Process Window improvement on 45 nm technology Non Volatile Memory by CD uniformity improvement

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ABSTRACT

For the next years optical lithography stays at 193nm with a numerical aperture of 1.35. Mask design becomes more complex, mask and lithography specification tighten and process control becomes more important than ever. Accurate process control is a key factor to success to maintain a high yield in chip production.

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 wafer CDU: mask CD uniformity, scanner repeatability, resist process, lens fingerprint, wafer topography 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 proven aerial imaging technology. The WLCD32 measurement data show an excellent correlation to wafer CD data. For CDU correction the CDC200™ tool is used which utilizes an ultrafast femto-second laser to write intra-volume shading elements (Shade-In Elements™) inside the bulk material 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. Furthermore we will show that the process window will be significantly enlarged by improvement of intra-field CDU. An increase of 20% in exposure latitude was observed.

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

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 required to drive the resolution to the theoretical limits. The k1 factor comes close to 0.25 which leads to a tremendously increased Mask Error Enhancement Factor (MEEF). This means that CD errors on mask are getting highly amplified on wafer. Process control becomes a key factor to success to maintain a high yield in production.

One key parameter to ensure a high 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 fingerprint, resist process etc. In the present work we focus on improvement of mask CD signature which is one of the main contributors to intra-field CD uniformity. The mask CD uniformity has been measured by WLCD32 which measures the CD based on proven aerial image technology. Based on this CD input the CD uniformity was corrected by CDC200™ and afterwards verified by WLCD32 measurement. Additionally, the impact of the improved CD uniformity on the lithography process window was investigated. Goal of the work is to establish a process flow for mask CD uniformity improvement based on mask CD metrology by WLCD32 and mask CD uniformity control by CDC200™ and to verify its impact on the lithography process window.

2. EXPERIMENTAL SET-UP

2.1 Mask description and wafer exposure

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 Feature 1 and 3 test patterns of the same technology specified as Feature 2. The CD in the test pattern is identical to Feature 1 with 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 mask fabrication process. In principle, a similar problem can be expected at wafer level.

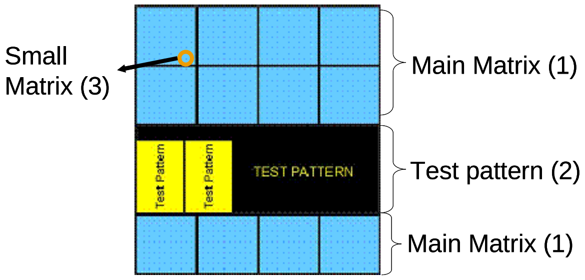

Figure 1: Schematic overview of the mask layout of the 45nm node NVM, consisting of Feature1 – Main Matrix(1), Feature2 – Test Pattern (2) and Feature3 – Small Matrix (3)

The wafer exposure was done at ASML scanner XT 1700i, using a NA of 1.2 and sigma inner/outer of 0.65/0.85. A 60° dipole illumination with polarization was applied.

The CD target on wafer is 51nm. For this experiment morphological 8” flat wafers have been used with a stack of: silicon/hard mask/barc/resist/top coat. Two wafers have been printed and 4 fields have been 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.

2.2 Mask Metrology - WLCD32 Aerial Image CD Measurement

Zeiss 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. The use of the WLCD32 significantly simplifies the CD measurement especially for complex mask designs and complex 2D features.

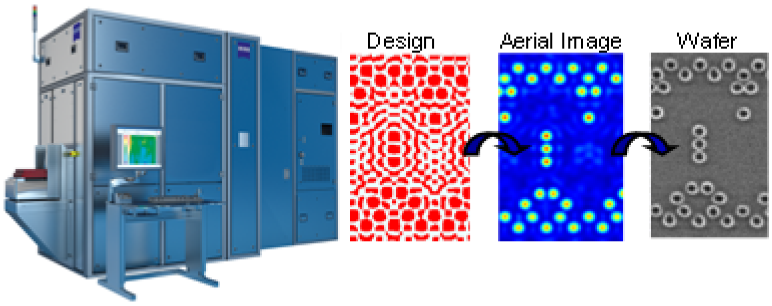

Figure 2: WLCD32 measures the CD on mask as it is relevant for printing, simplifying the CD measurement especially for complex mask design

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 CD Control - CDC200™

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.

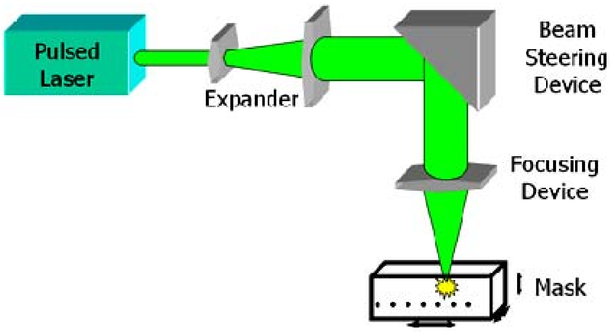

Figure 3: CDC Process: At the focal point of the laser beam a pixel is created. Quartz density is altered, and so is the local index of refraction. Each pixel acts as a scattering element.

In order to improve intra-field CD uniformity, 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:

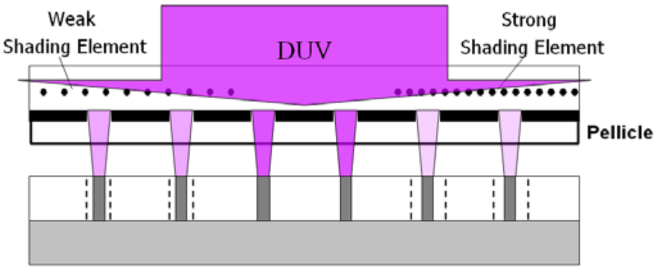

Figure 4: Applying shading elements to the mask reduces light transmission locally and effectively reduces the local dose. This causes all features to print at a CD closer to target.

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

3. CD UNIFORMITY IMPROVEMENT

The CDU tuning was performed with CDC200™ using WLCD32 mask metrology data as input. To maximize the intra-field CD uniformity improvement on wafer a calibration step was applied and the process was split into two steps:

- Calibration step
- CD uniformity correction step

In the calibration step the calibration factors between WLCD32 aerial image CD and wafer data as well as the CDC ratio, which determines the CD change as function of applied attenuation, have been derived. The derived calibration factors can be stored in a library for future process use.

The CD uniformity correction step utilizes the CDC200™ based on the WLCD32 data scaled with the calibration factor. The closed loop WLCD32/CDC200™ process flow it schematically shown in Figure 5. The complete process is described in more detail in an earlier paper [6].

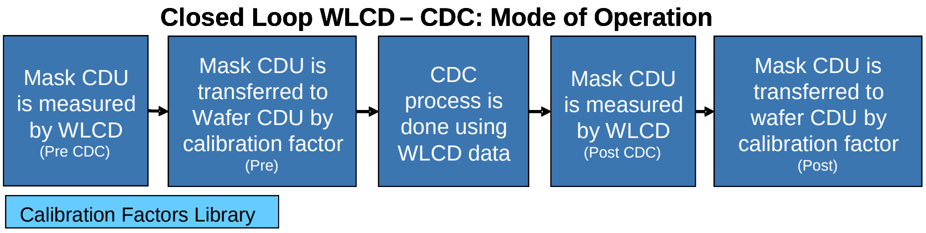

Figure 5: Proposed mode of operation for the closed loop WLCD – CDC process

Figure 6 shows a high-quality linear correlation of WLCD32 to wafer data measured by scatterometry with a R² value above 0.85. Due to the fact that WLCD32 captures the CD in the aerial image plane and not in the resist, we expect a slope which is larger than 1. The derived slope shows a value of 1.4 and represents mainly resist MEEF effects. Furthermore, the WLCD32 provides an excellent CD repeatability of average 3sigma of 0.19nm (wafer level) compared to average 3sigma of 0.67nm for the wafer data. For WLCD32 three repeats have been taken, whereas for the wafer data two wafers with 4 fields each have been exposed and the CD has been averaged over 8 fields totally. The exceptional CD repeatability of WLCD32 is one of the benefits compared to wafer data CD uniformity input and becomes especially important if the required CD uniformity goes below 3nm at wafer level. The comparison in CD repeatability for the WLCD32 and wafer scatterometry is demonstrated in Figure 7.

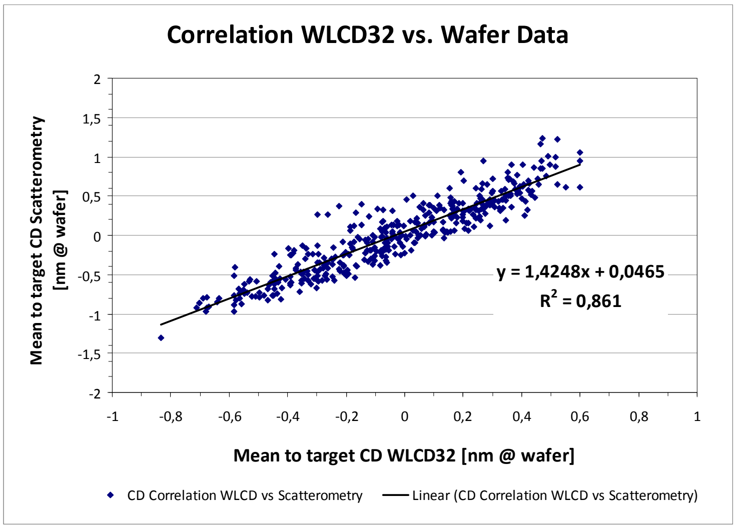

Figure 6: Excellent correlation between WLCD32 aerial image CD and wafer data measured by scatterometry

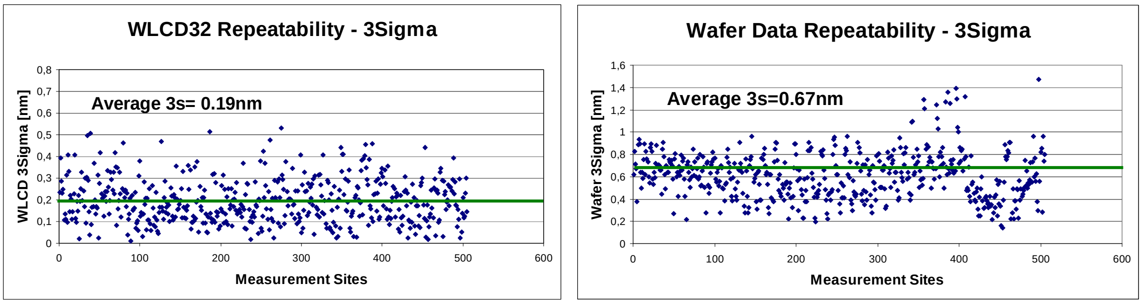

Figure 7: WLCD32 shows an excellent repeatability of average 3sigma of 0.19nm (wafer level) compared to 0.67nm for the wafer scatterometry data

The scaled CD uniformity data measured by WLCD32 have been used as input for the CDC200™ and the required attenuation map to flatten the CD signature was calculated and applied to the actual mask (see Figure 8).

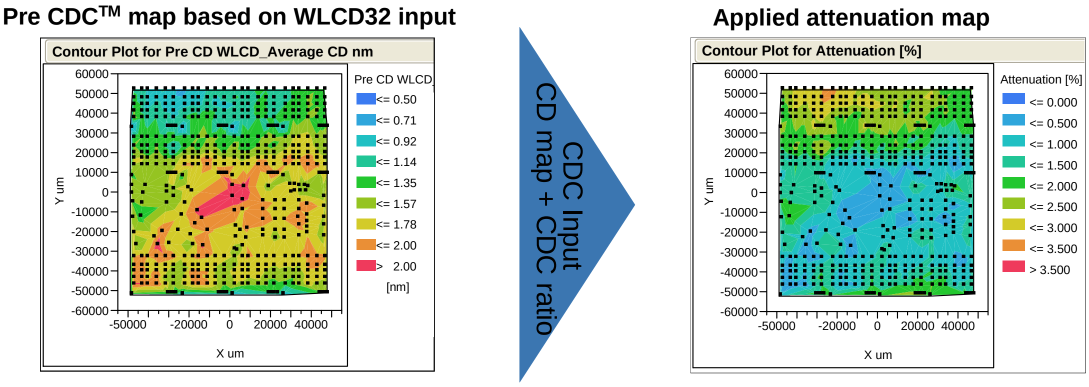

Figure 8: CD uniformity map measured by WLCD32 and applied attenuation map at CDC200™

Figure 9 shows impressively that the CD uniformity was significantly reduced for all 3 features groups applying the CDC process. The overall 3sigma uniformity was reduced from 1.36nm to 0.47nm, which is about 65% improvement. We like to emphasize that so far all CD data used for the CDC process are based on mask metrology only utilizing the WLCD32. To verify the validity of the WLCD32 data wafer prints have been performed, exposing 4 fields on 2 wafers. The CD's at exactly the same measurement positions have been measured applying optical scatterometry and averaging over 8 fields.

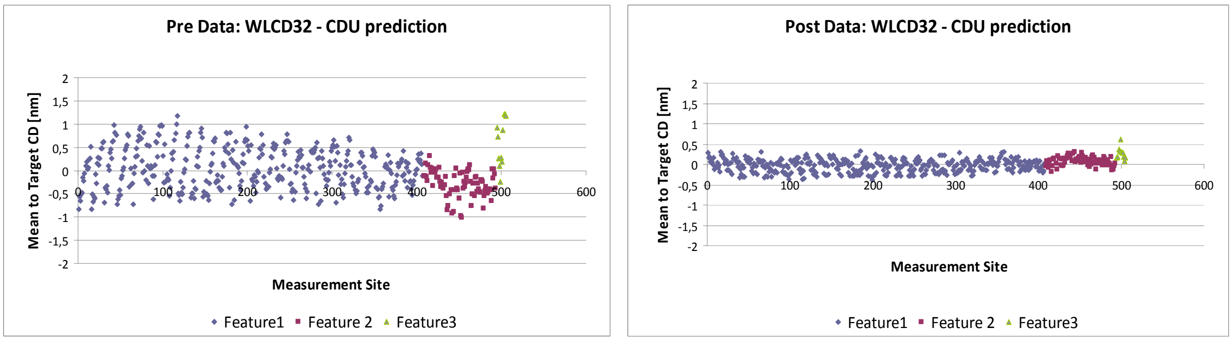

Figure 9: WLCD32 predicted CDU before (left) and after CDC process (right) shows significant CDU improvement

The extraordinary match between WLCD32 data and wafer data for both, pre CD uniformity and post CD uniformity for all three feature groups is shown in Figure 10. Again, we like to point out that the CD repeatability of the wafer data is in the range of 0.67nm. The wafer data confirm that the CDU was improved down to noise level of the wafer process by applying the CDC process. The achieved CDU improvement for each feature group is about 50%. The dedicated numbers for each feature group and each data set are summarized in Table 1.

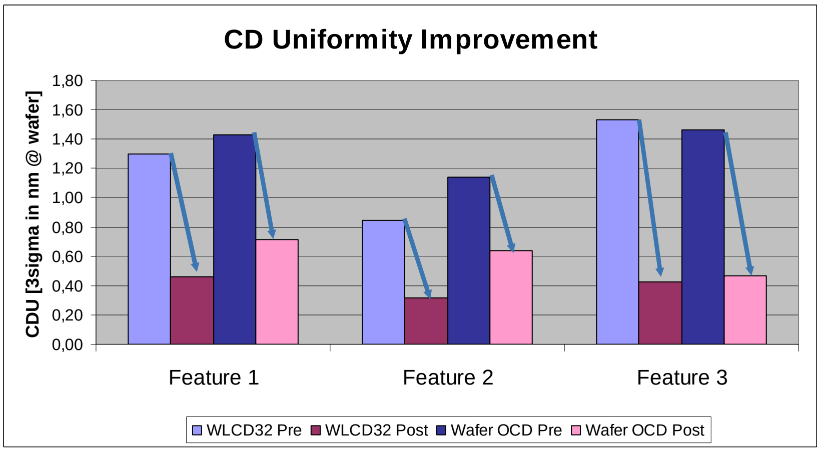

Figure 10: Validation of WLCD32 pre and post CDU data by wafer prints

Data Source	**CD Uniformity (3sigma) [nm at wafer]**	**Feature 1**	**Feature 2**	**Feature 3**
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 1: Pre and post CDU data measured on mask by WLCD32 and on wafer by scatterometry showing verifying a reduction in CDU down to the wafer noise level (wafer CD repeatability 0.67nm)

The demonstrated data sets verify nicely that the closed loop process WLCD32/CDC200™ as proposed in Figure 5 can be successfully applied. Furthermore, we like to emphasize that the closed loop process can be applied in any captive or merchant mask shop. Additionally, the process can be used for memory and logic devices as well as reported in an earlier work [7].

4. PROCESS WINDOW INVESTIGATION

Next the impact of CD uniformity improvement on lithography process window was investigated. The wafer exposure was done at ASML scanner XT 1700i, using a NA of 1.2 and sigma inner/outer of 0.65/0.85. A 60° dipole illumination with polarization was applied. As mentioned earlier for the experiment morphological 8" flat wafers have been used with a stack of: silicon/hard mask/barc/resist/top coat.

The focus exposure matrix has been performed in dose steps (column steps) of 1mJ/cm² around a central dose of 14mJ/cm² and in focus steps (row steps) of 0.04µm around a central focus of -0.08µm.

First we looked into the Bossung plots. For the Bossung plots totally 100 different locations have been measured representing all 3 feature groups. We concentrated on the CD distribution through focus for the different locations. Figure 11 shows as example the Bossung curves for feature group 2. Please note, that the Bossung curves have been taken at a fixed dose of 13mJ/cm² and each Bossung curve represents a different measurement location within feature group 2. It becomes very obvious that the spread in the Bossung curves has been significantly tightened after CDC process and CD uniformity improvement. The CD variation through focus for each measurement location has significantly been improved. This enhances the CD stability through focus and allows for a more relaxed focus control.

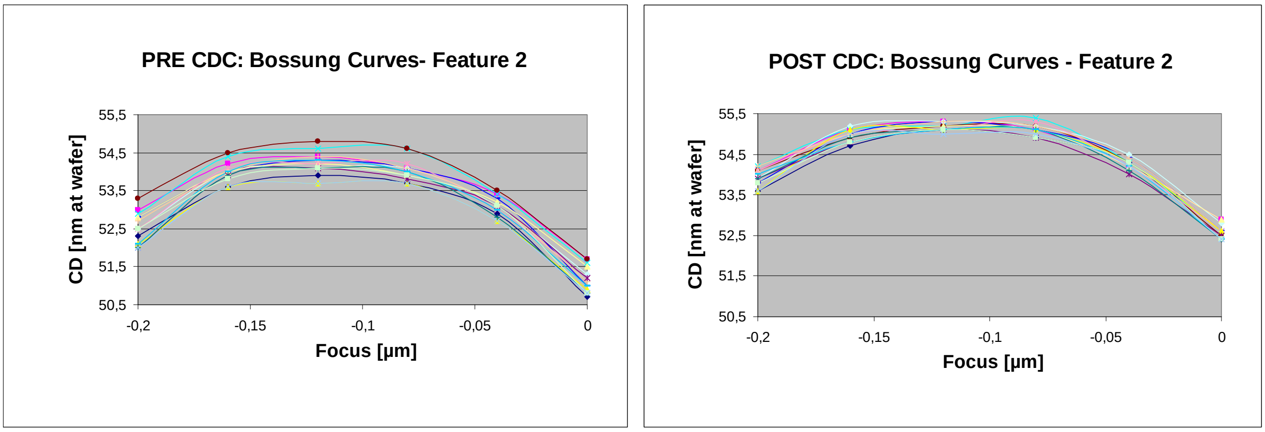

Figure 11: Bossung plots at a fixed dose of 13mJ/cm², each Bossung curve represents a different location within feature group 2. The spread in the Bossung curves is much tighter for post CDC (right) compared to pre CDC (left)

The improved CD variation through focus becomes more ovious, if we plot the 3sigma CD variation for all locations measured in feature group 2 over focus. Figure 12 demonstrates an improvement of CD variation though focus by about 50%. This is an important result which leads to an enhanced focus behavior, improved process control and finally enlarged process window.

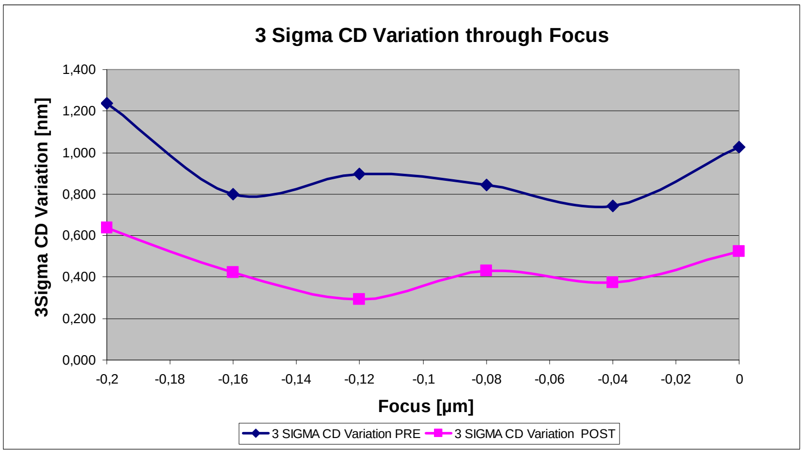

Figure 12: 3sigma CD variation through focus for the measurement locations within feature group 2 before and after CDC process

Finally, we looked into the lithography process window analyzing the exposure vs. defocus behavior for all three feature groups. The lithography process window, exposure vs. focus, is plotted in Figure 13.

If we fit a rectangular process window into the graph the maximum lithography process window before CD uniformity improvement is at 0.17µm Depth of Focus (DoF) and 7.4% exposure latitude. After CD uniformity improvement the maximum process window is enlarged to 0.19µm DoF and 8.1% exposure latitude. That means that CD uniformity improvement leads to an extension of both, exposure latitude as well as DoF.

If we fix the DoF at 0.17µm the exposure latitude before CD uniformity improvement is 7.4%, after CD uniformity improvement 8.9%. This is an improvement of 20% in exposure latitude which is extremely significant to process control.

Overall, the improvement in lithography process window leads to an improved process control and finally to an enhanced yield in chip production.

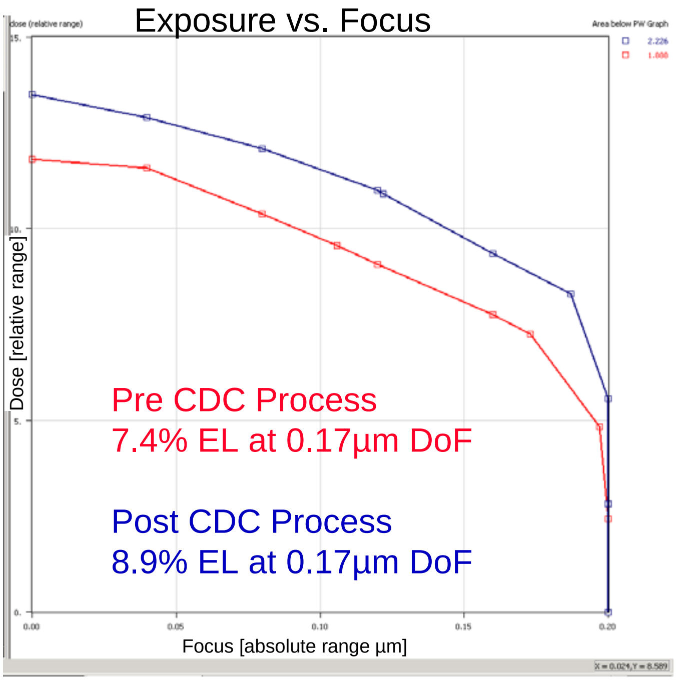

Figure 13: Lithography Process Window over all 3 features groups showing an improved process window after CDC treatment (blue curve)

5. SUMMARY AND CONCLUSION

In the present work we have focused on intra-field CD uniformity improvement by improving mask CD signature utilizing WLCD32 for mask CD metrology and CDC200™ for CD uniformity control. Furthermore, the impact of CD uniformity improvement on the lithography process window was investigated.

It was shown that the WLCD32 has an excellent correlation to wafer and an outstanding CD repeatability of below 0.25nm at wafer level. The WLCD32 provides a reliable input for CD uniformity correction and is the tool of choice to verify the CD uniformity improvement after CDC200™ treatment. This was finally validated by wafer-prints.

Furthermore, it was shown that the CDC200™ improves the CD uniformity significantly. The intra-filed CD uniformity was reduced by 50% down to the noise level of the wafer process. The final validation by wafer-prints confirms the viability of the closed loop solution WLCD32/CDC200™. This solution is optimal suited to be used in captive and merchant mask shops to control the mask CD performance without the need of wafer-prints.

Additionally, the impact of CD uniformity improvement on the lithography process window was investigated. It was worked out that the CD uniformity correction yields to an improved CD behavior through focus. Moreover, the CD uniformity improvement enlarges the exposure latitude by 20% and increases the overall process window.

Concluding, the CD control based on the closed loop WLCD32/CDC200™ expands the common lithography process window and leads finally to a better wafer yield.

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