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TSOM Method for Nanoelectronics Dimensional Metrology

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Abstract. Through-focus scanning optical microscopy (TSOM) is a relatively new method that transforms conventional optical microscopes into truly three-dimensional metrology tools for nanoscale to microscale dimensional analysis. TSOM achieves this by acquiring and analyzing a set of optical images collected at various focus positions going through focus (from above-focus to under-focus). The measurement resolution is comparable to what is possible with typical light scatterometry, scanning electron microscopy (SEM) and atomic force microscopy (AFM). TSOM method is able to identify nanometer scale difference, type of the difference and magnitude of the difference between two nano/micro scale targets using a conventional optical microscope with visible wavelength illumination. Numerous industries could benefit from the TSOM method —such as the semiconductor industry, MEMS, NEMS, biotechnology, nanomanufacturing, data storage, and photonics. The method is relatively simple and inexpensive, has a high throughput, provides nanoscale sensitivity for 3D measurements and could enable significant savings and yield improvements in nanometrology and nanomanufacturing. Potential applications are demonstrated using experiments and simulations.

Keywords: Nanometrology, nanomanufacturing, dimensional metrology, defect analysis, process control, critical dimensions, optical microscope, through-focus, MEMS, NEMS, overlay, FinFet, TSV, photonics, nanodots, nanowires
PACS: 06.20.-f, 06.30.Bp, 07.60.-j, 42.87.-d

INTRODUCTION

The demand for 3D measurements at the nanoscale is very high since dimensional information at the nanoscale is required to enable progress in nanotechnology and nanoscience [1,2]. It is often assumed 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]. However, this limitation can be circumvented by (i) considering the image as a dataset (or signal) that represents the target and (ii) making use of highly developed optical models [4,5]. In our work, we also (iii) use a set of through-focus images instead of one "best focus" image. Based on this and on the observation of a distinct through-focus signature for different parametric variations, we introduced a new optical method for nanoscale dimensional analysis with nanometer sensitivity for three-dimensional, nano-sized targets using a conventional brightfield optical microscope [6-15]: 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.

Through-focus optical information was used before for several applications. Most frequently it has been in use to find the best-focus image position by evaluating contrast in the image. Confocal microscopy is another method that makes use of through-focus optical image information. In this method, out-of-focus optical image information present in the through-focus images is selectively discarded to form a 3D confocal image. In our prior work, it was found that the through-focus contrast in the image of isolated line gratings was sensitive to the line width (CD) [16, 17]. In these type of studies, the plot of contrast in the profile as a function of focus position was termed the "through-focus focus metric". CD analysis was performed by studying variations in the through-focus focus metric profile. As a visual aid for CD analysis using through-focus focus metric, through-focus optical cross sectional intensity profiles were stacked to form an image similar to the TSOM images used in the current study in Ref. [18]. Differential optical images at various focus positions were also used to study defects [19]. As will be seen in the following sections, the TSOM method uses differential TSOM images (i.e., differential cross sectional intensity images) as opposed to the type of differential images as used in this defect analysis work.
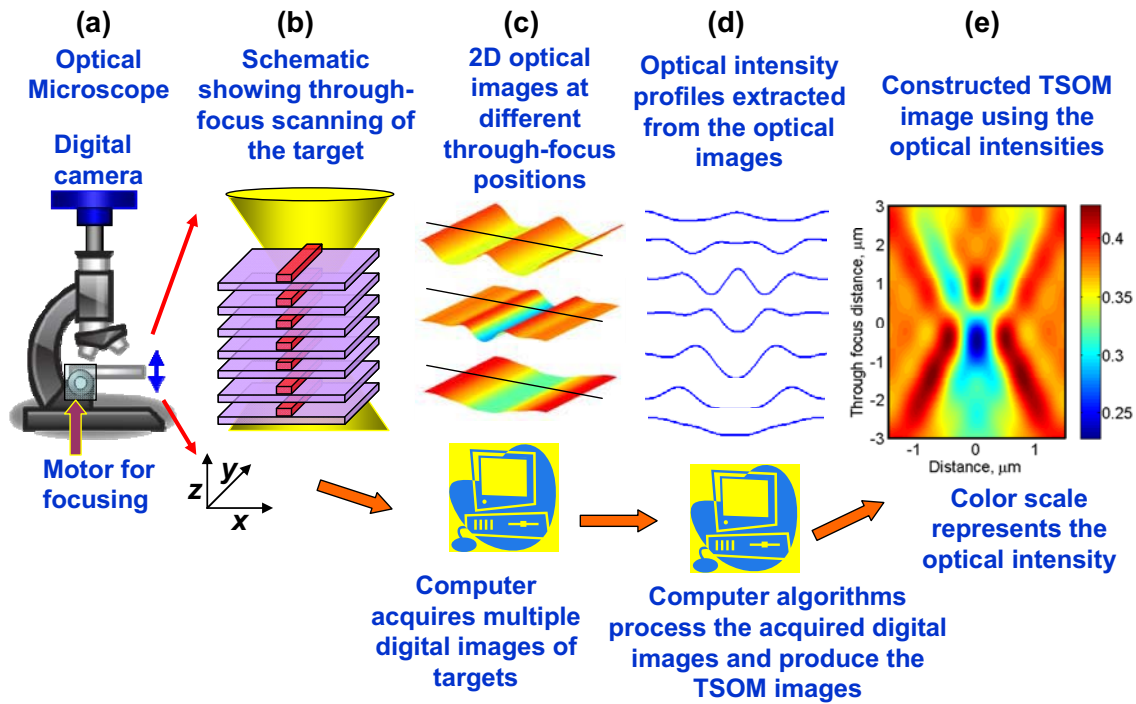
FIGURE 1. Method to construct TSOM images using a conventional optical microscope.

In the TSOM method, through-focus images are stacked as a function of focus position resulting in a 3D space containing optical information. From this 3D image space, cross sectional 2D TSOM images are extracted through the location of interest in any given orientation. In the TSOM method the entire 3D optical information is acquired and preserved for dimensional analysis. Neither the out-of-focus optical information is discarded, as in Confocal microscopy, nor is the intensity profile reduced to a number, as in the through-focus focus metric method.

METHOD TO CONSTRUCT A TSOM IMAGE

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 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
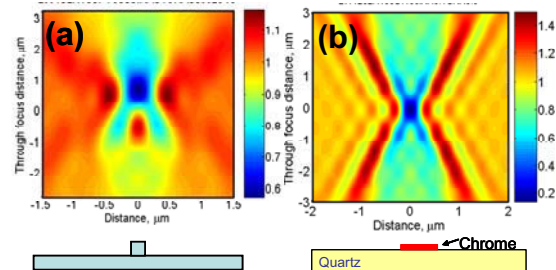

FIGURE 2. Simulated TSOM images for (a) an isolated Si line on a Si substrate (Linewidth = 40 nm, Line height = 100 nm, Illumination NA = 0.4, Collection NA = 0.8, and Illumination wavelength = 546 nm), (b) a chrome line on a quartz substrate photomask in transmission microscope mode (Linewidth = 120 nm, Line height = 100 nm, Illumination NA = 0.1, Collection NA = 0.8, Illumination wavelength = 365 nm).

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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.

CHARACTERISTICS OF TSOM IMAGES

TSOM Images Change with Target

The TSOM images vary substantially for different types of targets. This variation is illustrated in Fig. 2 for two types of targets, using optical modeling simulations. An isolated line, measured using a reflection-based optical microscope, is shown in Fig. 2(a). TSOM image for an isolated line on a photomask in transmission mode is shown in Fig. 2 (b).

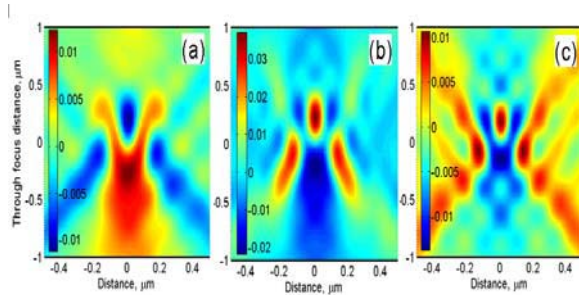### Differential TSOM Images Appear to be Distinct for Different Dimensional Changes

FIGURE 3. Simulated differential TSOM images obtained for (a) 2.0 nm difference in the line width (42 nm and 40 nm), (b) 2.0 nm difference in the line height (82 nm and 80 nm), and (c) 2.0° difference in the sidewall angle (90° and 88°).

A differential TSOM image is the difference between any two TSOM images. A small change in the dimension of a target produces a corresponding change in the TSOM image. For example, an isolated 2D line produces distinct differential TSOM images for line width, line height, and sidewall angle differences as shown in Figs. 3(a), 3(b), and 3(c), respectively. In this example the differential TSOM images facilitate identification of the dimensions that are different between these nanoscale targets. We have confirmed similar simulation and experimental based and results for several different types of targets.

Differential TSOM Images are Qualitatively Similar for Differences in the Same Dimension

For different magnitude changes of the same dimension, the differential TSOM images appear qualitatively similar. Figs 4(a) and (b) present differential TSOM images for 2.0 nm and 4.0 nm differences in linewidth, respectively, in an isolated line. These simulations yield qualitatively similar appearing differential TSOM images. We observed similar behavior using simulations under several conditions and also experimentally. This holds true as long as the difference in the dimensional magnitude is smaller than the dimension of the target.
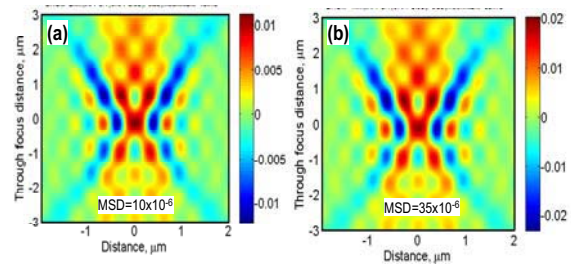

FIGURE 4. Simulated differential TSOM image obtained for (a) the linewidths of 102 nm and 100 nm (2.0 nm difference), and (b) the linewidths of 104 nm and 100 nm (4.0 nm difference). Isolated line, Line height = 100 nm, Illumination NA = 0.25, Collection NA = 0.95, Illumination wavelength = 546 nm, Si line on Si substrate.

Integrated Optical Intensity of a Differential TSOM Image Indicates the Magnitude of the Dimensional Difference

Integrated optical intensity of a differential TSOM image can be used to quantify the magnitude of the difference for a single parameter. The first method is the "mean square difference" (*MSD*), which is defined here as,

$$MSD_{AB} = \frac{1}{N} \sum_{i=1}^{N} (A_i - B_i)^2$$

Where A and B are the TSOM images from two targets, and n is the total number of pixels in the image. Differences of 2.0 nm and 4.0 nm in the linewidths of an isolated line (Fig. 4) produce *MSD* values of 10.0×10^{-6} and 35.0×10^{-6}, respectively. In this example the *MSD* values increased in direct relationship to the magnitude of the dimensional

differences. However, the amount of increase depends on the individual case.

The second method is "mean difference" (*MD*), which is defined as follows:

$$MD_{AB} = \frac{1}{N}\sum_{i=1}^{N}|A_i - B_i|$$

Both *MSD* and *MD* are used appropriately where needed.

TSOM Images Appear to be Unique

We tested the uniqueness of TSOM images for a small parameter space using simulations as explained in detail in Ref. 8. In this test we compared an "unknown" target with a library of simulations to identify the best match by evaluating the *MSD* values of their differential TSOM images. The minimum *MSD* value gives the best matched target. The dimensions of the "unknown" target matched with the best-matched-target identified under several repeat tests. The uniqueness and agreement is good for these simulated images, but must yet be verified experimentally.

TSOM Method is Robust to Optical Aberrations and Process Variation

For metrology applications, it is important to evaluate the robustness of the differential TSOM image method. All optical tools have a degree of optical aberration. Knowing the degree to which error is introduced in the measurement by an optical aberration is critical. We studied this using simulations for overlay measurement of an in-chip overlay target [10]. TSOM images were simulated under two conditions: without optical aberration and with third order spherical aberration (with Zernike coefficient of 0.01). The optical intensity simulated with the programmed spherical aberration was considerably different from the aberration-free profile. However, the evaluated *MSD* corresponding to overlay under the two conditions showed a very small variation of about 0.0004 nm for a 4 nm overlay. The small difference in the overlay value observed indicates this method is robust to optical aberration as long as the aberration remains constant between the compared TSOM images.

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 behavior 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. In the current work, two types of optical simulation programs were used [4,5], but rigorous experiment to simulation matching has not yet been generally demonstrated.

In practice, process variations that produce small changes in the dimensions of the metrology targets are common, including for overlay measurement targets [10]. For a 4 nm overlay, the selected target in Reference 11 produced an *MSD* value of 21.7×10^{-6}. A 5 nm change in the line height due to process variations produced an *MSD* value of 22.3×10^{-6}, which results in a 0.06 nm error in the overlay measurement. Similarly, simulated 4 nm difference in the linewidth produced an overlay error of 0.032 nm. This example shows a relatively small error in the overlay measurement due to process variations, and hence makes this method robust for the conditions studied in Reference 11.

SOME EXAMPLE APPLICATIONS

CD Analysis of Dense Line Gratings

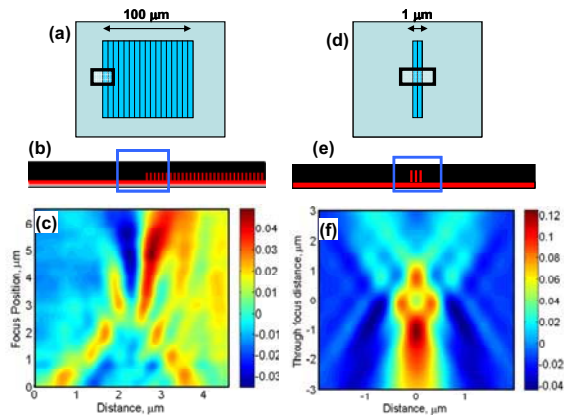Although dense, uniform line gratings with pitch below one-half the wavelength of the illumination

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. Experimental TSOM images for four dense gratings fabricated with intentional defects are shown in Fig 6. 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.
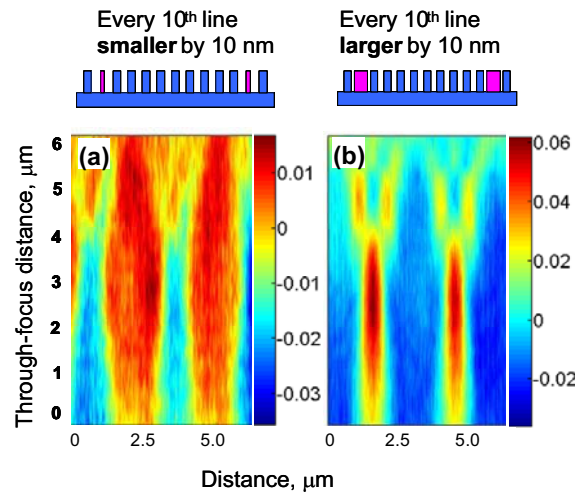
FIGURE 5. (a) and (b) Location of TSOM analysis for large dense gratings shown in two views. (c) Experimental differential TSOM image at the edge for 3.2 nm difference in the CD using λ = 546 nm (AFM measured CDs are 118.5 nm and 115.2 nm, Pitch = 300 nm and Line height = 230 nm, Illumination NA = 0.27, Collection NA = 0.8), (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)

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. 5(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. 5(c)). Consequently, we proposed a much smaller size line grating as shown in Fig. 5(d) for dimensional analysis. The simulated differential TSOM image for a nanometer difference in the linewidths shows a good signal (Fig. 5(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 6. Experimental TSOM images for dense line gratings fabricated with intentional defects. λ = 546 nm, nominal line width = 100 nm, nominal pitch = 300 nm, illumination NA = 0.36, imaging NA = 0.8.

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

Even though the nanodots are not exactly the same as nanoparticles, the measurement procedure remains the same. 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. 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
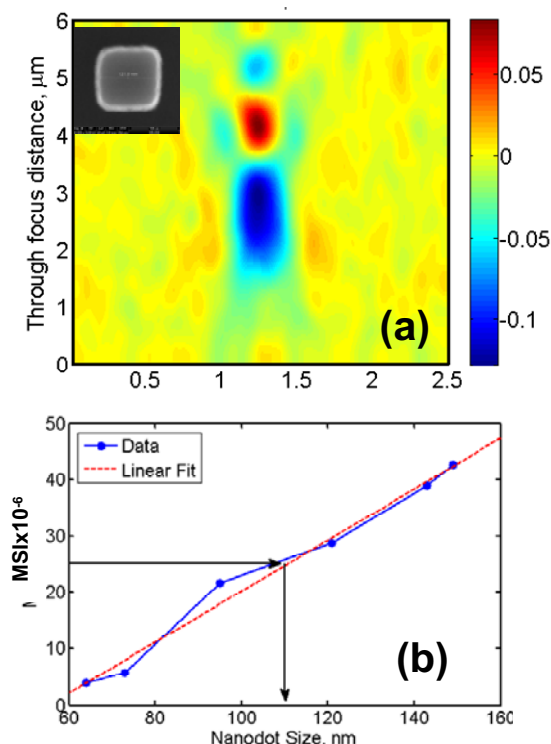
typical background intensity-normalized to zero

FIGURE 7. (a) SEM image of a 121 nm nanodot and its experimental intensity-normalized TSOM image (Wavelength = 546 nm, TE Polarization, Illumination NA = 0.27, Collection NA = 0.8, 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.

TSOM image for TE polarization is shown in Fig. 7(a). Using the 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). Standard deviation is less than 10%. 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.

SUMMARY

This paper introduces a relatively new and 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. 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. 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.

ACKNOWLEDGMENTS

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