Volumetric Inspection for Optical Wafer Inspection

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Abstract – As design node shrinks, optical inspection becomes more and more challenging. Volumetric (VM) inspection is a new method which leverages through focus information to enhance defect detection sensitivity. In volumetric inspection, a 3-D data structure is constructed by stacking through focus images together. The added information allows the creation of two new inspection concepts, solid angle rejection and focus fusion. Together, they provide differentiation between weak signal DOI and high intensity nuisance. This leads to higher defect detection sensitivity for pattern wafer inspection. In this paper, we describe the volumetric inspection methodology and the preliminary inspection results obtained from the VM prototype.

I. Introduction

Wafer inspection today relies only on intensity return of the wafer, and the intensity is generated from a fixed focus plane. It is known in the field of microscopy that phase interference can be effective to increase defect and nuisance differentiation. Theoretically, acquiring wafer images at different focus heights results in adding phase perturbation to the object being imaged. Hence, performing defect detection by moving the samples at different focus planes ultimately results in phase interference. Another known challenge with today's inspection strategy is that not all DOIs prefer the same focus plane. Limiting inspection at a fixed focus plane results in compromising defect detection performance. **Fig. 1** shows example of signal to noise ratio (SNR) from two different DOIs each prefers different optimal focus plane. Volumetric inspection, acquiring through focus data, mitigates this performance gap.

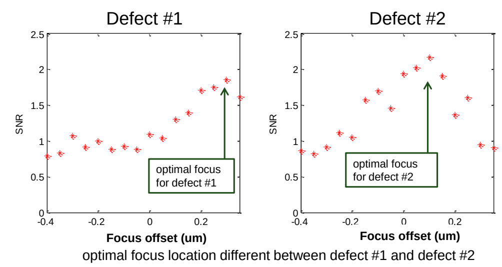

Fig. 1. Examples showing optimal focus setting for can be different between different DOIs.

II. Volumetric Inspection Methodology

A. Theoretical Treatment

Using the theory of Fourier optics and phase perturbation approximation, image intensity at (x, y) at a known focus plane, z, can be expressed as,

$$I((x,y,z) = A(x,y)z^2 + B(x,y)z + C(x,y) \quad \textbf{(Eq. 1)}$$

for small focus shift. The parameters [A(x, y), B(x, y) and C(x, y)] have physical meaning describing the behaviors of objects being imaged. The parameter A(x, y) represents rate of change in intensity with focus perturbation, B(x, y) represents the rate of change in phase with focus perturbation, and C(x, y) represents the intensity of object without any focus perturbation. The coefficients A(x, y), B(x, y), and C(x, y), are addressed as VM coefficients. The coefficients are determined at every pixel location (x, y) from the 3-D stacked VM data structure. Together, they map out the field information of wafer at all location. The VM parameters are the basis for building solid rejection detection algorithm.

B. Solid Angle Rejection Algorithm

From the stacked 3-D VM data, the coefficients A(x, y), B(x, y), and C(x, y) are computed pixel by pixel. **Fig. 2** shows the schematic of how the computation is done. The calculation are done at both target location (where DOI is present) and reference location. The difference of the coefficients, denoted as Adif(x, y), Bdif(x, y), and Cdif(x, y), between the target and reference location are computed. A three dimensional data representation is created based on Adif(x, y), Bdif(x, y), and Cdif(x, y). Each data point on the wafer is represented as a point on the 3 dimensional space spanned by Adif(x, y), Bdif(x, y), and Cdif(x, y) to form a 3D scatter plot (as illustrated in **fig. 3**). Each point in the scatter plot has an angular representation (θ, φ) and projected to a unit sphere. **Fig. 4** shows an example of such projection. Since DOI and nuisance has different behavior, the DOI is expected to locate at a specific solid angle in the unit sphere whereas nuisance, such as noise, is expected to be uniformly distributed across the unit sphere. The solid angle serves as discriminator. This leads to solid angle rejection algorithm. This can be seen in **fig. 4**. In it, the solid angle extended by DOI (shown in green) is different from the solid angle extended by nuisance (shown in red). Limiting the inspection to the fixed solid angle (shown in blue) near space spanned by DOI significantly increase the visibility of DOI resulting sensitivity improvement.

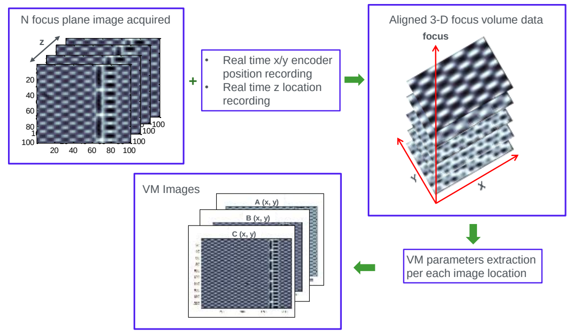

Fig. 2. Schematic showing how VM parameters are computed from stacked 3-D VM data structure.

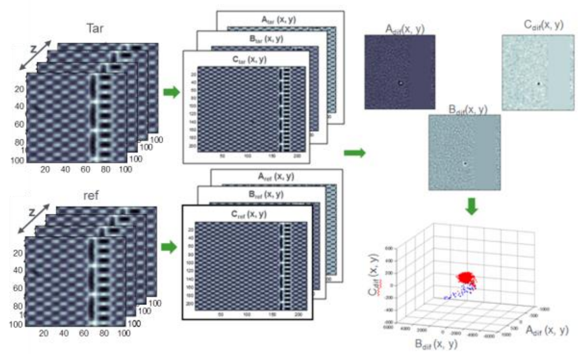

Fig. 3. Flow diagram showing how the 3-D scatter plot is generated from Adif(x, y), Bdif(x, y), and Cdif(x, y). In this example, the blue dots represents the defect of interest and the red dots represent background noise (or nuisance). It is clear from the 3D scatter plot that defects of interest can be well separated out from the 3D scatter plot.

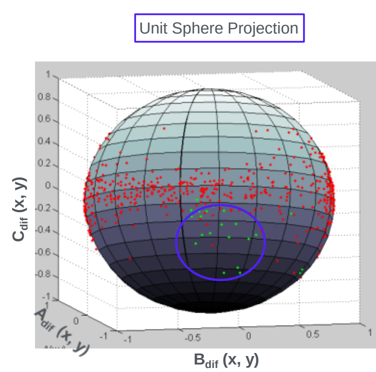

Fig. 4. Example of unit sphere projection. The DOI location is represented by green dots and the background noise / nuisance pixels are represented by the red dots. Detection algorithm filtered out the point outside of the desirable solid angle (shown in blue) enhances the visibility of the defect.

C. Focus Fusion Detection

A focus fused image is constructed by combining images across different image plane. The benefit of focus fusion is to further differentiate DOI and nuisance. **Fig. 5** shows the original difference image and focus fused difference image. Location of DOI is highlighted. The increase of visibility of DOI is clearly demonstrated.

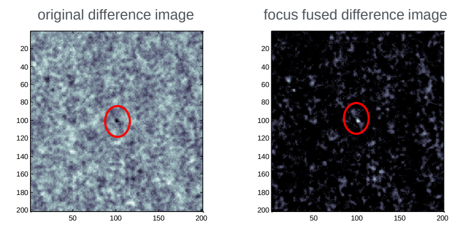

Fig. 5. Difference image comparison with and without focus fusion.

III. Initial Wafer Results from Volumetric Prototype

A prototype based on BBP tool was developed for the initial assessment of VM inspection. An image acquisition script was developed to go acquire images at different focus offsets with the (x, y, z) encoder positions recorded. The saved images were then aligned to create the stacked 3-D VM data. VM parameters and focus fusion images were generated from the stacked data. Solid angle rejection and focus fusion detection methods are applied to data collected. **Fig. 6** shows an example of (a) original difference image without VM inspection method, (b) difference image with focus fusion applied, and (3) difference image with focus fusion and solid angle rejection applied. The defect is shown in red circle. It is clear from the example that the visibility of the defect is highly enhance with VM inspection.

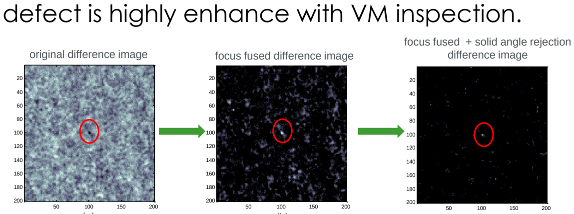

Fig. 6. Visibility of DOI (circled in red) comparison. (a) Original difference image from fixed focus plane acquisition, (b) VM inspection with focus fusion, and (c) VM inspection with focus fusion and solid angle rejection. It is clear that visibility of defect is highly enhance with focus fusion + solid angle methods.

1xnm design rule wafer was used for evaluating the performance of the new inspection method. **Fig. 7** shows the inspection flow using volumetric inspection. The inspection results are shown in **fig. 8**. Two new killer defect types, small particles (30-40nm) and thin residues, were detected with volumetric inspection, demonstrating the sensitivity enhancement with volumetric inspection.

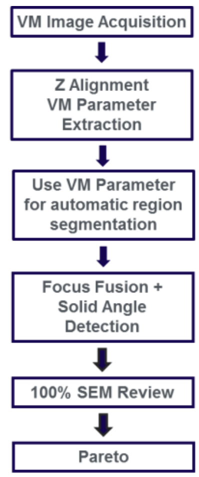

Fig. 7. Flow of VM inspection steps applied to the 1x nm design wafer target.

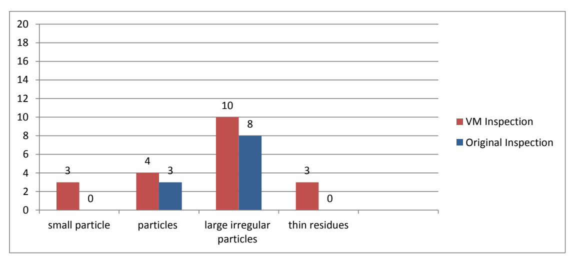

Fig. 8. Pareto Chart to Compare Sensitivities across Different Inspections.

IV. Conclusion

VM inspection is an advance detection method to further enhance optical inspection capability. We have demonstrated the value of VM with the prototype developed. The preliminary data from 1xnm design rule wafer showed that the sensitivity enhancement of VM is capable of uncovering two new yield killer defect types.