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Through Focus Optical Imaging Technique To Analyze Variations In Nano-Scale Indents

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There is a great demand for process control of feature dimensions below the resolution limit of visible wavelength microscopy. This research focuses on adopting a novel optical technique called through-focus scanning optical microscopy (TSOM) that shows nanoscale measurement sensitivity using conventional optical microscopes to analyze nano indents. Here through-focus images are acquired at different focus positions. The set of through-focus images are used to build a TSOM intensity image whose signature reflects the target pattern. This technique is used to identify relative nanoscale changes in dimension between two targets by finding the change in the signature of the TSOM image. This method finds application in critical dimension, overlay, nano-particles analysis, defect analysis, inspection and process control; Semiconductor industry, MEMS, NEMS, bio-technology, nano-manufacturing and nano-metrology.

1.0 Introduction

Conventional optical microscope is generally considered to be suitable for measurements greater than half the wavelength of visible light. Reducing the wavelength can improve the resolution. However the wavelength has to be selected based on the material system. Also increasing the numerical aperture increases the resolution. This is achieved using immersion optics.

In the recent years, optical based scatterometry has emerged as a validated method for performing CD metrology by the semiconductor industry [1]. The interaction of light striking the target produces phase and intensity information in the signal reflected off the target. This diffracted light is sensitive to the incident angle, wavelength and change in grating profile. Hence the profile information can be obtained by comparing the data obtained from the diffracted light with the theoretical model. But this method is applicable to mainly periodic structures, like a grating. Also it is hard to apply to 3D structures like nano-scale indents with many variables.

2.0 Concept of Through-Focus Imaging

Generally machine vision based measurement systems work with focused image with good contrast and well defined edges to extract the feature dimensions precisely. Conversely a set of de-focussed image around the focus position also carry information relating to the target geometry. Complex optical response has been reported when a structured target (particularly when structure repeats itself several times) is imaged when it is moved through focus [2]. Through-focus scanning optical microscopy (TSOM) is a measurement and analysis method that extends conventional optical microscopes resolution to nanometer scale and it has wide scope of application. The TSOM method preserves all the optical information by capturing in and around the focus position the scattered field reflected off the target, in the form of an image, which contain the target features and builds an overall intensity map of the target. This 3D intensity data represents an optical signature for that feature. This paper focuses on the above concept and shows the dimensional sensitivity to nanoscale feature variation using nano indents with varying depth on a silicon wafer

3.0 Experimental Setup

The developed system consists of a conventional bright field microscope with halogen light source, a digital camera, piezo controlled focus stage for target movement. Set of through focus images are captured as the target is moved along the focus position at every equal interval of 0.1 µ.

Experiment was conducted on nano indents to evaluate the sensitivity of the proposed method for change in dimension in nano scale. Nano indents were created on silicon wafer using a nano indenter with varying depths as shown in Fig.1 All the experiments were conducted with wavelength λ = 546 nm, numerical aperture at 0.9 and illumination numerical aperture at its minimum [3]. The image analysis software was developed in Labview.

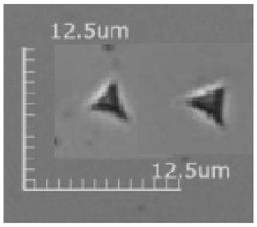


Fig.1 Nano indent of depth 600nm (left), 630 (right) with Berkovich (3-sided pyramid) tip on a Si wafer

4.0 Sensitivity of Focus Metric to Focus Position

As the target is stepped through the focus, different slices of images are acquired. The intensity profiles acquired at each focus position varies significantly and carries a fixed relation to the target geometry. Focus metric is a measure of intensity within the image like contrast, total intensity and standard deviation [4]. The focus metric algorithm calculates a focus metric value for each "slice" of the image for every focus position. Every image intensity is reduced to a numerical value called focus metric. The developed algorithm computes various focus metric values. However standard deviation is mainly used as focus metric for reporting the results in this paper

The standard deviation (S) is defined as the standard deviation of the image pixel values from the mean of all included pixels. It is computed by the following equation 1.

$$S = \sqrt{\frac{\sum |I_{XY} - \bar{I}|^2}{n-1}} \qquad \text{——} \quad 1$$

Where

Ixy = pixel intensity at XY
I = mean intensity
N = number of pixels within the region of interest (ROI).

Focus metric algorithm is applied to a selected ROI. Fig. 2 shows the variation of focus metric value with respect to focus positions for nano indent with varying depth. It is clear from the plot that at best focus the focus metric value reaches the peak. Hence the focus metric can be used as a measure to get the best focus position during auto focus. Also it is found that the through focus response shows a strong sensitivity to the depth of the nano indent.

The Fig. 2 reveals the sensitivity to 10nm variation in the depth of the indent. The small peak that appears in the negative focus offset is expected to be due to proximity effect from the pile-up of the indent. The light that gets scattered from the pile-up of the nano indent interferes and creates constructive / destructive interference of the scattered field. The same effect is not seen in the positive focus offset as the interference due to the nano pile-up is less pronounced there.

5.0 Through-Focus Scanning Optical Microscopy

Optical images are acquired as the target is scanned through the focus of the microscope at every 100 nm (along the *Z* axis from -3μ to +3 μ). The intensity profile within a ROI is extracted from each image at different focus position.

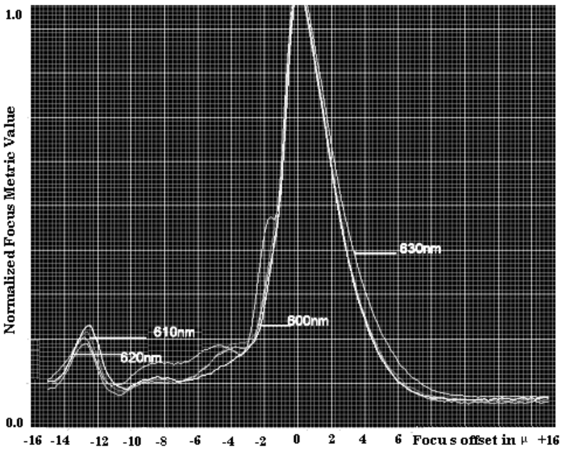


Fig 2 Through Focus Response for 600–630nm depth.

These intensity profiles are stacked at the respective focus position Z to form a 3 dimensional intensity map where x, y represent the spatial position of the target in x and y direction with the value of the pixel intensity at that position and z represents the corresponding focus position. From this 3D optical data, 2D X-Z TSOM data is extracted at appropriate y position along a line as shown in Fig.3. [7]

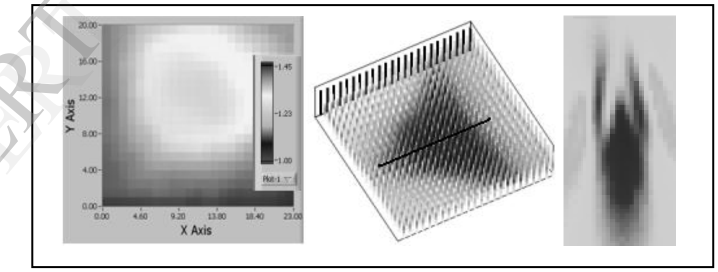


Fig 3 Optical image (left), 3D intensity map (middle), 2D TSOM image (right) at the center of the nano indent.

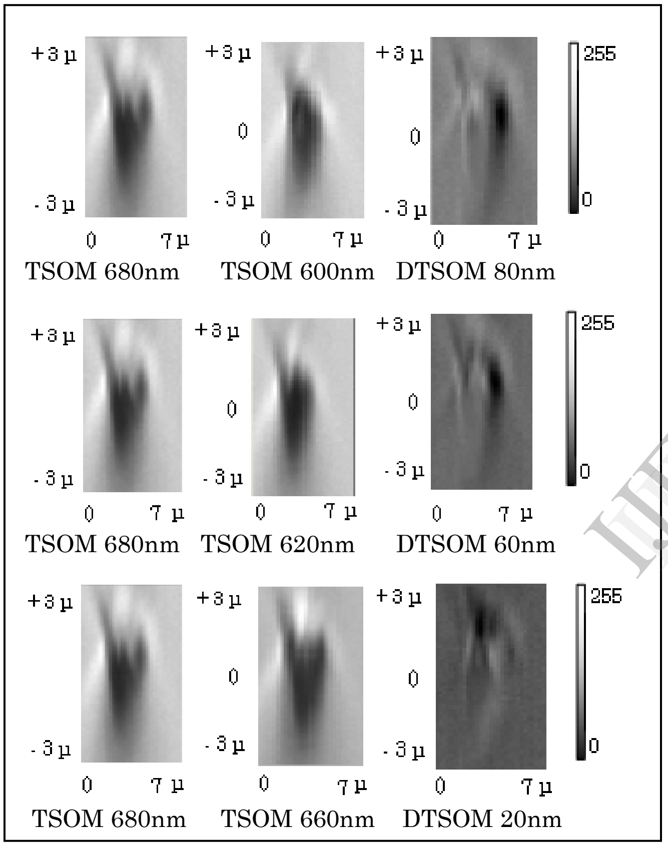
The signature of this 2D intensity map depends on the target feature and the optical parameters like wavelength, illumination numerical aperture [5]. By keeping all the optical parameters constant the variation in the signature is directly related to variation in the target feature.

6.0 Analysis of Taget Variation Through DTSOM

Any change in dimension will results in corresponding change in TSOM image signature [5]. To identify the nanometer scale variation, differential TSOM image is computed by first correlating the two TSOM image and then finding the difference between the two TSOM images. Fig.4 shows set of two TSOM images and the corresponding DTSOM image for varying indent depths. This differential TSOM image truly represents the dimensional difference between the two targets at that position. The differential image is quantified by finding the mean difference between the two corresponding TSOM images [5].

Sl. No.	Indent Depth TSOM1-TSOM2 In nm	Difference in depth In nm	Mean Diff. (MD) from DTSOM
1	700-600	100	24.59
2	680-600	80	18.04
3	680-620	60	13.93
4	650-610	40	10.07
5	680-660	20	7.17

Table 1 Mean Difference for varying indent depth difference



TSOM 680nm TSOM 600nm DTSOM 80nm

TSOM 680nm TSOM 620nm DTSOM 60nm

TSOM 680nm TSOM 660nm DTSOM 20nm

Fig.4 TSOM and DTSOM image for varying nano indent depths

It is given by equation 2

$$MD = \frac{1}{n}\sum_{i=0}^{n}(A_i - B_i) \qquad \text{—— } 2$$

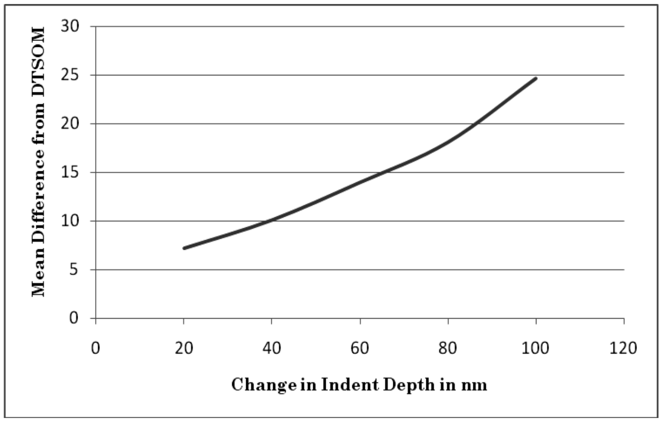


Fig.5 Change in Nano indent depth and the corresponding Mean Difference "MD" from DTSOM

The mean difference computed for every 20nm change in indent depth is shown in Table 1 and the variation is found to be almost linear as shown in Fig.5.

7.0 Conclusion

It is observed through experimentation that the '*focus metric*' computed from the intensity image of the targets are sensitive to the dimension of the target. Its response to nano-scale dimensional variation in the nano indents are evaluated and reported in this paper. Also by an alternative method of generating complete 3D intensity map known as TSOM, the nano level sensitivity is demonstrated. Further the results of these experiments have to be compared with reference measurements using SEM, AFM to validate the results. This method could be extended for finding nano-scale defects in semiconductor and MEMS industry.

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