

# „WLCD: A new System for Wafer Level CD Metrology on Photomasks“

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## ABSTRACT:

With decreasing feature size, the requirements for CD uniformity (CDU) on the wafer have become crucial for achieving the required yield in the wafer fab. This is related to tighter CDU specifications on the photomask. Currently, mask CDU is mainly measured by mask CD SEM tools. However, due to strong OPC and high MEEF mask CDU is not directly related to wafer CDU. A new Aerial Imaging based optical system has been developed by Carl Zeiss SMS which measures wafer level CD already on photomasks under scanner conditions. First results of the alpha tool show that the new tool has extremely good CD repeatability and stability. Furthermore, the effect of the scanner settings on CD uniformity is demonstrated.

**Keywords:** CD Metrology, Wafer Level CD, Aerial Imaging, Photomask, MEEF

## 1. INTRODUCTION

With the insertion of immersion lithography for the 45nm node, the quality of the photomask has become more and more crucial for achieving the required yield in the wafer fab. As the features sizes on the mask are coming close to the wavelength of the scanner, the complexity of the mask design has been increasing continuously. Strong Optical Proximity Correction (OPC) and application of assist features (AF) are required in order to get proper printing results on the wafer. Furthermore, approaches like computational or inverse lithography will become more popular in future for small feature lithography at 193nm [1]. All these lithography techniques result in mask features which are significantly smaller than the wavelength. At the same time the extension of 193nm lithography leads consequently to low k1 factors and an increased Mask Error Enhancement Factor (MEEF). For high MEEF areas, small CD errors on the photomask caused for example by manufacturing tolerances or proximity effects from pattern generator result in large CD uniformity errors on the wafer print. By further extension of the immersion lithography the photomask is becoming more and more an optical element whose imaging performance must be already controlled in the mask shop,

Reduced CD uniformity on the wafer will result in less device performance on the chip. For instance in microprocessor technology, the CD determines the device speed. For high speed chips a higher market price can be achieved. The economic value of controlling CD uniformity is obvious. The final CDU uniformity on the wafer depends on several factors like resist processing, scanner performance and finally mask CDU. For the mask maker tighter CDU specs due to low k1 mean that the CDU uniformity on the mask has to be controlled very accurately. In Figure 1 a mask layout of an inverse lithography approach [1] is shown. The complex pattern of small and tiny assist features is clearly visible. The designed pattern is used to print random contact holes. Small variations in the assist features can cause different printing behavior of the photomask. During mask manufacturing the CD uniformity of the generated pattern is classically measured by mask CD SEMs. The advantages of mask CD SEMs are high resolution (all assist features are resolved), high throughput of several hundred sites per hour and high CD repeatability.

However, measuring a mask pattern with tiny assist features would add a high complexity to a mask CD SEM measurement. For making sure that in the given example 4 contact holes are printed correctly about 70 subresolution features have to be measured in order to know the exact geometrical dimensions of the generated pattern. This will reduce the throughput of a mask CD SEM significantly and generate a tremendous amount of data which have to be handled. For predicting the lithographic imaging performance, these data must be used for modeling the wafer printing performance. Besides the disadvantage of handling huge amount of data such a modeling approach would not catch real word mask effects like 3D effects or variation of the optical properties of the mask materials. An alternative would be to use wafer prints with additional wafer CD SEM metrology. But, as a mask shop has no access to a scanner and wafer processing tools, these aren't real practical alternatives. These disadvantages of a classical mask CD metrology can be overcome by measuring the mask using an Aerial Imaging Technique. The measurement site on the mask is illuminated under the same wavelength and illumination conditions as the scanner and is magnified on a CCD camera. By doing so the CCD camera will see the aerial image as the wafer will see it. In the example of Figure 1 the aerial image under scanner conditions is compared with the wafer print. This illustrates well that an aerial image technique will reduce the complexity to a measurement of 4 pinholes in the shown example.

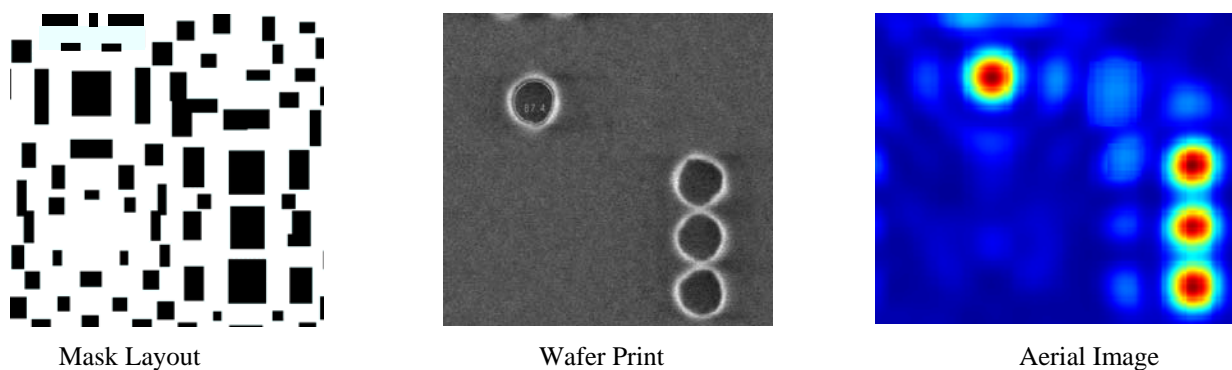


Fig. 1: Example of a complex mask layout [1] with about 70 subresolution features which are necessary to print 4 pinholes on the wafer and the corresponding aerial image taken under scanner illumination and imaging conditions which is equal to the wafer print

Compared to classical mask CD measurement approaches which are measuring the geometrical shape of the mask features, an aerial imaging technique gives several advantages:

- Aerial Imaging sees mask with “scanner eyes” and measures the lithographic imaging performance of the mask directly
- Wafer level CD and printing performance of OPC/AF is captured
- Can be done in the mask shop and wafer fab
- Saves cost by reducing wafer prints and wafer metrology in the wafer fab
- Enables the separation of mask contributions and lithographic process contributions to CDU independently

Aerial imaging by using AIMS™ tools [2, 3] has been applied for more than 15 years in the mask shop for reviewing and qualifying mask defects and repairs under scanner conditions. Recently, it has been shown in some case studies that Aerial Imaging Technology is per se able to measure the wafer level CD uniformity of a mask correctly [4-8]. Applying this technique to mask CD metrology can lead to added value for the mask shop and the wafer fab as the optical performance under scanner conditions can be already measured in the mask shop. However, CD metrology has different requirements than repair verification and defect disposition for which AIMS™ has been specifically developed and designed [2, 3]. Generally, CD metrology requires the ability to measure several hundreds of sites on the mask in a short time whereas for repair verification only a few sites per mask are reviewed. So, high throughput, high repeatability as

well as automated job generation and tool matching are the main requirements for a CD metrology tool. These specific requirements triggered the development of a new Aerial Imaging Tool for mask CD metrology called WLCD (“Wafer Level CD Metrology Tool”) at Carl Zeiss SMS.

## 2. THE WLCD TOOL CONCEPT

The newly developed WLCD tool (Figure 2) has been specifically developed for mask CD metrology applications. The tool is equipped with Zeiss 193 nm imaging and illumination optics. This optics can illuminate and image the mask with the conditions of a 193 nm immersion scanner. The variable NA allows measurements up to a scanner equivalent NA of 1.4. A new 193 nm laser is used for ultrafast CD measurements of several hundred sites per hour. The whole beam path has been designed to stabilize and monitor the laser energy accurately in order to achieve long term CD repeatability values below 1 nm at mask level or below 0.25 nm at wafer level. The tool is equipped with user defined aperture planes for off-axis illumination in order to illuminate the mask under the same conditions as a scanner. Additionally, different polarizations (tangential, x, y) are available. The system uses the Zeiss proprietary scanner mode which measures the image in resist under high NA imaging [3] by taking into account vector effects. An important feature is that the tool is able to measure the CD in-die which means that within the field of view the user can define several measurement regions of interest (ROI). This allows CD measurements also directly on arbitrary features.



Fig. 2: The newly developed WLCD tool for in-die mask CD metrology using aerial imaging. Multiple ROIs can be placed in the field of view to measure the CD on arbitrary features

The tool software enables the user to set up measurement jobs fully automatically. For data input a Zeiss input XML-file format has been developed. The customer data preparation can easily export the measurement plan into the XML file. The XML contains information about the location of the measurement site, the measurement region of interest (ROI) and information about the type of measurement. Besides CD information special analysis functions for contact holes, line edge or line width roughness are available. The output data are the measured evaluation results which can be stored either in an XML or another ASCII format.

### 3. FIRST RESULTS

#### 3.1 CD repeatability

Besides throughput CD repeatability is the most important parameter for a CD metrology tool in order to control CD uniformity. A specific requirement for the WLCD tool is the capability to achieve high repeatability for in-die measurements. This requirement fundamentally limits the possibility to average over larger areas in the field of view. Therefore, in the tool design all internal sources of noise for CD measurements have been removed or minimized.

On the WLCD alpha-tool first repeatability tests have been performed. The long term dynamic CD repeatability has been tested on 180nm features @ mask level (line and space pattern 1:1). The measurements have been taken over 3 days by measuring two dies 10 times a day with one load and unload per day. Figure 3 shows the results. For both dies the 3 sigma values are well below 1 nm at mask level. This demonstrates that the performance of the WLCD tool is equal to state of the art mask CD metrology tools. As 1nm repeatability at mask level corresponds to 0.25 nm at wafer level the tool is also able to deliver wafer level data at extremely high precision.

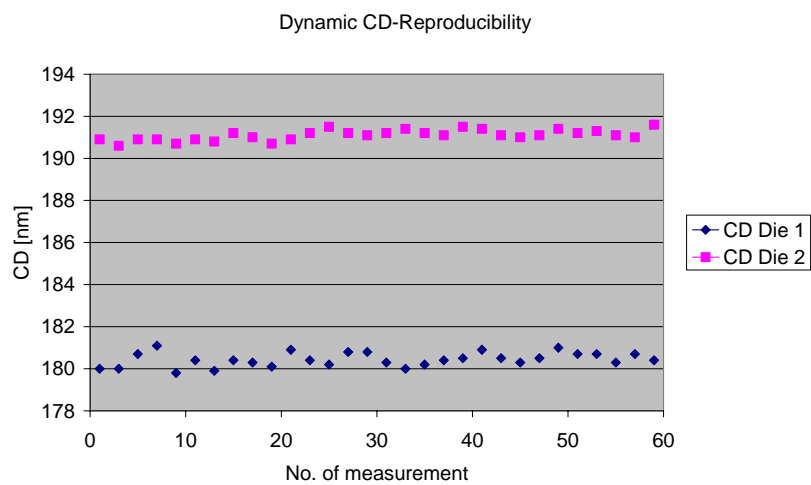


Fig. 3: Long term dynamic CD repeatability results on the WLCD alpha-tool. The 3 sigma value is well below 1 nm at mask level which corresponds to 0.25 nm at wafer level. CD values are given at mask level.

#### 3.2 Long term repeatability of mask mean CD and mask CD uniformity measurements

Besides CD repeatability, the long term stability of a CD metrology tool is of practical importance. To study tool stability the repeatability of mask CD uniformity and the mask mean CD of a test mask has been measured on 3 different days. The measured features were again lines and spaces (1:1). The target mean CD of the test mask was 200nm (in mask dimensions) which corresponds to 50 nm on wafer dimensions. The results are shown in Figure 4. The measured mean CD is slightly off target and in the range of 204 nm at mask or 51 nm at wafer level. The measured mean CD varies only from 204.1 nm to 204.4 nm at mask level over three days. This shows the excellent stability and repeatability of the WLCD tool. The measured CD uniformity of the photomask varies from 5.2 nm to 5.9 nm at mask level which corresponds to a half range of 0.35 nm over 3 days. Scaling these data to wafer level, this corresponds to a half range well below of 0.1 nm at wafer level. This demonstrates that CDU and mean CD can be measured with a high stability using the WLCD tool.

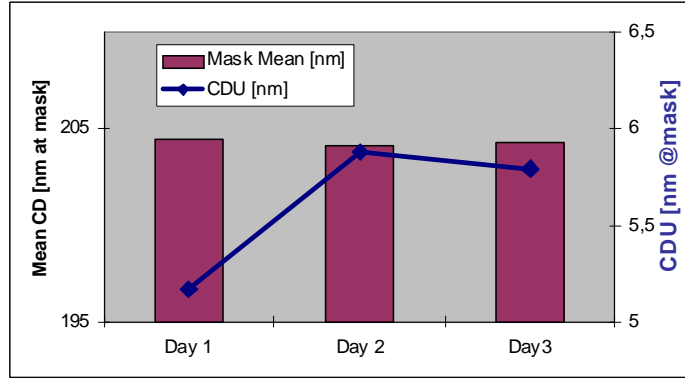


Fig. 4: Results of mask CD uniformity and mask mean CD measurements on a test mask on 3 different days

### 3.3 Mask CD uniformity as a Function of Scanner Settings

It is well known that by printing mask features on the wafer, small variations in the mask CD are amplified by the lithographic process. This amplification is called the Mask Error Enhancement Factor (MEEF) and is normally defined as

$$MEEF = \frac{\partial CD_{wafer}}{\partial CD_{mask}} \cdot m \text{ where } m \text{ is the reduction factor of the scanner (usually } m = 4).$$

One part of the MEEF which we call “optical MEEF” is related to the aerial image and can be measured by the WLCD. The other part of the MEEF is related to the wafer processing, the resist parameter etc. and is naturally not visible in the aerial image. The optical MEEF depends mainly on feature types (e.g. lines, contact holes), pitch (iso versus dense), CD, scanner NA and scanner illumination settings. Generally, the scanner settings are chosen to minimize MEEF. In the most cases this means that the aerial image has a high contrast. However, often the scanner settings can not be chosen to be optimal for all features on the mask. This is especially true for logic layouts which can have different feature types on the mask and therefore the setting is a kind of compromise to the different MEEF values. Naturally, the impact of optical MEEF cannot be measured by classical mask CD metrology techniques. Classical CD mask metrology measures the geometrical shape of the mask features as written by the pattern generator and gives no information about the lithographic imaging performance.

Using WLCD to measure mask CD will show the dependence of the MEEF: Small variations in the geometrical mask CD will be transformed into different CD uniformities in the aerial image depending on the different settings. To demonstrate this effect experimentally, we have measured the CD uniformity of a test mask using two different settings. The test mask had a line and space test pattern with a nominal target CD of 180 nm on mask. Setting 1 was a disar illumination in optimal orientation for the line and space pattern. As expected the aerial image measured by the WLCD tool shows a high contrast (Fig. 5). Setting 2 was an annular illumination setting which is not optimal for a line and space pattern. Consequently a significantly reduced contrast in the aerial image was measured by the WLCD tool (Fig. 5). The first measurement point on the test mask has been used as anchor point to determine the threshold in the aerial image to get the target CD of 180nm on mask. From Fig. 5 it can be clearly seen that due to the reduced contrast, setting 2 has a significant smaller threshold in the aerial image compared to setting 1.

On purpose, some CD non-uniformity has been artificially built in the test mask. The CDU uniformity has been measured which each setting using the corresponding threshold from the anchor point. The CD maps of both settings are shown in Figure 6. Setting 1 (disar illumination) which is optimal for lines and spaces shows a quite smooth CD contribution. The overall mask CDU is in the range of 12.5nm ( $3\sigma$ ) in mask dimensions which corresponds to about 3.2 nm on wafer level. Setting 2 (annular illumination) shows a significantly higher CD uniformity of about 74.4 nm ( $3\sigma$ ) on mask or 18.6 nm on wafer. Clearly, such a mask in combination with setting 2 will hardly be used for printing real wafers.

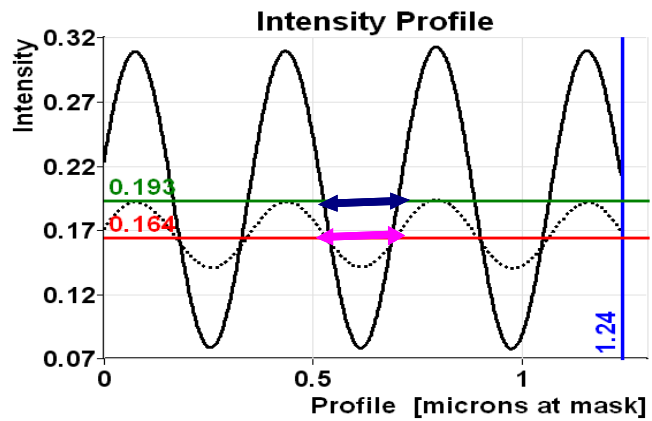


Fig. 5: Aerial Image measured by WLCD with 2 different settings. Setting 1 (solid like): disar illumination, setting 2 (dotted line): annular illumination. To achieve 180nm CD the threshold at the anchor point is different for each setting.

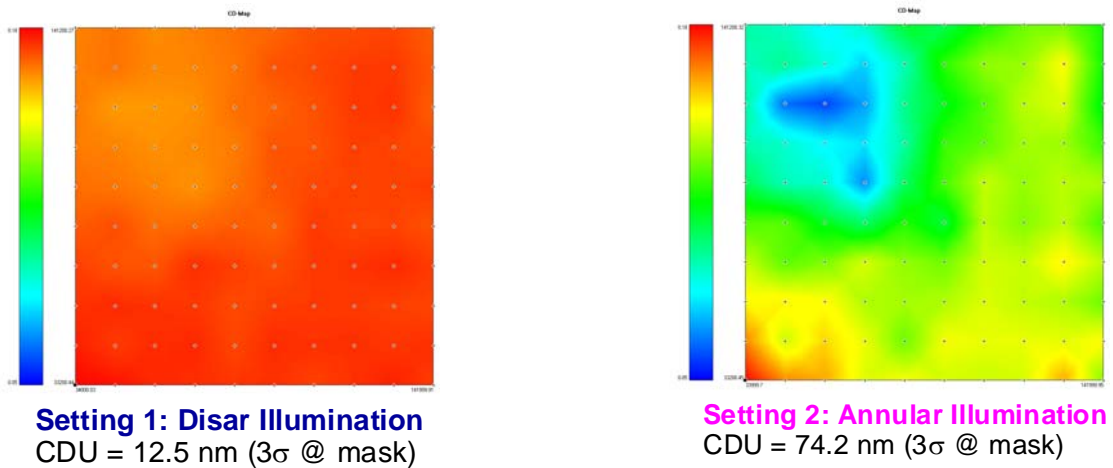


Fig. 6: CD uniformity maps of the same mask measured with different illumination settings. The colour scale is the same on both maps.

The reason for the bad CD uniformity is the increased MEEF due to setting 2 which is not optimal for line and space features. In Fig. 7 the CD values of all CD measurements points on the mask are plotted for setting 1 and setting 2. It can be clearly seen that for setting 1 the variations of the mask CD are transferred in relatively small CD non-uniformities on the aerial image. However, for setting 2 these variations are highly amplified due to the bad contrast of setting 2 (Fig. 8) which leads to high optical MEEF.

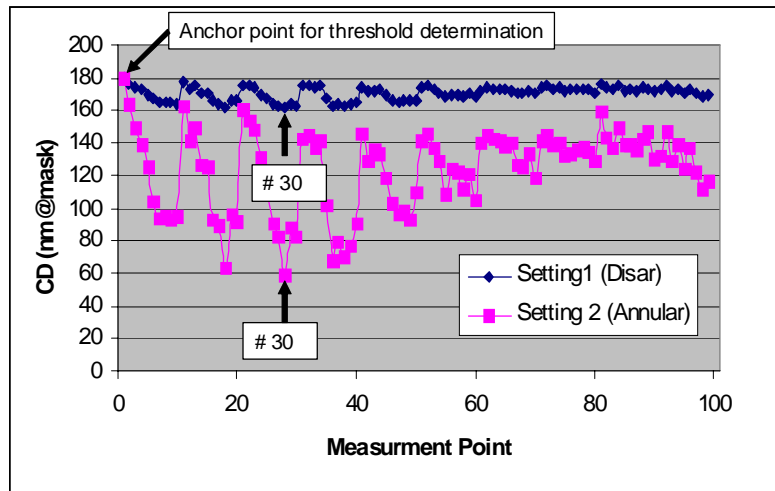


Fig. 7. Same mask measured at different settings. Measurement point #30 illustrates how mask errors are highly amplified by setting 2 .

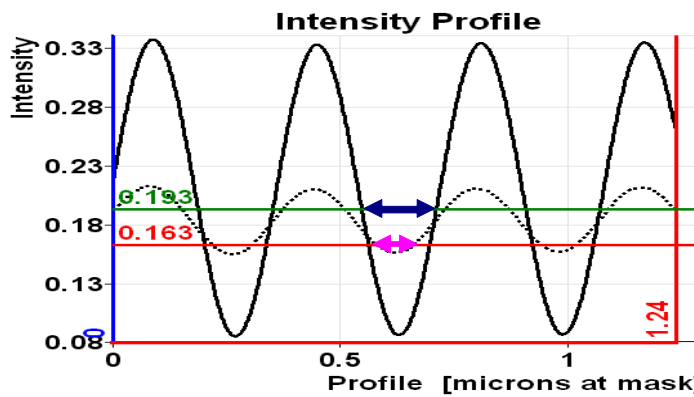


Fig. 8: Aerial image of measurement point #30 from Fig 7. The low contrast of setting 2 highly amplifies the CD error of the mask.

This example demonstrates that CD uniformity also strongly depends on the lithographic settings of the scanner. The new WLCD tool can measure this effect with high precision and repeatability. By WLCD the lithographic performance or the imaging performance of the photomask can be measured already during the mask manufacturing and no wafer prints are required.

#### 4. CONCLUSION

CD metrology on photomasks requires high throughput and excellent CD repeatability as well as in-die measurement capability on all kind of features. The newly developed Zeiss WLCD tool (“Wafer Level CD Metrology”) addresses

these requirements. Several hundred points on the mask can be measured by an aerial imaging technique under scanner conditions. In this paper the first results of the WLCD tool showed that the alpha tool already achieves a long term CD repeatability well below 1 nm in mask dimensions. Additionally, it has been demonstrated that CDU uniformity strongly depends on the scanner settings used. WLCD can measure this with high precision and repeatability.

By extending 193nm immersion lithography to 45nm and below, the photomask becomes more and more an important factor in lithography. On the one hand technologies like double patterning increase the CDU uniformity requirements, on the other side approaches like computational lithography or inverse lithography increase the complexity of the mask layout tremendously. Aggressive OPC and small assist features are needed to image small patterns. In future the mask will become more and more similar to an optical element. Therefore, it will become necessary to characterize and optimize the lithographic imaging performance of the photomask already during the mask manufacturing process. Especially, the CDU uniformity of the photomask is an important contribution to the wafer level CDU. CDU impacts device performance and, therefore, is a yield limiting factor in the wafer fab. The new WLCD tool enables the mask shops to measure wafer level CDU and the lithographic imaging performance of the mask already in the mask shop. The photomask can be optimized without the need of cost and time consuming wafer prints.

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