CD Uniformity correction on 45 nm technology Non Volatile Memory

Ute Buttgereit[a], Robert Birkner[a], Mark Joyner[a], Erez Graitzer[b], Avi Cohen[b], Hiroyuki Miyashita[c], Benedetta Triulzi[d], Alejandro Fasciszewski Zeballos[d], Carmelo Romeo[d]
[a]Carl Zeiss SMS GmbH, Carl-Zeiss-Promenade 10, 07745 Jena, Germany;
[b]Carl Zeiss SMS, 44 Maale Camon, Karmiel, 21613 Israel
[c]DPE Via C. Olivetti 2/A, Agrate Brianza (MI) 20041, Italy
[d]Numonyx Italy S.r.l Via C. Olivetti 2, Agrate Brianza (MI) 20041, Italy

ABSTRACT

One of the key parameters necessary to assure a good and reliable functionality of any integrated circuit is the Critical Dimension Uniformity (CDU). There are different contributors which impact the total CDU: mask CD uniformity, scanner and lens fingerprint, resist process, wafer topography, mask error enhancement factor (MEEF) etc.

In this work we focus on improvement of intra-field CDU at wafer level by improving the mask CD signature using a CDC200™ tool from Carl Zeiss SMS. The mask layout used is a line and space dark level of a 45nm node Non Volatile Memory (NVM). A prerequisite to improve intra-field CDU at wafer level is to characterize the mask CD signature precisely. For CD measurement on mask the newly developed wafer level CD metrology tool WLCD32 of Carl Zeiss SMS was used. The WLCD32 measures CD based on aerial imaging technology. The WLCD32 measurement data show an excellent correlation to wafer CD data. For CDU correction the CDC200™ tool is used. By utilizing an ultrafast femto-second laser the CDC200™ writes intra-volume shading elements (Shade-In Elements™) inside the bulk of the mask. By adjusting the density of the shading elements, the light transmission through the mask is locally changed in a manner that improves wafer CDU when the corrected mask is printed.

In the present work we will demonstrate a closed loop process of WLCD32 and CDC200™ to improve mask CD signature as one of the main contributors to intra-field wafer CDU.

Key words: CD, CDU, CDC, WLCD, reticle metrology, CDU correction

1. INTRODUCTION

Further extension of 193nm lithography to the next technology nodes, staying at a max NA of 1.35, pushes the lithography to its utmost limits. Various techniques are needed to drive the resolution to the theoretical limits of a k1 factor of 0.25. This leads to tremendously increased Mask Error Enhancement Factor (MEEF), which means that CD errors on mask are getting highly amplified on wafer. Mask design is getting more complex and mask specifications are tightened. Process control becomes a key factor to success to maintain a high yield in production.

One key parameter to ensure a good and reliable functionality for any integrated circuit is the critical dimension uniformity (CDU). There are different contributors which impact the intra-field CD performance at wafer such as mask CD uniformity, scanner and lens fingerprint, resist process etc. For many critical layers the main contributor to wafer intra-field CD variation is the reticle CD uniformity. In the present work we focus on improvement of intra-field CD performance by improving the mask CD non-uniformity without performing extensive wafer prints and wafer CD measurements utilizing the CDC200™ from Carl Zeiss SMS. For our demonstration we have chosen a line/space dark level of a 45nm node Non Volatile Memory (NVM) device. The mask CD uniformity was measured using the newly developed WLCD32 which measures the CD of the mask based on aerial imaging technology. This CD measurement is used as input for the CDC200™ to generate the CD correction map. To verify the successful application of the CDU correction the mask was again measured with WLCD32 and the intra-field CD uniformity improvement at wafer was predicted.

2. EXPERIMENTAL SET-UP

2.1 Mask description

The mask layout used is a line and space dark level of a Non Volatile Memory (NVM) for the 45 nm node. As illustrated in Figure 1 the full area of the reticle includes 12 identical devices, the main matrix, specified as Feature1 and 3 test patterns of the same technology specified as Feature2. The CD in the test pattern is identical to Feature 1 with the some variation in density. Within the main matrix there is a small isolated matrix, called Feature3 with the same line and space dimensions. The mask level CD of this matrix is critical in terms of loading effects during the mask fabrication process; a similar problem can in principle be expected at wafer level.

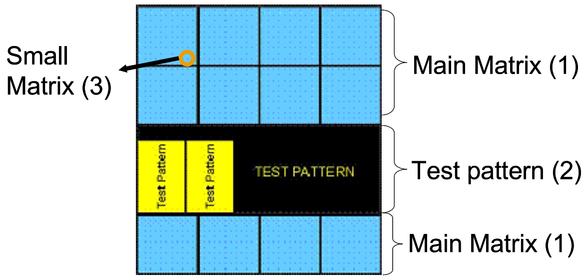

Figure 1: Schematic overview of the mask layout of the 45nm node NVM, consisting of Feature1 – Main Matrix(1), Feature2 – Test Pattern (2) and Feature3 – Small Matrix (3)

2.2 WLCD32 Aerial Image CD Measurement on mask

Zeiss' newly developed Wafer Level CD metrology system WLCD32 is based on proven aerial imaging technology. It measures the CD on the reticle in the wafer level plane as it is relevant to printing (see Figure 2) [1, 2]. By doing that it captures optical proximity effects and optical MEEF effects induced by the scanner illumination. Using the WLCD32 significantly simplifies the CD measurement especially for complex mask designs and complex 2D features.

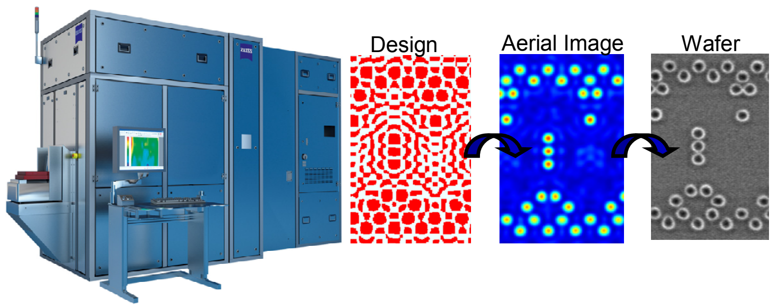

Figure 2: WLCD32 measures the CD on mask as it is relevant for printing, simplifying the CD measurement especially for complex mask design

The WLCD32 is equipped with new Zeiss 193nm imaging and illumination optics. The LITO™-grade optics has extremely low aberrations and comes close to the quality of the scanner optics. The variable NA allows measurements up to a scanner equivalent NA of 1.4. A new 193nm laser is used for ultra fast CD measurements of several hundred CD's per hour. The tool is equipped with two user defined aperture planes for off-axis illumination in order to illuminate the mask under the same conditions as a scanner. Additionally, newly developed "FreeForm Illumination" devices can be used to adopt the illumination not only in geometrical shape but also in intensity distribution. Furthermore, different polarizations (tangential, x, y) are available. Vector effects by high NA imaging can be taken into account by using Zeiss proprietary scanner mode.
For CD measurement the user can define several regions of interest within the field of view, which allows CD measurements on arbitrary features. The WLCD32 has CD repeatability below 0.25nm at wafer level.

2.3 CDC200™ - CD control

The CDC200™ process utilizes shading elements inside the mask bulk to attenuate the light during the wafer exposure. The CDC process creates small pixels that consist of QZ with a different morphology which create a slightly different refractive index (delta n). This delta n causes a small amount of scattering outside of the scanner objective pupil and hence causes attenuation.

The CDC200™ process basic set-up is described in Figure 3.

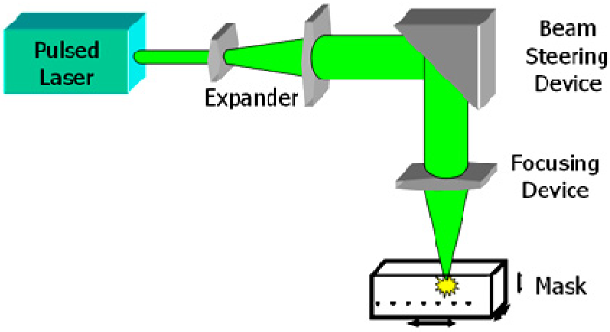

Figure 3: CDC Process: At the focal point of the laser beam a pixel is created. Quartz density is altered, and so is the local index of refraction. Each pixel acts as a scattering element.

In order to improve intra-field CDU, shading elements of specific attenuation level or pixel density are applied to each specific area in the mask. Figure 4 shows the relevant shading elements:

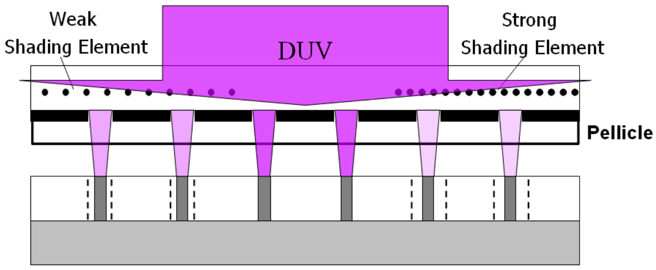

Figure 4: Applying shading elements to the mask reduces light transmission locally and effectively reduces the local dose. This causes all features to print at a CD closer to target.

The utilization of CDC200™ process was thoroughly investigated using wafer CDU data as input [3, 4, 5] and in production. In this work the use of mask CDU data as input for the wafer intra-field CD uniformity improvement is investigated.

2.4 Wafer intra-field CDU measurement

The CD target of 51nm line with a CDU 3s of 2.0nm on wafer is lithographically reached using an ASML XT 1700i exposure tool with off-axis illumination (polarized dipole). For this experiment morphological 8" flat wafers have been used with a stack of: silicon/hard mask/barc/resist/top coat.

The CD sampling at wafer level was: 408 points in Feature Group1, 85 points in Feature Group2 and 12 in Feature Group3. Two wafers have been printed and 4 fields measured on each wafer. The CD data have been averaged over 8 fields totally.

CD uniformity characterization on the printed wafer was performed using a KLA-Tencor SpectraCD-XT, taking advantage of the excellent repeatability and of the high measurement throughput of this system, ideal for high-sampling applications like scanner qualifications. Spectroscopic Ellipsometry (SE/OCD) technology provides the highest sensitivity to pattern profile changes. We estimated that metrology noise contribution of this technique to CD budget analysis was inferior to 0.1nm. Systematic CD non-uniformities as small as 0.2 nm can be easily detected and eventually corrected.

Unfortunately the measurement field of the Ellipsometry was to big compared to size of the small matrices (Feature3) that we could not take advantage of this technology. We had rather to use an in line CD SEM: Hitachi 9800.

Considering also the wafer process noise the overall repeatability for wafer CD data is 0.67nm (3sigma) as shown in Figure 5.

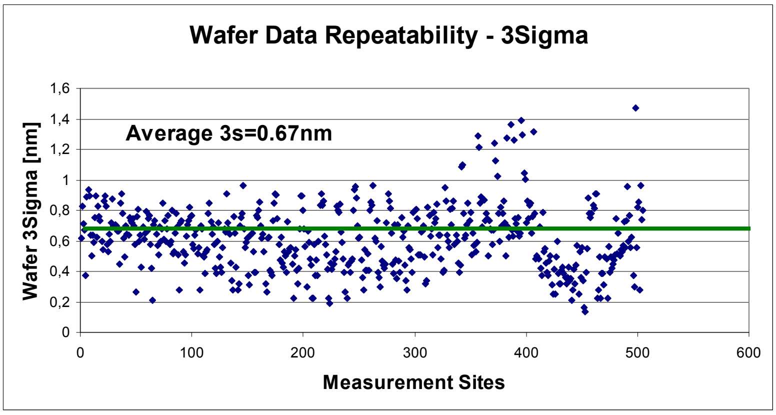

Figure 5: CD repeatability of wafer OCD data (2 wafers, 4 fields each = 8 fields totally) achieving an average 3sigma value of 0.67nm

3. CDU CORRECTION – CLOSED LOOP PROCESS

In order to align and calibrate all three processes one to the other (Numonyx lithographic process, Carl Zeiss WLCD32 measurement and CDC200™ process) the work was done in two steps:

- Step 1- Calibration step: All correlation factors and CDC Ratio (CDCR) have been derived
- Step 2- CDU correction step: The process was applied on full mask using the calibration data derived in step 1

3.1 Calibration step

The calibration step was done at Feature1 on two chips out of the whole mask area using the following:

1. Printing calibration mask and measure CD data using OCD tool as described in section 2.4 – Numonyx
2. Measuring the same locations on WLCD32 with the same illumination settings as the scanner – Zeiss Jena
3. Appling different attenuation levels from 0.5% to 3 % in 0.5% steps as described in Figure 6 - Zeiss Israel
4. Re-measure CD (post CDC) in the same locations by the WLCD32 system – Zeiss Jena
5. Wafer print and re-measure CD data (post CDC) – Numonyx

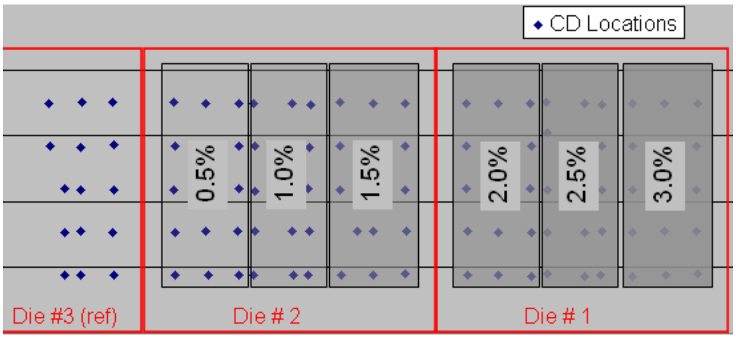

Figure 6: The CD locations (dark points) and the applied attenuation levels in the two selected calibration dies

In the calibration step the CD measurement was limited to Feature1. Exactly the same locations have been measured on wafer using OCD and on the mask using WLCD32. The results from the above measurements are shown in Figure 7. Figure 7a shows an excellent correlation with R^2 of 0.82 between the WLCD32 and wafer CD. The WLCD32 measures CD of the mask in the aerial image and does not consider MEEF effects caused by the resist. This explains the difference in the magnitude of the CD Uniformity (CDU) [wafer CDU =1.64 WLCD CDU]. The correlation factor of 1.64 will be used to predict the pre CD data at wafer based on the measured WLCD32 data correctly. Figure 7b shows the CD change (delta CD) vs. applied attenuation. A very similar CDC Ratio (CDCR=0.6) can be seen in both, wafer based data and WLCD32 data. The wafer CD outlier data shown at 1% attenuation was confirmed as a wafer CD measurement error and was excluded from the calculations.

The derived calibration factors can be stored in a library and re-used for similar layer and lithography process.

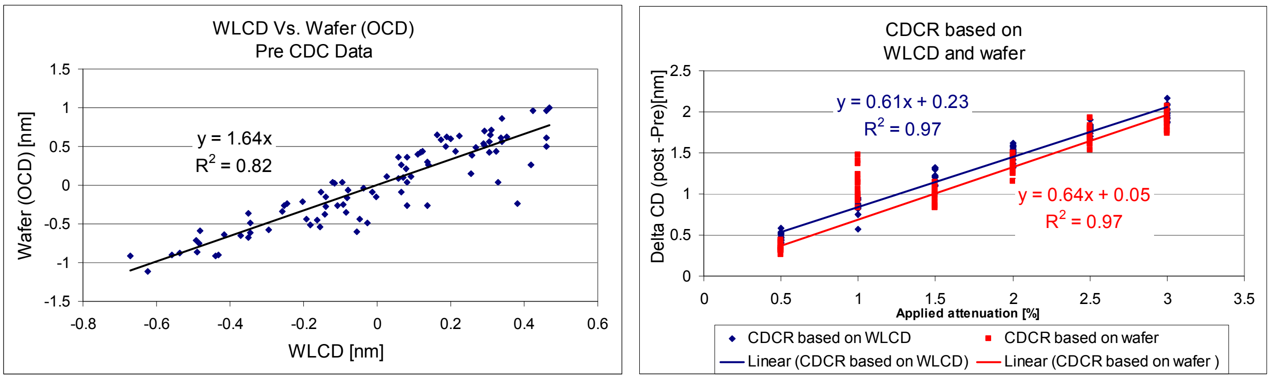

Figure 7 a (left): Correlation between wafer CD and WLCD32 measured CD on the same locations. Figure 7b (right): The wafer based and WLCD32 based CDC ratio (CDCR)

3.2 CDU correction step

In the calibration step all required calibration factors as pre-/post correlation factor between WLCD32 data and wafer data and CDC ratio have been derived. After completing the calibration step the actual mask, an active 45 nm node layer of a Non Volatile Memory device, was processed with the CDC200™. Three different features have been considered: Feature1, Feature2 and Feature3. For comparison and process verification the actual mask was measured at the same locations in terms of intra-field CD uniformity using WLCD32 on mask and OCD on wafer (see section 2.4), both before and after CDC200™ process application.

The first essential step before CDC200™ treatment is to measure the CD non-uniformity of the mask using the WLCD32. Identical illumination conditions as for the scanner have been applied for the measurement. The threshold was set to a target CD of 51nm and equal lines and spaces have been realized in the aerial image. For each measurement site the CD was averaged over 9 ROI's (region of interest) in the FoV (field of view) and totally 3 repeats have been performed. As shown in the left graph of Figure 8 the WLCD32 provides an average 3sigma repeatability of 0.19nm at wafer level. The right graph of Figure 8 shows the measured mean to target CD distribution for the 3 different features over the mask.

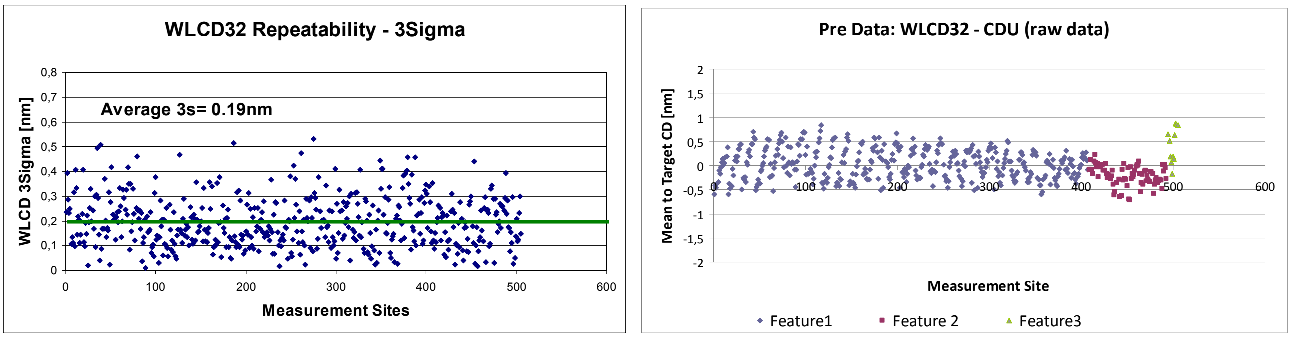

Figure 8: Left: CD repeatability for WLCD32 over 3 repeats achieving an average 3sigma value of 0.19nm (wafer level). Right: WLCD32 CD uniformity measurement results over the mask covering 3 different feature types

The WLCD32 measures the CD of the mask in the aerial image. This means that resist effects are not considered. The wafer data have been measured in resist using OCD, the resist effects are of course included. Due to this fact we expect a higher variation in CD uniformity for the wafer data compared to the WLCD32 raw data. This can be seen in Table 1. As shown in the calibration step the correlation between WLCD32 and wafer data is linear. The calibration factor between wafer and WLCD32 data is 1.64 [wafer CDU =1.64 WLCD CDU] and represents mainly the resist effects. To predict the wafer data based on the WLCD32 measurement data correctly the raw data needs to be scaled by this calibration factor. Figure 9 shows that there is an excellent match between wafer data and WLCD32 data after applying the calibration factor. There is a slight off-set for Feature2, which was not completely understood. A possible reason is the variation in density for Feature2. Some further investigation is necessary.

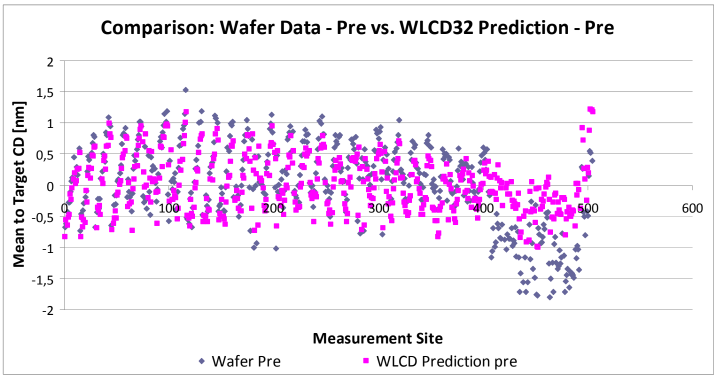

Figure 9: Comparison between wafer data and WLCD32 prediction (raw data + calibration)

Table 1 summarizes the CD uniformity data at wafer level as range and 3 sigma values for the 3 different feature types, showing that the CD non-uniformity is in the same range for the WLCD32 prediction and wafer data. Please note that the average 3sigma repeatability for the wafer measurement was in the range of 0.7nm (see Figure 5), for the WLCD32 in the range of 0.2nm (see Figure 8).

CD uniformity [nm at wafer]	Data Source	Feature 1	Feature 2	Feature 3
Range	WLCD32 raw data	1,43	0,94	1,05
	WLCD32 prediction	2,01	1,32	1,46
	Wafer OCD	2,54	1,54	1,35
3 sigma	WLCD32 raw data	0,93	0,60	1,10
	WLCD32 prediction	1,30	0,84	1,54
	Wafer OCD	1,43	1,14	1,46

Table 1: CD uniformity data (range, 3sigma) for three different feature sites on the mask measured on WLCD32 (raw data), WLCD32 prediction (raw data scaled with calibration factor) and OCD wafer data

The WLCD32 CDU data have been scaled using the correlation factor (wafer prediction) and used as CD input for the CDC200™ as shown in Figure 10a. The required attenuation level (Figure 10b) was calculated using the CDC ratio as derived in the calibration step.

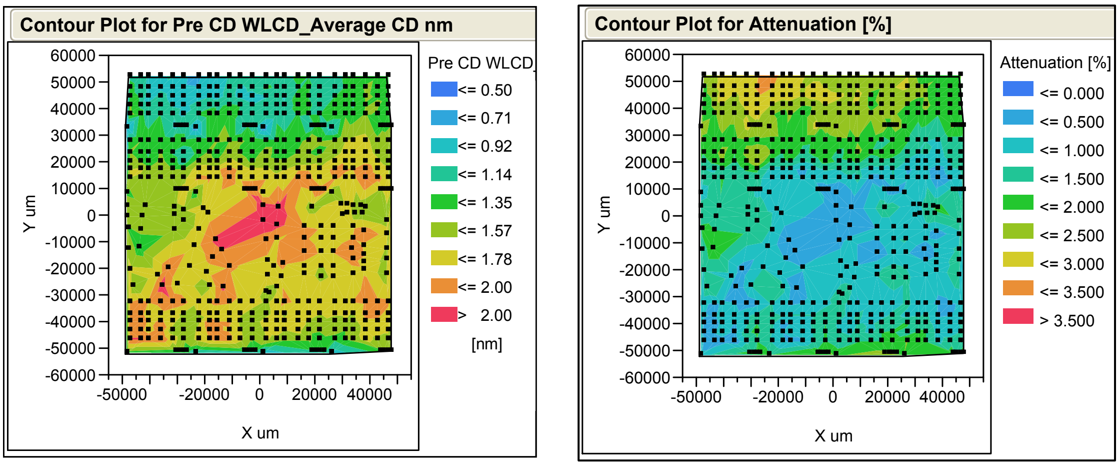

Figure 10 a (left): the mask CDU error converted to wafer, Figure 10b (right): The required attenuation level for this CDU error.

After the CDC200™ process is applied the CDU correction needs to be verified. This is done by measuring the mask again with the WLCD32, applying the same illumination conditions as for the scanner. To predict the wafer data correctly the WLCD32 raw data are scaled with calibration factor derived in the calibration step. Figure 11 shows very impressively that the CD uniformity is significantly improved for all three feature groups after applying the CDC200™ process.

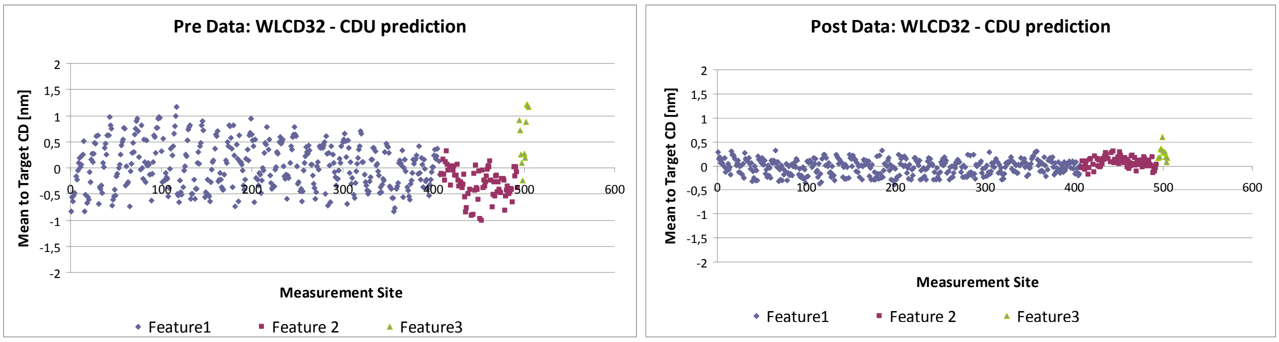

Figure 11: WLCD32 CD uniformity data prediction (raw data + calibration factor) for 3 different features: Left: before CDC200™ process, Right: after CDC process. A significant improvement in CD intra-field variation was achieved.

Table 2 summarizes the CD intra-field uniformity before and after CDC200™ treatment for the WLCD32 prediction and the OCD measured wafer data. For WLCD32 an improvement in CD uniformity of about 65% has been predicted for all features, for the wafer data an improvement of about 50% was measured. There have been 6 outliers identified in Feature group2 and 1 outlier in Feature group3 which showed a systematic error in wafer data. These outliers have been excluded in the analysis.

If we look at the CD uniformity data measured at wafer after CDC200™ treatment (Table 2) we see that the 3sigma intra-field CD uniformity is between 0.47nm and 0.71nm. On the other hand, the repeatability for the wafer data is in the range of 0.7nm (3sigma). Looking at both values we see that the achieved intra-field CD uniformity is in the same range as the 3sigma repeatability of the wafer data (process + measurement). In other words the intra-field CD uniformity has been improved down to the noise level of the wafer process. We would not have been able to measure a further improvement. It was proven by wafer prints that the CDC200™ process was successfully applied.

CD uniformity [nm at wafer]	Data Source		Feature 1	Feature 2	Feature 3
Range	WLCD32	Pre (prediction)	2,01	1,32	1,46
		Post (prediction)	0,70	0,49	0,52
		Improvement	65%	63%	65%
	Wafer OCD	Pre	2,54	1,54	1,35
		Post	1,33	0,90	0,65
		Improvement	48%	41%	52%
3 sigma	WLCD32	Pre (prediction)	1,30	0,84	1,54
		Post (prediction)	0,46	0,31	0,42
		Improvement	65%	63%	72%
	Wafer OCD	Pre	1,43	1,14	1,46
		Post	0,71	0,64	0,47
		Improvement	50%	44%	68%

Table 2: CD uniformity (range, 3sigma) before and after CDC200™ process based on WLCD32 prediction (raw data scaled with calibration factor) and OCD wafer data, improvement of ~65% respectively ~50% was achieved.

4. DISCUSSIION

In present work we investigated the feasibility of applying the CDC200™ process to improve the intra-field uniformity without performing extensive wafer prints and wafer CD measurements. The study was carried out in two steps:

- Calibration step
- CDU correction step

The mask CD uniformity data required as input for CDC200™ have been measured using the WLCD32, which measures the CD based on aerial imaging. For correlation and verification wafer prints have been performed in all steps.

In the calibration step the correlation between WLCD32 data and wafer data was investigated. The correlation between WLCD32 data and wafer data is linear; the regression coefficient represents mainly the resist effects. The calibration factors are required to predict the intra-field wafer data correctly. The CDC ratio has also been derived in the calibration step and represents the result in CD change as function of the applied attenuation level. Our proposal is to store the calibration factors, pre/post calibration factor WLCD32 vs. wafer and CDC ratio, in a library, so that they can be re-used for the same litho process without performing wafer prints again.

Furthermore, it was shown that the WLCD32 can predict the wafer data correctly. The scaled WLCD32 data can be used as input for the CDC200™ process. Based on this input data the CDC200™ can successfully improve the CD uniformity of the mask by applying a dedicated attenuation map. This can be verified by measuring the mask after the CDC200™ process using again the WLCD32. All data have been verified by wafer prints. The wafer prints confirmed an intra-field CDU improvement of about 50% (3s).

Based on the current investigation we propose a mode of operation according to Figure 12 for the closed loop between WLCD32 and CDC200™ to improve the CDU performance of the mask.

This process can be applied in any captive or merchant mask shop.

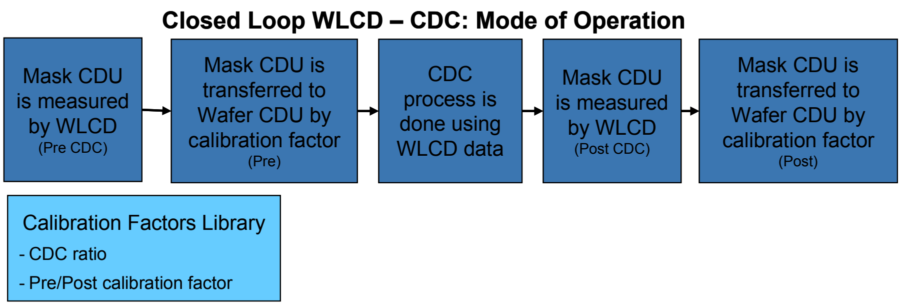

Figure 12: Proposed mode of operation for the closed loop WLCD – CDC process

5. SUMMARY AND CONCLUSION

In this work the strategy to correct mask CD non uniformity, using the CDC200™ process without printing wafers, was evaluated. The mask CDU was measured by the WLCD32 system and this data was used as input for the CDC200™ process. The WLCD32 shows excellent correlation to the wafer data. Post CDC wafer results confirmed that the intra-field CDU was significantly improved by more than 50% to below 1nm (3sigma) while using the WLCD32 data as input. This work proves that mask CDU can be improved in the mask house without the need of wafer prints by using the CDC200™ technology in combination with the WLCD32 system as metrology tool. This solution is optimal suited to be used in captive and merchant mask shops for improving or achieving mask CD performance.

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