

Nondestructive and Economical Dimensional Metrology of Deep Structures

Ravi Kiran Attota^{1,4}, Hyeonggon Kang², and Benjamin Bunday³

¹ *Microsystems and Nanotechnology Division, NIST, Gaithersburg, MD 20899, USA*

² *Coppin State University, Baltimore, MD 21216, USA*

³ *No affiliation, USA*

⁴ *Corresponding author: Ravikiran.attota@nist.gov*

INTRODUCTION

Low-cost, high-throughput and nondestructive metrology of truly three-dimensional (3-D) targets for process control/monitoring is a critically needed enabling technology for high-volume manufacturing (HVM) of nano/micro technologies in multiple areas^{1,2}. A survey of the typically used metrology tools indicates the lack of a tool that truly satisfies the HVM metrology needs of 3-D targets, such as high aspect ratio (HAR) targets and through silicon vias (TSVs). TSVs are a key component to enable 3-D stacked integrated circuits (3DS-IC), which themselves are key to extended scaling of integrated circuits and enabling heterogeneous integration¹. Hence it is crucial to find suitable metrology solutions for truly 3-D targets such as HAR targets.

To be used in high volume manufacturing, a metrology tool must – in addition to providing statistically significant results² – be fast (high-throughput), low-cost, inline capable, automated, robust, easy to use, non-contact and non-destructive. The requirements for satisfactory measurement sensitivity and resolution have been identified in the International Technology Roadmap for Semiconductors (ITRS) and International Roadmap for Devices and Systems (IRDS) 2017 Edition: Metrology. All currently available tools have certain advantages and disadvantages. It is difficult to find a metrology tool that satisfies all the above-mentioned requirements, especially for metrology of 3-D/HAR targets. Here we show that through-focus scanning optical microscopy (TSOM)^{3,4} could supplement currently available metrology tools in filling this gap for 3-D shape metrology. However, there is still room to improve optical tools⁵.

THROUGH-FOCUS SCANNING OPTICAL MICROSCOPY (TSOM)

TSOM is a method that collects and preserves the entire through-focus optical intensity information in 3-D space using a conventional optical microscope. Developments in image acquisition techniques have significantly reduced the acquisition time for a set of through focus images to be as fast as a single conventional microscope image, making TSOM suitable for HVM⁶. A vertical cross-section extracted from this 3D data results in a TSOM image. D-TSOM images are generated by taking a pixel-by-pixel difference between two TSOM images obtained using two different targets. D-TSOM images expose small (down to sub-nanometer) differences hidden in nominally identical targets. The color patterns of D-TSOM images are usually distinct for different types of parameter changes and serve as a "fingerprint" for different types of parameter variations, but remain qualitatively similar for different magnitude changes in the same parameter. However, the magnitude of the optical content of D-TSOM images is proportional to the magnitude of the dimensional differences. The Optical Intensity Range (OIR, the difference between the maximum and the minimum optical intensity, multiplied by 100), provides a quantitative estimate of the difference between two images. The utility of D-TSOM is that the color pattern of the D-TSOM image is an indicator of the difference in 3D shape, while the magnitude of the OIR scales with the dimensional difference between the two targets.

DEMONSTRATION OF TSOM FOR PROCESS MONITORING

Application for High Aspect Ratio (HAR) Trenches

As a demonstration of the application of TSOM to HAR structures, trench targets in SiO₂ layer on a 300 mm Si substrate with nominally 100 nm CD and 1100 nm depth were studied ⁷. A mosaic of D-TSOM images obtained (with central die as a reference target) for the entire wafer is presented in Fig. 1(a). From this, four major types of D-TSOM image patterns (Fig. 1(b)) can be identified with their corresponding FIB cross-sectional profile differences as shown in Fig. 1(c). Considering the information available in Figs. 1(b) and (c) as a library, a simple process monitoring procedure can be proposed as shown in Fig. 2, based on the following selected rules: If the OIR of the D-TSOM image is more than 12, reject the target, as the dimensional differences are more than the tolerable limits. On the lower side, if the OIR of the D-TSOM image is less than 7, accept the target as the dimensional differences are within the acceptable level. If the OIR value is in between 7 and 12, accept the production target if the profiles are symmetric (T1 and T3) and reject if the profiles are asymmetric (T2 and T4).

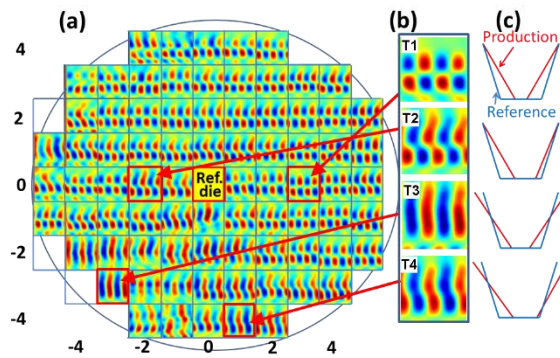


FIGURE 1. (a) A mosaic of the D-TSOM images obtained by subtracting the TSOM image of the central reference target from the TSOM images of the targets in the other dies (with color scale bar set to automatic). (b) Four major types (T1, T2, T3 and T4) of D-TSOM image color patterns are identified. (c) Schematic cross-sectional profile differences corresponding to (b) obtained from FIB cross-sectional analysis. Nominal pitch = 1,000 nm. Illumination wavelength = 520 nm, numerical apertures (NA) = 0.75, illumination NA (INA) = 0.25.

Row no. (Die location)	Production target (unknown Profile)	Library				Possible D-TSOM image	Inferred shape difference type	OIR	Accept(✓) or Reject(✗) status
		T1	T2	T3	T4				
1 (-2,2)		0.96	0.69	0.66	0.61			8.4	✓
2 (1,-4)		0.64	0.79	0.78	1.00			8.0	✗
3 (-2,1)		0.84	0.85	0.59	0.54			6.3	✓
4 (4,2)		0.90	0.77	0.65	0.52			13.6	✗

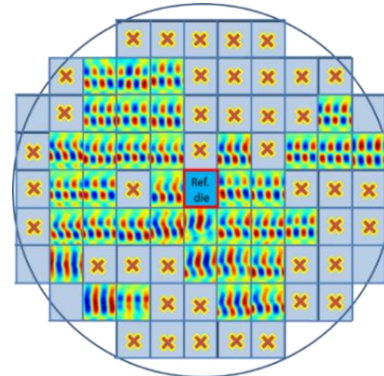


FIGURE 2. (Left) Proposed TSOM-based automated 3-D-shape process control method. The selected test production targets in column 1 are considered to have unknown 3-D-shape profile (column 2). Comparing the correlation coefficients of the D-TSOM images of the test targets with the library provides the best match (green boxes) from which the possible 3-D shape difference type can be inferred (column 8). Based on the type of 3-D shape difference and the magnitude of the dimensional difference (OIR), the process control decision of accept/reject status can be made. (Right) Dies marked by an X are rejected after applying the automated TSOM-based process control criteria. The rest of the dies are deemed acceptable.

Application for Through Silicon Vias (TSVs)

The premise of the TSOM approach is that the use of conventional optical microscopy components, as opposed to infrared reflectometry, may provide a cost-effective method for TSV metrology, especially for process control. In the example we present here, dimensional differences between three TSVs from three dies are evaluated by comparing the TSVs, pairwise, using D-TSOM images. The comparison can be evaluated numerically (OIR) and can also be displayed graphically. Figure 3 shows experimental D-TSOM data for TSVs with a nominal diameter and depth of 1 μm and 20 μm , respectively. The bar graphics above the image plots indicate which two TSVs are being compared in each plot; the values of the OIR indicate the overall magnitude of the dimensional differences between the TSVs being compared; and the colors indicate the spatial distribution of dimensional differences between each pair of TSVs. The similarity of the two differential images on the right indicates a similar pattern of dimensional differences between the pairs of TSVs compared. The OIR value of the image at the right is the highest, indicating the largest magnitude dimensional difference, while the lowest OIR value of the left image indicates the smallest difference. If a library of differential TSOM images corresponding to known dimensional differences were available, the actual dimensional differences corresponding to these image patterns could be evaluated.

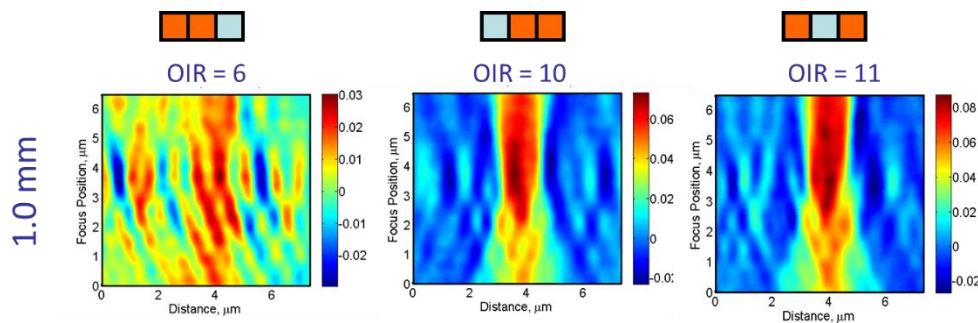


FIGURE 3. D-TSOM images representing the pairwise differences between TSOM images of three TSVs in three different dies.

Here we have briefly presented potential applications of TSOM for dimensional metrology of deep structures such as HAR targets and TSVs using a reference library. TSOM is a nondestructive, low-cost, and high-throughput 3-D shape process monitoring method that uses a conventional optical microscope. TSOM could fill a gap by satisfying the HVM metrology needs of not only HAR targets and TSVs, but also other types of truly 3-D targets for which 3-D shape process control/monitoring is needed, complementing other widely used metrology tools.

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KEYWORDS

TSOM, nondestructive process control, three-dimensional metrology, through-focus scanning optical microscopy, nanometrology, packaging metrology, high-throughput semiconductor metrology