Through-focus scanning-optical-microscope imaging method for nanoscale dimensional analysis

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Received May 30, 2008; accepted June 23, 2008;
posted July 3, 2008 (Doc. ID 96835); published August 27, 2008

We present a novel optical technique that produces nanometer dimensional measurement sensitivity using a conventional bright-field optical microscope, by analyzing through-focus scanning-optical-microscope images obtained at different focus positions. In principle, this technique can be used to identify which dimension is changing between two nanosized targets and to determine the dimension using a library-matching method. This methodology has potential utility for a wide range of target geometries and application areas, including nanometrology, nanomanufacturing, semiconductor process control, and biotechnology. © 2008 Optical Society of America

OCIS codes: 100.6640, 120.4630, 150.5495, 150.1835, 120.3940, 180.5810.

In the current world of nanotechnology, fast and reliable nanoscale feature measurements are extremely useful [1,2]. It is further advantageous if the tools used are simple and inexpensive, such as optics-based tools. However, it is often incorrectly believed that optical microscopes are not well suited for dimensional measurement of features that are smaller than half the wavelength of illumination (200 nm for visible region), owing to diffraction [3]. Diffraction-dominated images make meaningful analysis of the targets difficult. We have circumvented this limitation by (i) considering the image as a "signal" that represents the target [4], (ii) using a set of through-focus images instead of one "best-focus" image, and (iii) making use of current highly developed optical models. On the basis of this, and on the observation of distinct signatures for different parametric variations, we introduce a new method for nanoscale dimensional analysis with nanometer sensitivity for three-dimensional, nanosized targets using a conventional bright-field optical microscope.

In conventional optical microscopy, it is usually deemed necessary to acquire images at the "best-focus" position for a meaningful analysis, on the basis of 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 useful information regarding the target. This information may be obtained using an appropriate data-acquisition and analysis method. Here, we present the through-focus scanning-optical-microscope (TSOM) method, which is related to our previously published through-focus focus metric and through-focus image-map methods [5–7]. The TSOM method is applicable to 3D targets, enabling the method to be used for a range of target geometries.

In Fig. 1 we demonstrate the method to construct the TSOM images using a spherical gold particle (typically encountered in medical applications) 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 Fig. 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 on the target and the Z axis is the scanned 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 gold particle, for example) can be conveniently plotted as a 2D image resulting in a 2D-TSOM image as shown in Fig. 1(b), where the X, Y, and Z axes represent the spatial position on the target, the focus position, and the optical intensity, respectively. For 3D targets, appropriate 2D-TSOM images are selected for dimensional analysis.

At present we are exploring two applications of the TSOM images. They are to identify (i) which dimensional parameter is changing (e.g., a change in height or width) and to estimate (ii) the magnitude of these changes. 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

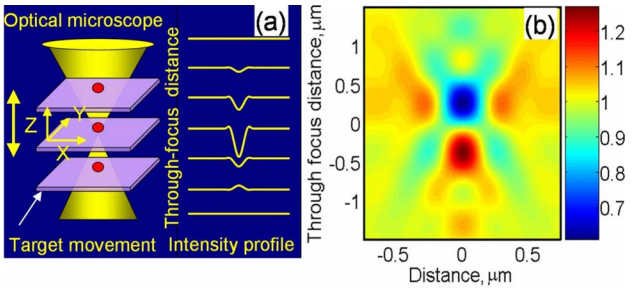

Fig. 1. (Color online) Method to construct TSOM images. (a) Schematic showing the image-acquisition process by through-focus scanning of a gold particle on a quartz substrate. A schematic of the cross-sectional image-intensity profiles passing through the center of the gold particle at the various scan positions is shown on the right side. (b) Simulated 2D TSOM image (X–Z plane) passing through the center of the 60 nm gold particle on the quartz substrate: $\lambda = 365$ nm, illumination NA = 0.3, imaging NA = 0.95.

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are not necessary for the first type of application, they greatly enhance the rigor of the method. 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. In the current work we have used three types of optical simulation programs [8–10].

Dimensional changes produce corresponding changes in the TSOM images. Nanoscale dimensional changes produce differences in the corresponding TSOM images that are not easy to identify. However, the differential TSOM images highlight the dimensional differences. For example, the size and the shape differences for 3D gold particles produce distinct differential TSOM images, as shown in Figs. 2(a) and 2(b), respectively. Similarly, a 2D line-array target (typically encountered in semiconductor industry applications) produces distinct differential TSOM images for linewidth, line height, and sidewall angle differences, as shown in Figs. 3(a)–3(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., linewidth) is identified, one approach to quantify the difference in this parameter is to evaluate the mean-square difference (MSD), which is defined as

$$\mathrm{MSD} = \frac{1}{n}\sum_{i=1}^{n}(\text{TSOM image 1} - \text{TSOM image 2})^2,$$

where n is the total number pixels in the image. For example, 1.0 and 2.0 nm differences in the linewidths of an isolated line (mean linewidth = 40 nm, line height = 100 nm, $\lambda = 546$ nm, NA = 0.8, illumination NA = 0.4, Si line on Si substrate) produce MSD values of 0.58×10^{-6} and 2.45×10^{-6}, respectively. Similarly, 1.0 and 2.0 nm differences in the line heights produce MSD values of 0.38×10^{-6} and 1.56×10^{-6}, respectively. In these two examples, MSD values increased

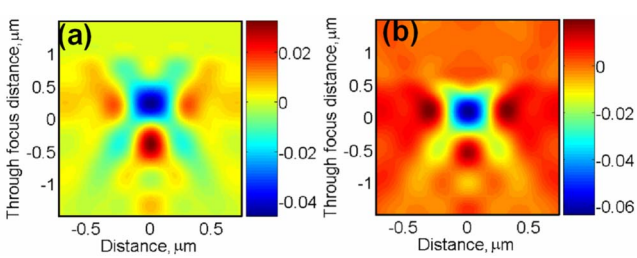

Fig. 2. (Color online) Simulated differential 2D-TSOM images in the X–Z plane passing through the center of the gold particle, obtained for (a) the size difference of 2.0 nm in diameter (62.0 nm and 60.0 nm) and (b) the shape difference as a result of 5.0 nm elongation in the height (Z-axis dimension) of the gold particle (60 nm × 60 nm × 65 nm and 60 nm × 60 nm × 60 nm) on the quartz substrate: $\lambda = 365$ nm, illumination NA = 0.3, imaging NA = 0.95.

in direct relationship to the magnitude of the dimensional differences. For consistent results and comparison, the total number of points in the images, the selected X-axis distance, and the focus range must be kept constant.

As a first demonstration of this technique, we compare the simulation data with experimental results for 2D line grating targets. Using an atomic force microscope (AFM) for reference metrology we measured a grating target bottom linewidth, line height, sidewall angle, and pitch as 140 nm, 230 nm, 87°, and 601 nm, respectively. Using these as input parameters to the model, we then obtained the simulated TSOM images. The experimentally constructed TSOM images were independently normalized to a mean intensity and then aligned to obtain the differential TSOM images. Figures 4(a) and 4(b) are simulation results and experimental TSOM images, respectively, for the selected grating target. Figures 4(c) and 4(d) are the simulated and the experimental differential TSOM images, respectively, for a 3.0 nm difference in the linewidth. Agreement between the experiment and the simulation is satisfactory in this initial comparison.

We assume the TSOM images to be unique for a given target under a given experimental condition. We then compare the experimental TSOM images with that of a library of simulated TSOM images. We report the dimensions of the best match between the experimental images and the simulated images. We applied this approach to determine experimentally the linewidth of the grating target shown in Fig. 4(a). The results are preliminary in nature. The AFM measured reference linewidth was 140 ± 0.5 nm 1 σ standard uncertainty. However, we assumed the linewidth to be unknown for library-matching purposes. Using the reference measurement dimensions we simulated a library of TSOM images using an optical simulation model [10], by keeping all the parameters constant, except the linewidth. We varied the linewidth with a step increment of 0.5 nm. The comparison gave the best linewidth match as 126 nm using the optical model. The discrepancy between the AFM and the TSOM image optical technique requires further study and is beyond the scope of the current paper. However, greater optical measurement accuracy can be achieved with improved optical models and experimental data facilitating improved simulation to experiment matching [11].

The proposed TSOM image method, as presented above, facilitates evaluation of size and shape with nanoscale dimensional sensitivity, using a conventional optical microscope. This method has a range of applications in 2D and 3D target geometries and materials. In addition, it eliminates the requirement to precisely set the target at the best focus position. In the current world of nanotechnology, this method has application to a wide range of multidisciplinary areas, and target geometries, including particles, lines, and 3D geometries.

The primary limitations of this method are the requirement for accurate simulations and satisfactory experiment-to-simulation agreement. For the TSOM

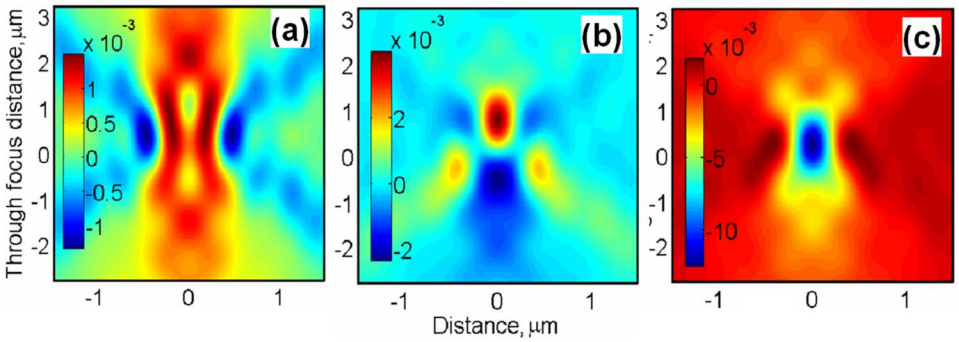

Fig. 3. (Color online) Simulated differential TSOM images obtained for 2D isolated line targets for (a) 1.0 nm difference in the linewidth (41 nm and 40 nm), (b) 1.0 nm difference in the line height (101 nm and 100 nm), and (c) 1.0° difference in the sidewall angle (90° and 89°). Si line on Si substrate. $\lambda = 546$ nm, illumination NA=0.4, imaging NA=0.8.

method to achieve its full qualitative potential, the microscope needs to be well characterized with these optical characteristics input to the model (see [12]) as well as more-complex sample descriptors beyond the trapezoidal geometries used here.

In summary, we have presented a novel optical technique to construct TSOM images, using a conventional bright-field optical microscope. The TSOM images exhibit nanoscale dimensional sensitivity and parametric signature difference. The technique facilitates identification of the dimension that is different between two nanosized targets and the ability to derive the actual target dimensions using a library-matching method.

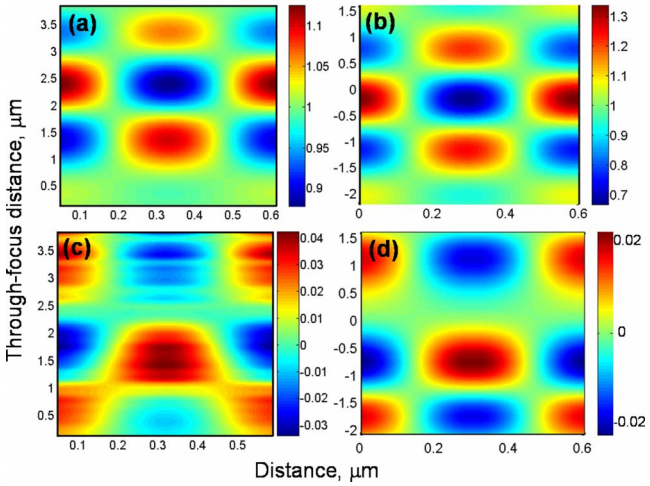

Fig. 4. (Color online) (a) Experimental TSOM image for the 2D line grating target with 152 nm linewidth. (b) Simulated TSOM image obtained for the same target shown in (a). (c) The experimental differential TSOM image for 3.0 nm difference in the 2D grating target linewidth (149 nm and 146 nm). (d) The simulated differential TSOM image for the same 3.0 nm difference in the linewidth as shown in (c). Si line on Si substrate. $\lambda = 546$ nm; line height=230 nm; pitch=601 nm; illumination NA=0.36, imaging NA=0.8.

The authors thank the NIST-OMP and the NIST-Scatterfield Competence project for the financial support. Sematech and Ron Dixson are acknowledged for AFM measurement support. We thank Jim Potzick, Mike Stocker, and Bryan Barnes for the helpful discussions.

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