 3D random structure. (a) Simulated random 3D structure showing a 25 nm defect at the bottom of the features. (b) Simulated differential TSOM image at the x-z plane showing the presence of defect. (Feature linewidth = 100 nm, Line height = 100 nm, λ = 365 nm, Si features on Si Substrate.

Differential TSOM images appear to be distinct for different parametric changes. They enable us to identify which parameter is different between two targets. However, the differential TSOM images obtained for different magnitude changes of the same parameter appear qualitatively similar. In this case, the MSD value enables us to determine the magnitude of the difference in the dimension. The TSOM images enable us to determine the dimensions of an unknown target by the library matching method, if we are able to generate accurate simulations and verified by experimental measurement results for a fully characterized optical microscope. We expect the TSOM method to be applicable to a wide variety of targets with a variety of applications including, but not limited to, CD metrology, overlay metrology, defect analysis, inspection, and process control.

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