# Illuminating EUVL Mask Defect Printability

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## 1. ABSTRACT

For the next few years, the EUV Lithography (EUVL) community must learn to find mask defects using non-actinic inspection wavelengths. The non-actinic light cannot always determine the exact nature of the defect; whether it is a particle, pattern, or defect in the multilayer. It also cannot predict which defects will induce phase errors and which will induce amplitude errors on wafer. Correlating the signature of the defect as seen by a non-actinic inspection tool and on wafer resist image will inject essential knowledge into the non-actinic defect classification. This paper will explore the correlation between EUVL mask defect signatures detected (and *not* detected) at both 193 nm and e-beam inspection wavelengths and wafer-printable defects. The defects of interest will be characterized at mask level using atomic force microscopy (AFM) and critical dimension scanning microscopy (CDSEM). Simulations will be deployed to explain the signatures illuminated by both EUVL and 193nm exposures. This work addresses the gap between inspection sensitivity at non-actinic wavelengths and EUVL mask defect printability, and provide generalized understanding of how the two views differ.

Keywords: EUVL, mask inspection, non-actinic, wafer-printable defects

## 2. INTRODUCTION

Over the next few years, mask makers face the daunting challenge of delivering high-quality masks in a timely manner without the advantages of actinic inspection or mask defect analysis equipment. For optical masks, traditional 193 nm wavelength mask inspection equipment uses both transmitted and reflected light during inspection. Due to the opacity of the multilayered EUV substrate, only reflected light is available for the inspection of EUV masks. The lack of transmitted light during defect review often makes it difficult to discern the actual nature of the EUV defect, be it foreign material, absorber defect, or defect in the multilayer.

An additional challenge is that the 193nm inspection result may not be indicative of impact of the defect under 13.5nm EUVL illumination.

Non-actinic 193 nm inspection penetrates only to top two or three layers of the MoSi stack that make up the EUV substrate[1]. Actinic EUV mask inspection will not be available for at least three years[2]. Limited penetration into the multilayer combined with high defect densities inherent in the EUV substrate will make it an essential requirement to correlate the signature of the defects seen by the non-actinic inspection tool to their subsequent wafer image[3]. Tailoring what the non-actinic inspection tool sees, and does *not* see will be required to achieve reasonable yield on wafer, especially since the mask industry currently lacks EUV AIMS capability to assist in evaluating potentially printable defects[4, 5, 6].

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The focus of this paper will be twofold. First we will explore the various ways mask defects are transferred to the wafer and second, explore non-actinic inspection sensitivity as it pertains to mask defect printability on wafer, followed by a gap analysis between non-actinic inspection tool sensitivity and EUV mask-to-wafer defect printability. Finally, we simulate the changes we expect to see with the 0.33 NA EUV scanner compared to the printed results at 0.25 NA.

## 3. DEFINING DEFECTIVITY

Before we can determine how to detect printable mask defects, we must first define what 'printable' means. The literal definition of 'defect' according to the Merriam-Webster Dictionary is '*an imperfection that impairs worth or utility*'. Further, Webster defines 'printable' as '*capable of being printed*.' Fortunately for mask makers, 'defective' does not always mean 'printable'. There are several approaches to define what a defect is, but the primary objective in that effort is to maximize wafer quality while minimizing impacts to yield for both mask makers and lithographers.

In the world of optical mask inspection, it was common to implement a "see it/fix it" policy at mask inspection, combined with AIMS analysis of defects to assess the printing impact. In the EUV world, two factors make the optical approach impractical: the defect density inherent in the EUV substrate, and the lack of actinic AIMS analysis capability. So we find ourselves in the position of optimizing mask inspection sensitivities to detect only those defects that matter, in order to avoid having to detect or repair defects that are below the wafer 'defect printability' threshold. The challenges here are how to define that threshold and how to accomplish that goal with non-actinic inspection capability. To that end, this paper will focus on potential approaches to define what an absorber defect is, specifically relative to normal variation on the wafer, and the defect's affect on wafer image area or CD size.

For the analysis included in this paper, a programmed defect test mask was designed and built on an industry-standard 40-multilayer EUV substrate. The mask was written on a 50KeV writer on PCAR resist. Since the first insertion layers for EUV lithography are most likely to be on contact layers, the designs we will focus on in this paper are rectangles and holes. The test mask was exposed on the 0.25 NA scanner at IBM's Albany Nanotech facility in Albany, New York, using chemically amplified EUV resist. Figure 1 provides examples of several types of edge and corner defects, as well as sizing defects that affect the linear size and area of the images. The design size for the rectangular images is 36 nm x 85 nm on wafer, and the design size for the hole images is 32 nm x 32 nm on wafer, roughly equivalent in size to 14 nm node logic designs.

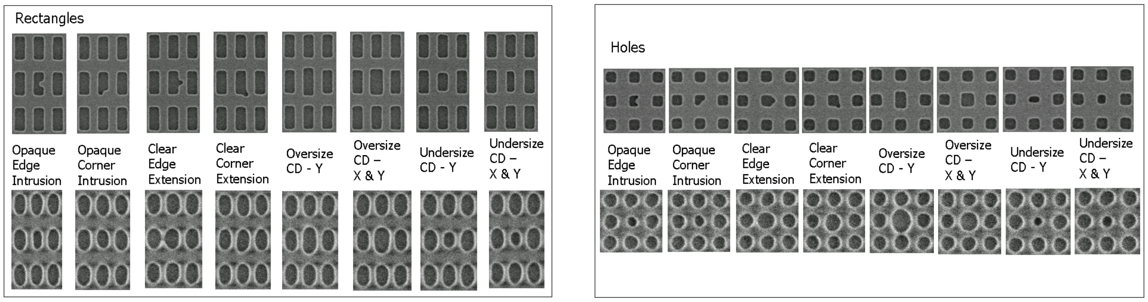


Figure 1. 36 nm x 85 nm rectangles and 32 nm x 32 nm holes with programmed defects.

## 4. VARIABLITY VERSUS 10% WAFER IMPACT

We begin with a discussion about wafer variation. Figure 2a provides an example of typical image variation on a line-space EUV design, exposed at 0.25 NA. This naturally occurring variation is a result of pushing the EUV scanner resolution to its limit. There is a programmed defect placed exactly in the center of the image as seen in Figure 2b. While examining Figure 2a, it is nearly impossible to discern the programmed defect location from the normal image variation around it. It is assumed that a certain amount of variation is expected, and acceptable within a given tolerance. It follows then that mask defects that cause line width changes on wafer that exceed the normal wafer variation could be defined as printable.

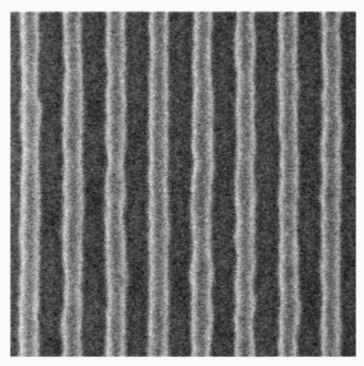


Figure 2a. Typical wafer variation

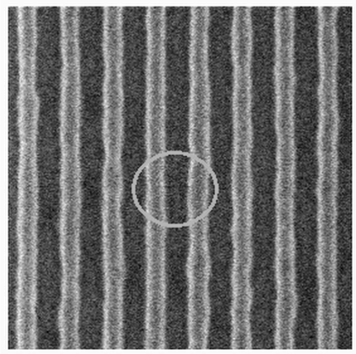


Figure 2b. Programmed defect in center

Two challenges are evident relative to defining defectivity as it relates to wafer variation. First, how to determine which defects fall beyond the limits of normal variation, and second, determine how far outside the range of normal variation does an imperfection have to fall to be considered a defect.

The second discussion centers on the impact an imperfection may have on the wafer image area or size. The ITRS roadmap defines a defect as follows:

> ***Defect Size:*** *A mask defect is any unintended mask anomaly that prints or changes a printed image size by 10% or more. The mask defect size listed in the roadmap is the square root of the area of the smallest opaque or clear 'defect' that is expected to print for the stated generation.*

This definition takes into account the square root area of the defect and its impact on the *size* of the printed wafer image, but does not necessarily address the following three things: first, how the square root area of the defect affects the *area* of the printed wafer image, second, how the overall defective area of the mask image affects the overall area of the printed wafer image, and finally, how the defective mask linear CD affects the linear CD of the printed wafer image. This paper will provide analyses of these cases.

### CRITICAL TERMS AND DEFINITIONS:

Five primary defect definitions will be evaluated, three of which apply the square root area of the mask defect to various wafer area and CD size impacts. The final two approaches apply the linear defect size on mask to the linear CD impact on wafer. Each of these five defect definitions will be evaluated relative to whether they fall outside the normal wafer variation, and how they compare to the standard 10% wafer CD impact approach to defectivity. Vital to that evaluation is an understanding of the following definitions:

**Reference Area and Reference CD**

- **Wafer Reference Area**: Determined by taking 30 reference wafer images and calculating the average of their areas.
- **Mask Reference Area**: Determined by taking the same 30 reference mask images that correlate to those used for reference wafer area and calculating the average of their areas.

- **Wafer Reference Clear CD**: Determined by taking 30 reference wafer clear images and calculating the average of their CD's.
- **Mask Reference Clear CD**: Determined by taking 30 reference mask clear images and calculating the average of their CD's.
- **Wafer Reference Opaque CD**: Determined by taking 30 reference wafer opaque spaces and calculating the average of their CD's.
- **Mask Reference Opaque CD**: Determined by taking 30 reference mask opaque spaces and calculating the average of their CD's.

**Defect Area and Defect CD**

- **Area of the Wafer Defect**: Determined by taking the difference between area of the defective wafer image and the wafer reference area
- **Area of the Mask Defect**: Determined by taking the difference between area of the defective mask image and the mask reference area
- **CD of the Wafer Defect**: Determined by taking the difference between CD of the defective wafer image and the wafer reference CD (clear or opaque as appropriate)
- **CD of the Mask Defect**: Determined by taking the difference between CD of the defective mask image and the mask reference CD (clear or opaque as appropriate)

**Wafer Area Variability**: Defined as the 3-sigma value calculated from the standard deviation of the reference wafer area measurements. The hashed area in Figure 3 represents the wafer area variability. The size of the hashed variability area for each of the charts in this analysis change, depending on whether mask or wafer area or CD are being analyzed (i.e., an analysis of opaque space CD or area would have a different 3-sigma than an analysis of a clear image CD or area).

**Scatter Plot Points:** Each X,Y coordinate on the chart represents a one-to-one correlation between the mask and the wafer. The X axis represents the mask area (or CD) that is directly responsible for the wafer area (or CD) plotted on the Y axis. Depending on which of the five definitions being evaluated, the units on the chart are either area or linear CD (clear or opaque).

**Defining 'Outside Variability'**: A defect on mask that causes a change beyond the variability on wafer is found by first fitting the scatter plot to a linear line (also representative of the process MEEF). The intersection between the variability line (defining the upper edge of the hashed area on the charts) and the linear, 'best fit' line represents the point at which the defect on the mask will cause a change on wafer that exceeds the normal variability on wafer. In other words, the X value of the intersection between the variability line and the best fit line will provide the area of the mask defect necessary to cause an area defect on wafer that is beyond its variability. The square root of this number is considered to be the square root area of the mask defect.

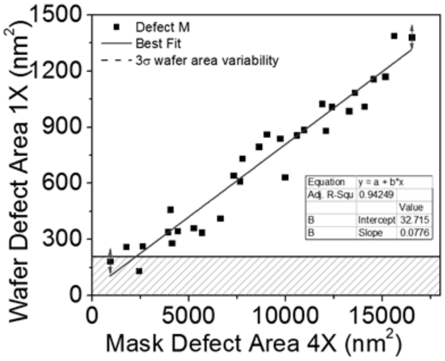
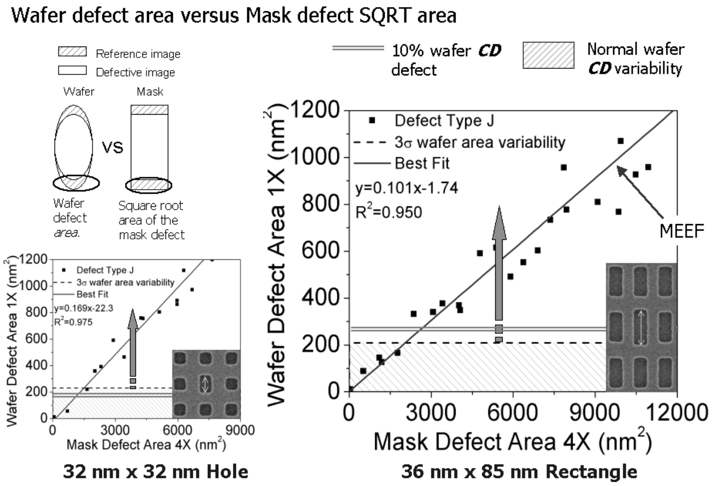


Figure 3. Example of variability analysis chart

## FIVE WAYS TO DEFINE A DEFECT:

**Definition #1 - Wafer defect area versus Mask defect square root area** – Determines the degree of wafer area change caused by the square root area of the associated mask defect. Represented by Figure 4, the variability is based on the standard deviation of the wafer reference *area*. All points above the 3-sigma line represent mask defects large enough to cause anomalies on wafer that exceed normal wafer area variation. The double line shown on both the rectangle and hole layer charts represents the point at which defects would cause a 10% area impact on wafer. All points above the double line represent mask defects large enough to cause anomalies on wafer that result in 10% or greater area impact on wafer. Note that for the hole pattern, the variation is actually larger than the 10% wafer impact line.



**32 nm x 32 nm Hole** **36 nm x 85 nm Rectangle**

Figure 4. Rectangular Image – Wafer defect area versus Mask defect square root area.

**Definition #2 - ITRS Approach – Wafer clear defect size versus Mask defect square root area** – Determines the degree of wafer CD size change caused by the square root area of the associated mask defect. Represented by Figure 5, the variability is based on the standard deviation of the wafer reference clear *CD size*. Again, all points above the 3-sigma line, represent mask defects large enough to cause anomalies on wafer that exceed normal wafer variation. The double line represents the point at which mask defects will impact the wafer CD size by 10% or more. Points above the double line represent mask defects that result in a 10% or greater CD impact on wafer. Interestingly, there are several defects that fall *between* the variability and 10% lines (circled). Depending on the method chosen to define defectivity, these few defects could be considered critical.

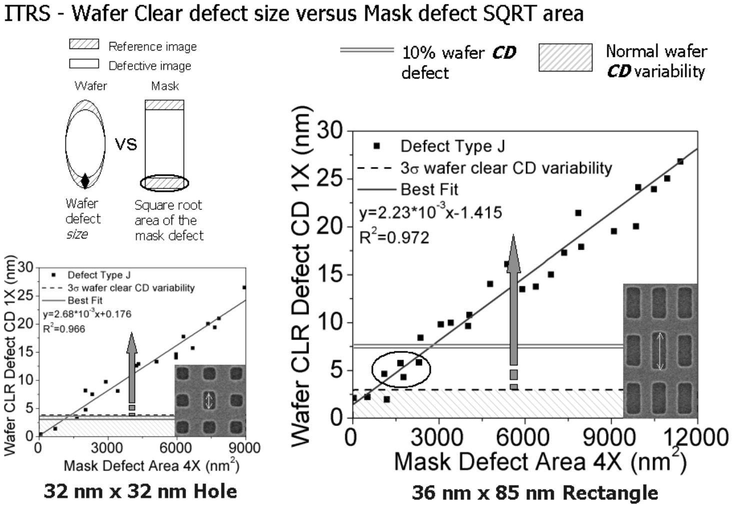


Figure 5. Rectangular Image – Wafer clear defect size versus Mask defect square root area.

**Definition #3 - Wafer opaque defect size versus Mask square root area** – Determines the degree of wafer opaque (space) CD size change caused by the square root area of the associated mask defect. Represented by Figure 6, the variability is based on the standard deviation of the wafer reference *opaque (space) size*. Once again, all points above the 3-sigma line represent mask defects large enough to cause anomalies on wafer that exceed normal wafer variation. Also note the cluster of defects that fall between the variability and 10% impact lines (circled).

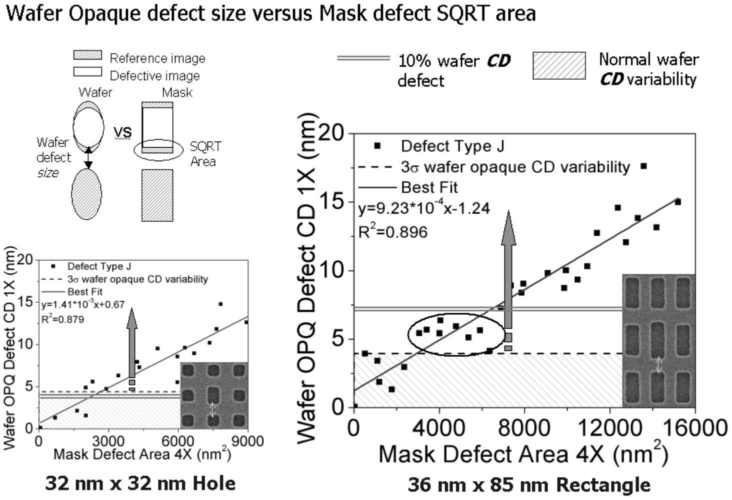


Figure 6. Rectangular Image – Wafer opaque defect size versus Mask defect square root area.

**Definition #4 - Clear Wafer defect size versus clear Mask defect size** – Determines the degree of wafer clear CD size change caused by the degree of mask clear defect CD change. Represented by Figure 7, the variability is based on the standard deviation of the wafer reference clear *CD size*. All points above the 3-sigma line represent mask defects large enough to cause anomalies on wafer that exceed normal wafer variation. Once again, there are defects that fall between the variability and 10% wafer impact lines.

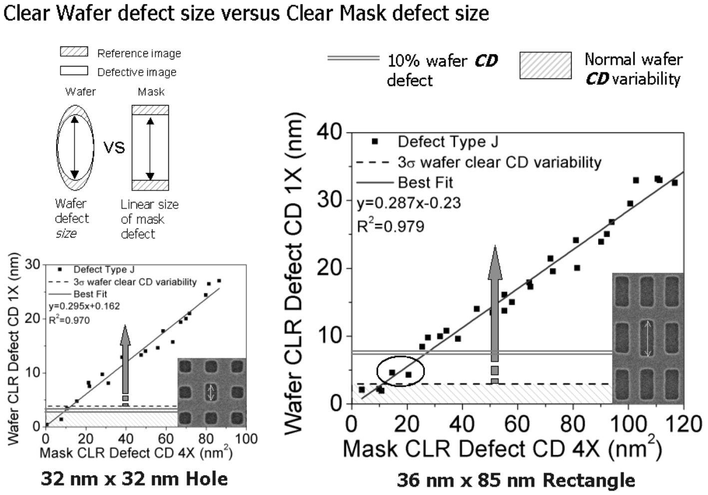


Figure 7. Rectangular Image – Clear Wafer defect size versus Clear Mask defect size.

**Definition #5 - Opaque Wafer defect size versus opaque Mask defect size** – Determines the degree of wafer opaque (space) CD size change caused by the degree of mask opaque (space) defect CD change. Represented by Figure 8, the variability is based on the standard deviation of the wafer reference opaque *CD size*. All points above the 3-sigma line represent mask defects large enough to cause anomalies on the corresponding wafer images that exceed normal wafer variation. As with the previous four examples, there are potentially printable defects that fall between the variability and 10% wafer impact lines.

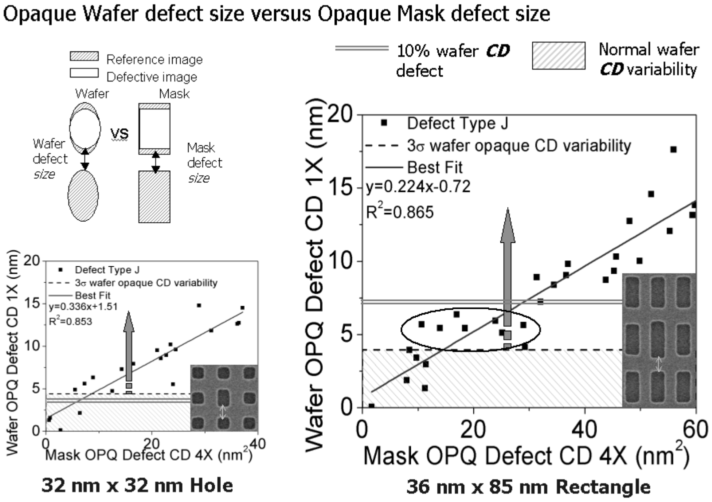


Figure 8. Rectangular Image – Opaque Wafer defect size versus Opaque Mask defect size.

## 5. MASK INSPECTION SENSITIVITY VS DEFECTIVITY APPROACH

As mentioned earlier in this paper, is it essential to correlate the signature of the defects seen by the non-actinic inspection tool to their subsequent wafer image in order to optimize inspection sensitivity and minimize yield loss. To that end, one must first settle on a method to define printability (i.e., identifying those defects that exceed variability versus those that cause a 10% CD impact signature on wafer), followed by a thorough characterization of inspection tool defect sensitivity. That sensitivity would then be tailored to detect primarily, printable defects. With the current lack of EUV AIMS capability to assist in evaluating potentially printable defects, our goal would be to minimize the detection and repair of non-printable defects. Keep in mind the identification of what is or isn't printable will vary with the two approaches.

An in-depth study was performed using an EUV programmed defect mask to fully characterize both 193 nm optical and E-beam mask inspection sensitivity relative to the five defect definitions already discussed in this paper. The programmed defect test mask is the same one used for the defectivity portion of this study and is referenced in Figure 1. For this paper, we focus on edge defects, with results demonstrated on a clear extension on edge, and on critical dimension (CD) defects, with results demonstrated on an oversized hole. In the results that follow, the five defect definitions will be shown in terms of defects that cause 10% wafer CD impact, and those which exceed the normal wafer variability.

**Analysis #1 - Defectivity versus Inspection Sensitivity for Clear Edge Extension Defect on a 36 nm x 85 nm Rectangular Shaped Image** – Sensitivity results seen in Figure 9 indicate that there is adequate optical and E-beam inspection sensitivity for mask *edge* defects resulting in a 10% Wafer CD impact, and for those that fall outside the normal variation on wafer.

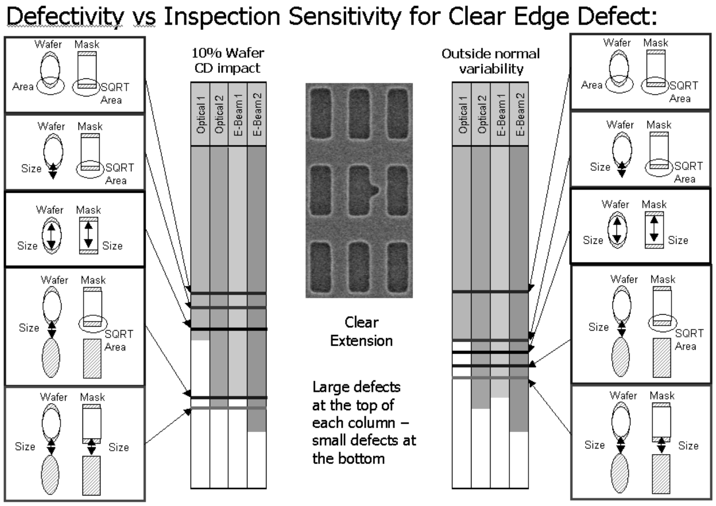


Figure 9. Defectivity vs Inspection Sensitivity for Clear Edge Extension Defect – 36 nm x 85 nm Rectangular Image.

**Analysis #2 - Defectivity versus Inspection Sensitivity for Asymmetric Oversized CD Defect on a 36 nm x 85 nm Rectangular Shaped Image** – Sensitivity results seen in Figure 10 indicate that for both the 10% wafer CD impact approach, and the variability approach, there is limited inspection sensitivity with either 193 nm optical or E-beam inspection for mask defects that have a direct affect on the clear wafer CD, however sensitivity does exist for the two methods that focus on the size of the opaque space between hole images. Compared to the results provided in Figure 9, CD defects will require a smaller defect criteria than edge defects.

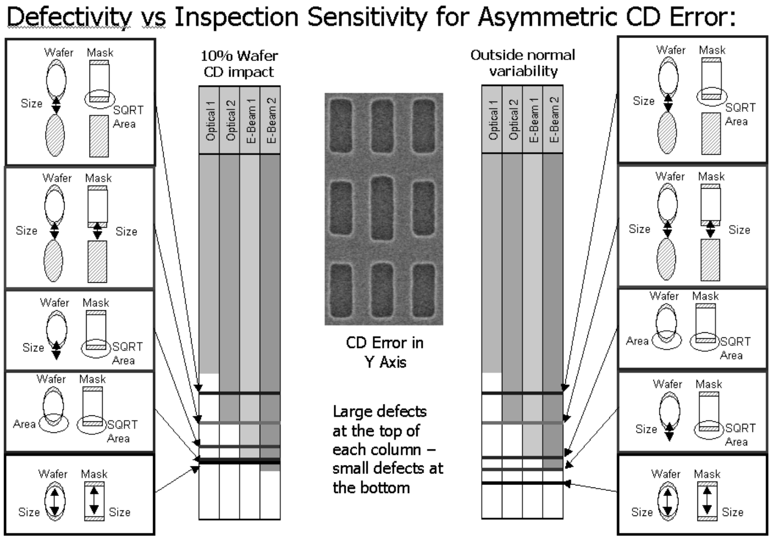


Figure 10. Defectivity vs Inspection Sensitivity for Asymmetric Oversized CD Defect – 36 nm x 85 nm Rectangular Image.

**Analysis #3 - Defectivity versus Inspection Sensitivity for Clear Edge Extension Defect on a 32 nm x 32 nm Hole Image** – Sensitivity results seen in Figure 11 indicate that for edge defects, 193 nm optical inspection sensitivity exists for the ITRS definition but not for the remaining defect definitions when evaluating either the 10% wafer CD impact approach or variability approach. On the other hand, E-beam sensitivity is acceptable for all defect definitions. For the variability approach to defectivity, there is adequate sensitivity for all defect definitions for both optical and E-beam inspections. It is surmised that inspection sensitivity is improved with the variability approach to defectivity due to the fact that the calculated 3-sigma variability is larger than the 10% wafer CD impact for hole layers. This same phenomenon explains why smaller defect criteria is required for hole layers for the 10% wafer CD impact approach than for the variability approach. See Figures 4 through 8 for a comparison between the variability and 10% CD impact lines for both hole and rectangle images.

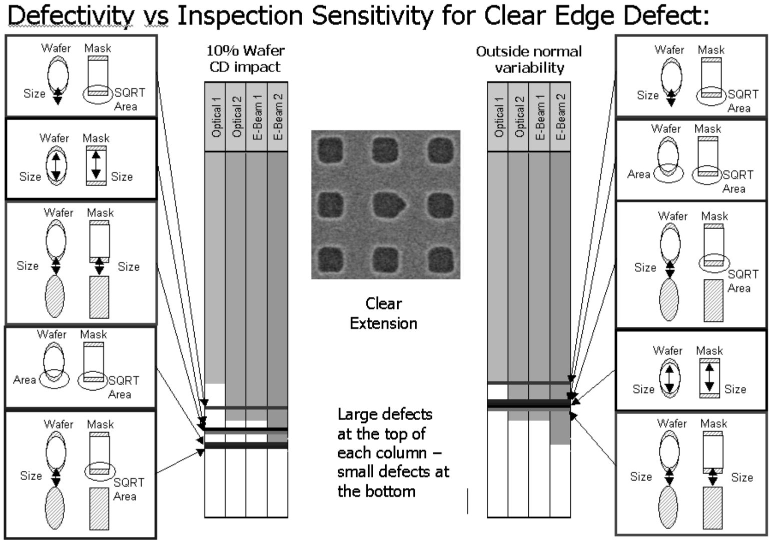


Figure 11. Defectivity vs Inspection Sensitivity for Clear Edge Extension Defect – 32 nm x 32 nm Hole Image.

**Analysis #4 - Defectivity versus Inspection Sensitivity for Asymmetric Oversized CD Defect on a 32 nm x 32 nm Hole Image** – Sensitivity results seen in Figure 12 indicate for the 10% wafer CD impact approach there is very little inspection sensitivity with 193 nm optical inspection or E-beam inspection. For the variability approach, there is acceptable 193 nm and E-beam inspection capability for mask defects that affect the opaque space between contact holes, however, there is very little sensitivity with either inspection tool for the defect definitions that affect clear wafer CD. In addition, CD defects on hole layers require smaller defect criteria compared to edge defects on the same pattern (see Figure 11).

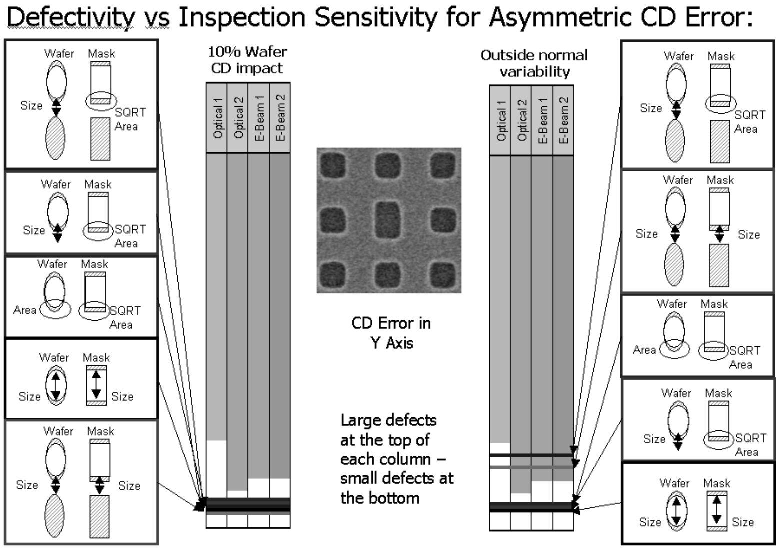


Figure 12. Defectivity vs Inspection Sensitivity for Asymmetric Oversized CD Defect – 32 nm x 32 nm Hole Image.

**General Observations about Inspection Sensitivity**

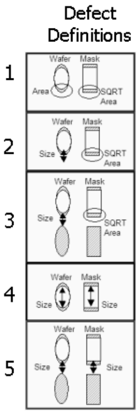
- Relative to the ITRS roadmap, the results of this evaluation suggest that the roadmap's 'one size fits all' approach may not be adequate for all image types, nor all defect types.

- The size of defects that fall outside normal variability varies with geometry and pitch. For rectangular images, defects that result in a 10% CD impact on wafer are generally larger than those that fall outside the normal wafer variability. For hole images, there was very little difference in size between mask defects that result in a 10% CD impact on wafer and those which fall outside the normal wafer variability, most likely because the variability on the square hole layer was larger than the 10% wafer CD impact point.

- Relative to defect size, edge defects have a larger defect criteria than CD defects. This was true for both the rectangular and hole shaped images. In addition, mask defects which caused printability defects on the hole layer used in this study were smaller than the printable defects on the rectangular layer.

- Relative to mask inspection sensitivity versus the five defect definitions evaluated, no single approach detects all wafer-printable defects for all defect types and image types with either 193 nm optical, nor E-beam inspection. This situation is worse for CD errors than it is for edge defects… and it is worse for the variability approach than it is for the 10% wafer CD approach. Figure 13 provides a summary of inspection capability for the five defect definitions and two defectivity approaches. For the rectangular layer, optical and E-beam inspection provided comparable capability. Both were successful for edge defects, but struggled somewhat with CD defects. For the hole layer, E- Beam sensitivity was slightly better than optical for edge defects, but again, both struggled with CD defects, especially when evaluating the 10% wafer CD impact approach to defectivity. This is due in part to the variability on this particular hole layer being larger than the 10% wafer CD impact point.

Mask Inspection Die-2-DB Sensitivity for Printable Defects



| | | Defect Definition | 10% Wafer CD Impact | | Outside Variation | |
|---|---|---|---|---|---|---|
| | | | Optical | E-Beam | Optical | E-Beam |
| Rectangle | Edge Defects | 1 | ☺ | ☺ | ☺ | ☺ |
| | | 2 | ☺ | ☺ | ☺ | ☺ |
| | | 3 | ☺ | ☺ | ☺ | ☺ |
| | | 4 | ☺ | ☺ | ☺ | ☺ |
| | | 5 | ☺ | ☺ | ☺ | ☺ |
| | CD Defects | 1 | ☹ | ☺ | ☹ | ☺ |
| | | 2 | ☹ | ☺ | ☹ | 😐 |
| | | 3 | ☺ | ☺ | ☺ | ☺ |
| | | 4 | ☹ | ☺ | ☹ | ☹ |
| | | 5 | 😐 | ☺ | 😐 | ☺ |
| Holes | Edge Defects | 1 | ☹ | 😐 | ☺ | ☺ |
| | | 2 | ☺ | ☺ | ☺ | ☺ |
| | | 3 | ☹ | 😐 | ☺ | ☺ |
| | | 4 | ☹ | ☺ | ☺ | ☺ |
| | | 5 | ☹ | ☺ | ☺ | ☺ |
| | CD Defects | 1 | ☹ | ☹ | ☹ | ☹ |
| | | 2 | ☹ | ☹ | ☹ | ☹ |
| | | 3 | ☹ | ☹ | ☺ | ☺ |
| | | 4 | ☹ | ☹ | ☹ | ☹ |
| | | 5 | ☹ | ☹ | ☺ | ☺ |

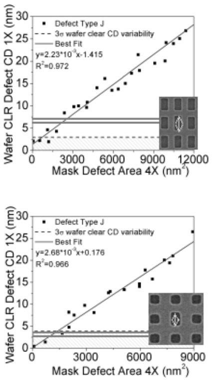
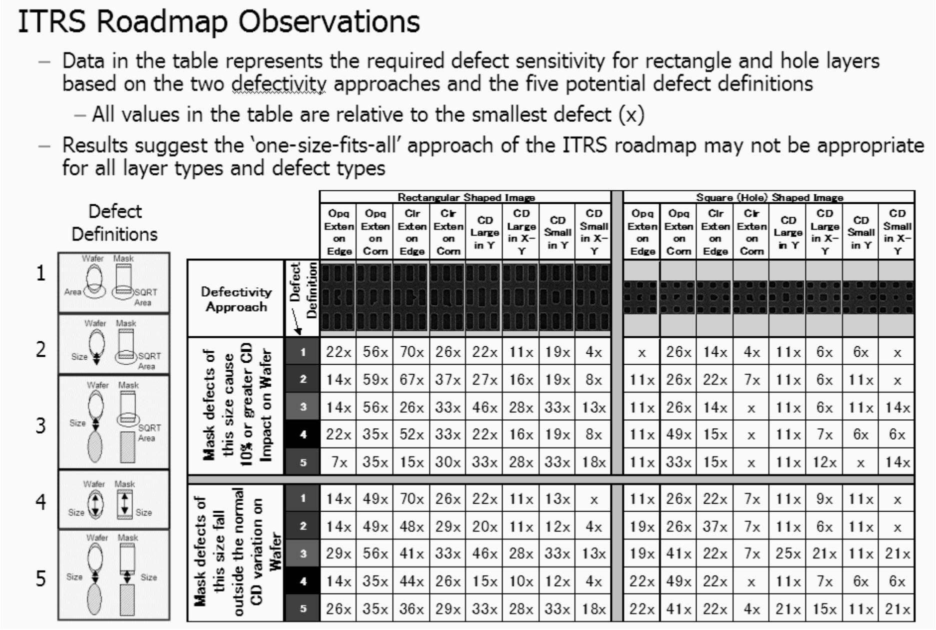


Figure 13. Mask Inspection Die-2-Database Sensitivity for Printable Defects

## About the ITRS Roadmap

As mentioned earlier in this paper, the ITRS roadmap defines defect size as: "any unintended mask anomaly that prints or changes a printed image size by 10% or more. The mask defect size listed in the roadmap is the square root of the area of the smallest opaque or clear 'defect' that is expected to print for the stated generation." The roadmap further provides defect sizes of 25 nm on the mask in 2012 and reducing in size yearly until 2026 with a target defect size of 5 nm. Generally, this value becomes the target defect size for all defects on the mask. Evaluation results from the EUV programmed defect test mask used in this study, suggests the 'one-size-fits-all' approach of the ITRS roadmap is not sufficient for all layer types, or for all defect types. The table in Figure 14 provides the relative defect sizes obtained in this study, for each defect type deemed to print on wafer, based on the preferred approach to defectivity. The data suggests that whether the 10% wafer CD impact, or the variability approach is used, the defect criteria requirements for a 32 nm x 32 nm hole layer needs to be much smaller than for a 36nm x 85 nm rectangular layer. The data also implies the required defect criteria should be dependent on defect type.



## ITRS Roadmap Observations

- Data in the table represents the required defect sensitivity for rectangle and hole layers based on the two defectivity approaches and the five potential defect definitions
  - All values in the table are relative to the smallest defect (x)
- Results suggest the 'one-size-fits-all' approach of the ITRS roadmap may not be appropriate for all layer types and defect types

Defect Definitions

| | | Rectangular Shaped Image | | | | | | | | Square (Hole) Shaped Image | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Defectivity Approach | Defect Definition | Opq Exten on Edge | Opq Exten on Corn | Clr Exten on Edge | Clr Exten on Corn | CD Large in Y | CD Large in X–Y | CD Small in Y | CD Small in X–Y | Opq Exten on Edge | Opq Exten on Corn | Clr Exten on Edge | Clr Exten on Corn | CD Large in Y | CD Large in X–Y | CD Small in Y | CD Small in X–Y |
| Mask defects of this size cause 10% or greater CD Impact on Wafer | 1 | 22x | 56x | 70x | 26x | 22x | 11x | 19x | 4x | x | 26x | 14x | 4x | 11x | 6x | 6x | x |
| | 2 | 14x | 59x | 67x | 37x | 27x | 16x | 19x | 8x | 11x | 26x | 22x | 7x | 11x | 6x | 11x | x |
| | 3 | 14x | 56x | 26x | 33x | 46x | 28x | 33x | 13x | 11x | 26x | 14x | x | 11x | 6x | 11x | 14x |
| | 4 | 22x | 35x | 52x | 33x | 22x | 16x | 19x | 8x | 11x | 49x | 15x | x | 11x | 7x | 6x | 6x |
| | 5 | 7x | 35x | 15x | 30x | 33x | 28x | 33x | 18x | 11x | 33x | 15x | x | 11x | 12x | x | 14x |
| Mask defects of this size fall outside the normal CD variation on Wafer | 1 | 14x | 49x | 70x | 26x | 22x | 11x | 13x | x | 11x | 26x | 22x | 7x | 11x | 9x | 11x | x |
| | 2 | 14x | 49x | 48x | 29x | 20x | 11x | 12x | 4x | 19x | 26x | 37x | 7x | 11x | 6x | 11x | x |
| | 3 | 29x | 56x | 41x | 33x | 46x | 28x | 33x | 13x | 19x | 41x | 22x | 7x | 25x | 21x | 11x | 21x |
| | 4 | 14x | 35x | 44x | 26x | 15x | 10x | 12x | 4x | 22x | 49x | 22x | x | 11x | 7x | 6x | 6x |
| | 5 | 26x | 35x | 36x | 29x | 33x | 28x | 33x | 18x | 22x | 41x | 22x | 4x | 21x | 15x | 11x | 21x |

Figure 14. Rectangle vs Hole layer defect requirements

## 6. 0.25 NA VERSUS 0.33 NA EUV SCANNER SIMULATION

The results in Figure 15 represent a simulated comparison between mask defects expected to cause a 10% CD error on wafer when printed at 0.25 NA versus 0.33 NA with conventional illuminators. The solid lines represent the ITRS roadmap approach to defect definition as seen in Figures 9 and 10. This result reflects exposures at 0.25 NA. The dotted line identifies those defects expected to result in a 10% or greater wafer CD impact at 0.33 NA. Although case dependent, imaging at higher NA produces improved resolution and subsequently, reduced variability. Along with reduced variability, comes the increased probability that smaller mask defects will fall outside the normal variability. If one chooses the variability approach to defining which defects are printable, target defect sensitivity will have to improve with the introduction of the 0.33 NA scanner.

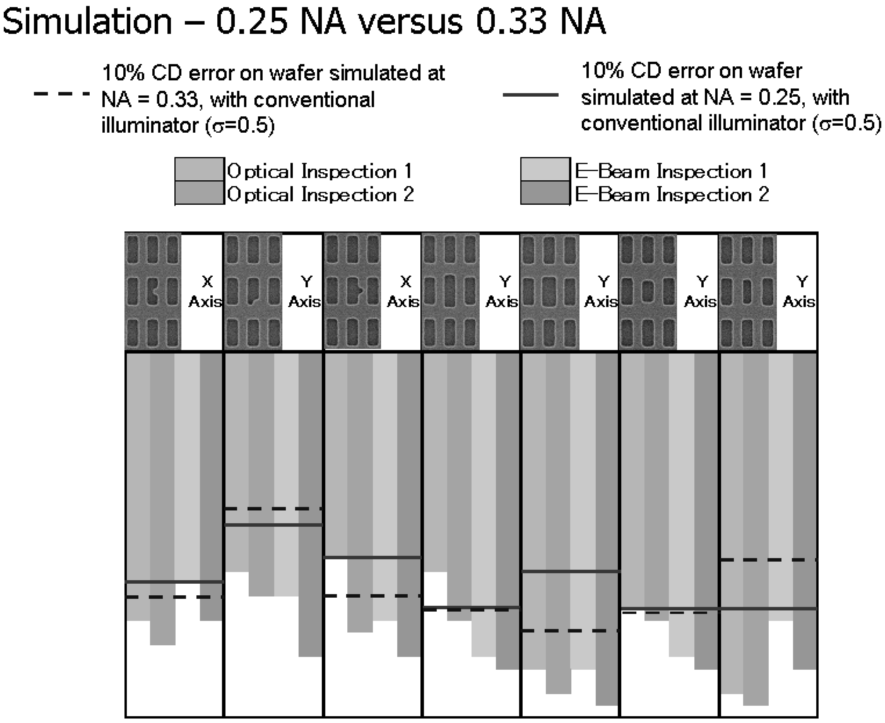


Figure 15. Simulation – 0.25 NA vs 0.33 NA

## 7. SUMMARY AND CONCLUSIONS

The goal of this paper was to apply a variety of approaches to defining how defects transfer from the mask to the wafer. We focused on two primary methods for defining defectivity. The first method explores the signature of mask defects that result in anomalies on the wafer that fall just outside the window of normal CD variability on wafer. The reasoning is that defects of the size that fall within the variation on wafer are simply part of the noise and those that fall outside the noise are defects. The second method for defining defectivity is aligned with the ITRS roadmap, in that it is concerned with mask defects whose signature translates to a 10% or greater CD impact on wafer.

Within each method, we reviewed five potential defect definitions: Mask defects whose square root area affects the *area* of a wafer image, Mask defects whose square root area affects the *size* of a primary wafer image, Mask defects whose square root area affects the *size* of space between primary wafer images, Mask defects whose linear size affect the *linear size* of a wafer image and finally, Mask defects whose linear defect size affects the *linear defect size* on wafer.

From a variability approach it is important to understand wafer process variations, i.e., if a defect causes an impact on wafer that falls within the variation, it is simply noise, however if it falls outside the normal window of variation, it is a defect. Allowable defect sizes with the variation approach are larger than the variation itself, so understanding the magnitude of that variation will help define the minimum defect size. It follows then, that since the defect size is based on print/process wafer variation, feature width may not be the limiting geometry as is the case with the ITRS roadmap. Furthermore, as can be seen in Figure 16, without the benefit of EUV AIMS capability, the variability approach to defectivity provides a guard-band for defects that fall between the normal variability limits and the 10% ITRS Roadmap specification.

**Gap Between Variability and ITRS Roadmap**

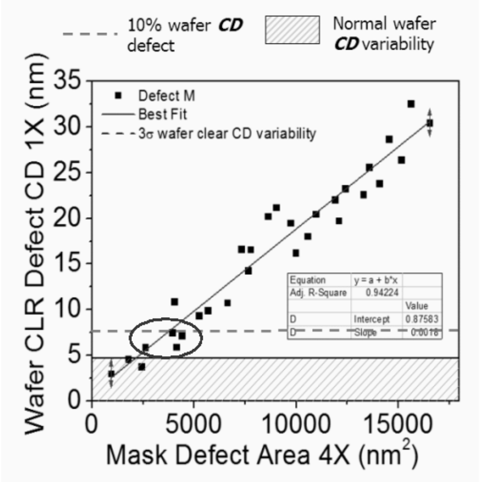


Figure 16. Gap between Variability and the ITRS Roadmap.

From an ITRS perspective, it was found that all defects are not created equal. The ‘one size fits all’ definition that assigns the same defect criteria to all layers and all defect types may not be adequate. This is demonstrated in Figure 14 with a stricter requirement for hole layers over rectangles, and for CD errors over edge defects. On the plus side, one benefit of the 10% wafer CD impact approach is that it is a fixed target, i.e., a single value that can be used to characterize and optimize inspection tool setups. This fixed target also allows inspection tool manufacturers to design and build systems that assure detectability of required defect sizes, with a margin of assurance to spare.

Relative to mask inspection sensitivity, the variability approach to defectivity will require much smaller defect sensitivity in some cases, than the ITRS roadmap requires. With this approach, the minimum defect requirement is a function of pattern geometry and wafer processing – neither of which is under the control of the mask maker. The mask maker is dependent on wafer print/process stability in order to provide inspection sensitivities that correlate to the degree of wafer variability. Higher NAs improve the resolution of everything on the wafer – including defects. As wafer variability changes, the target defect criteria may also change. If variability worsens and inspection sensitivity remains the same, a higher wafer defect density will result, some of which will fall within the variability noise. If variability improves and inspection sensitivity remains the same, there is an increased risk of missing printable defects. On the downside, if variability improves, it may require additional sensitivity from non-actinic optical and E-beam inspection approaches that may already struggle to detect all critical defects. Choosing the variability approach to defectivity creates a moving target that is harder to hit. To provide an effective mask inspection, the mask maker must guard band the inspection sensitivity to compensate for possible fluctuation in process variability, and thus use up the margin of assurance built into most inspection systems.

Relative to the 10% wafer CD impact approach to defectivity, both optical and E-beam inspection sensitivities are comparable for detection of most mask edge defects, but struggle to detect all critical CD defects. Compared to optical, E-beam inspection has slightly greater success detecting smaller mask CD errors that translate into 10% or greater wafer CD errors, however long inspection times make this method impractical for full field mask inspection within a Manufacturing environment.

Finally, as the industry moves from the 0.25 NA EUV scanner to 0.33 NA, images… and defect resolution will improve. As resolution improves, variability will reduce. With a reduction in variability, comes a reduction in the size of defects that exceed the variability. It follows then, that inspection tool sensitivity will need to improve along with the reduction in variability with the 0.33 NA scanner.

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