PHOTOMASK

BACUS—The international technical group of SPIE dedicated to the advancement of photomask technology.

BACUS NEWS

OCTOBER 2011
VOLUME 27, ISSUE 10

EMLC 2011 Invited Paper 7985-19

Mask Tuning for Process Window 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 specifications tighten. 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 more important than ever. Accurate process control is a key factor to success to maintain a high yield in chip 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. The CDC200™ tool 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.

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. The proposed process flow will be validated by wafer prints.

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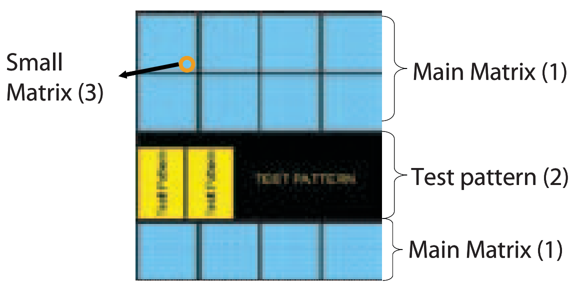

Figure 1. Schematic overview of the mask layout of the 45nm node NVM, consisting of Feature1 – Main Matrix(1), Feature2 – Test Pattern (2) and Feature3 – Small Matrix (3).

TAKE A LOOK INSIDE:

SPIE

Editorial

No substitute for Innovation .....

Frank E. Abboud, Intel Mask Operation, Santa Clara, CA USA

As I look back at last week's Photomask Lithography conference "BACUS" 2011, I am excited about what our wonderful, and sometimes crazy, mask community and lithography engineers have come up with. It never ceases to amaze me how last years' problems are now passé and quickly forgotten, or how the solutions that were thought of as being impossible are now generally accepted, adopted and are the norm rather than the exception. For example, shifting patterns to avoid EUV blank defects, Cr migration and MoSi Oxidation and general confidence in EUV mask manufacturing. Equally innovative or even more daring are the mask equipment engineers and scientists. Without them, neither would our business have advanced to the level it has reached today, nor would the Mask have advanced in importance to being an essential and vital part of the semiconductor industry. We took the Mask from a commodity in the nineties to an enabler in the early 2000's, to an integral part of the optical path in the late 2000's, and now possibly an integral part of the future lithography solution decision. Seeing the Mask on the short list of the EUV Lithography solution obstacles list both pleases and worries me. It is excellent that the lithography engineers are thinking ahead, but it is also worrisome as we, the mask makers, may become the cog in the wheel for EUV. It is Mask innovation that will chart the path for next lithography paradigm!

I spent a good portion of my career in mask equipment and had the pleasure of working alongside many great innovators in the mask equipment and interacting with mask makers. I later had the opportunity for a role reversal, where I worked alongside many great innovators in mask making and interact with equipment makers. I have to say, the challenges, the deadline pressures, the fear of the competitor outsmarting you, the customer's unrealistic demands, the market uncertainty, the cost pressures are all there. Everyone has a customer and everyone has a supplier! (I hope I am speaking on behalf of many of my fellow engineers, both equipment and mask making). A sure thing for winning has always been and will continue to be innovation! The ability to create a positive change by creating something new within the constraints on hand that allows for a better, faster, and cheaper way has no substitute.

The key operative word is "within the constraints". Often it is unrealistic to start over with a clean slate. We are all taught to work harder, be more efficient, improve the process incrementally and increase yield and process Cpk, etc. All are good, but none will create a step function improvement! The world is full of such examples where innovation is the only way to do it. Consider the creation of the gas engine. No matter how diligent the process improvement and manufacturing efficiencies of the steam engine, they pale in comparison to the step function improvement of the gas engine. Similarly, in our industry, no efficiencies in binary mask would have matched or even come close to the benefits of a Phase shift mask. This goes to show that innovation, innovation, and innovation is the engine that keeps our mask industry going.

I am impressed with our collective ability, as a mask industry, to achieve data treatment, blanks, resist material, mask writers, inspection and metrology to be able to meet and exceed the wafer Lithography expectations! I am impressed with all the new mask types that are being invented in support of double patterning, quadruple patterning and EUV. Honestly, I am not sure how we do it in such organized and timely manner, but I have to guess it is all about innovation!

BACUS

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BACUS News is published monthly by SPIE for BACUS, the international technical group of SPIE dedicated to the advancement of photomask technology.

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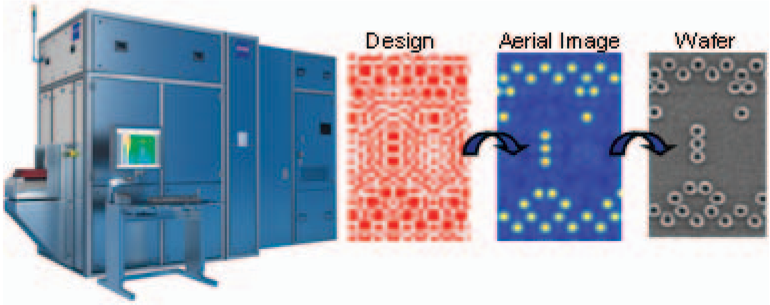


Figure 2. WLCD32 measures the printing relevant CD on mask and simplifies the CD measurement especially for complex mask design.

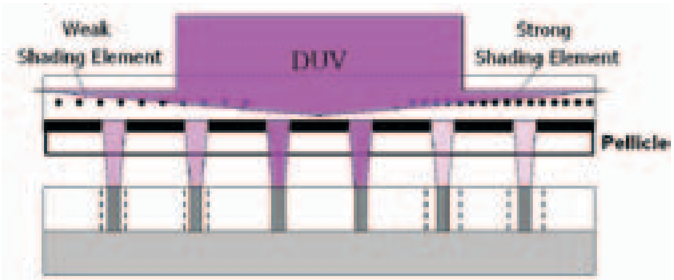


Figure 3. Applying shading elements to the mask reduces light transmission locally and effectively reduces the local dose. This causes all features to print at a CD closer to target.

It was shown that the WLCD32 has an excellent correlation to wafer data and an outstanding CD repeatability. It provides a reliable input for CD uniformity correction and is the tool of choice to verify the CD uniformity improvement after CDC200™ treatment.

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 optimally 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.

1. Introduction

Extending 193nm lithography to the next technology nodes and keeping 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 concentrate on improvement of mask CD signature as one of the key 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. Furthermore, the impact of 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 consists of a 45nm node line and space dark level of a Non Volatile Memory (NVM). 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 Feature 3 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.

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 target CD at 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.

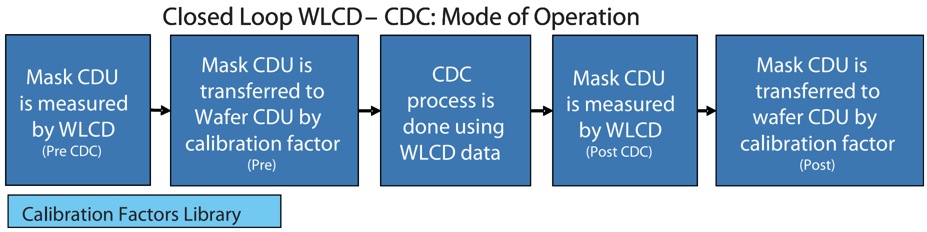


Figure 4. Proposed mode of operation for the closed loop WLCD – CDC.

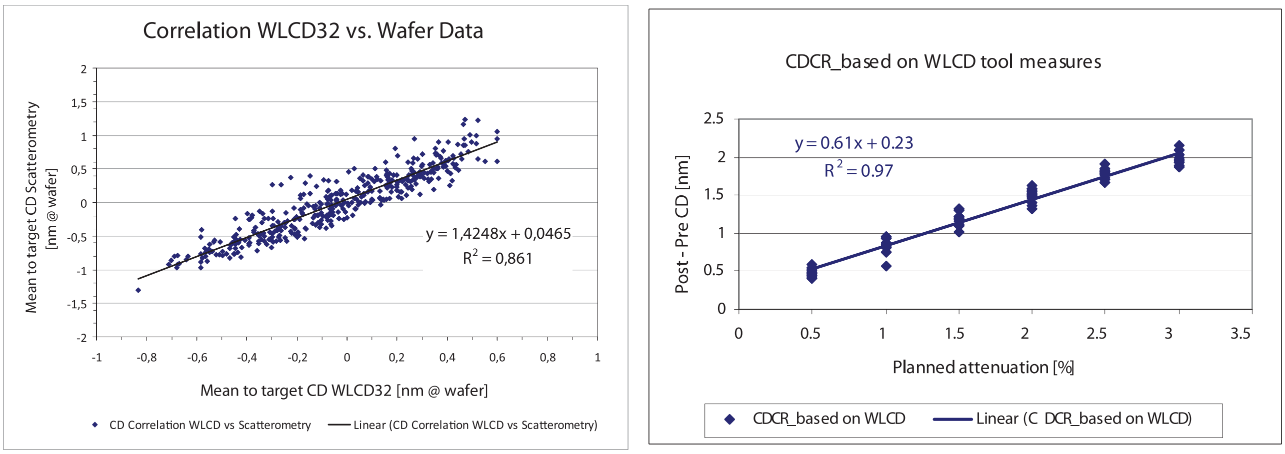


Figure 5. Excellent correlation between WLCD32 aerial image CD and wafer data measured by scatterometry (left) and CD ratio representing the CD change as function of applied attenuation (right).

The CD uniformity on the printed wafer was characterized by scatterometry using a KLA-Tencor SpectraCD-XT, taking advantage of the excellent repeatability and of the high measurement throughput of this system.

2.2 Mask Metrology - WLCD32 Aerial Image CD Measurement

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

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 enables a large number of off-axis illumination schemes in order to illuminate the mask under the same conditions as a scanner. Furthermore, newly developed "FreeForm Illumination" devices can be used to adopt the illumination not only in geometrical shape but also in intensity distribution, to support SMO application. Additionally, 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 CDC200TM 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.

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, which is shown in Figure 3.

The utilization of CDC200TM process was already thoroughly investigated using wafer CDU data as input.[3,4,5] In this work we focus on the use of reticle 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 reticle 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 CD 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

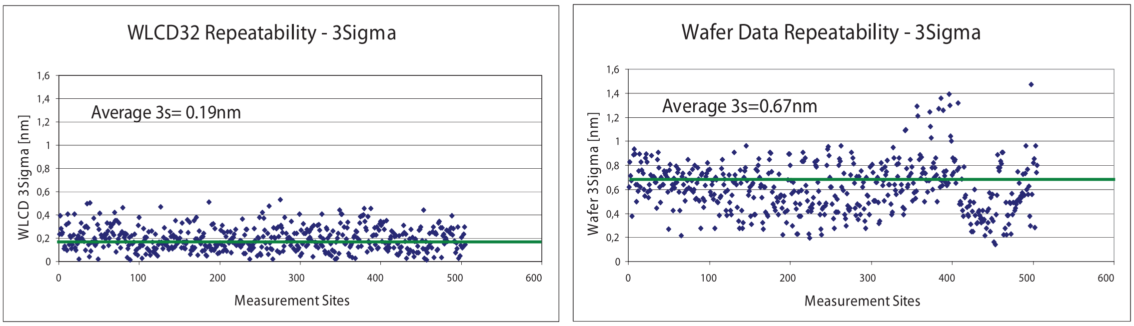


Figure 6. WLCD32 shows an excellent repeatability of average 3sigma of 0.19nm (wafer level) compared to 0.67nm for the wafer scatterometry data.

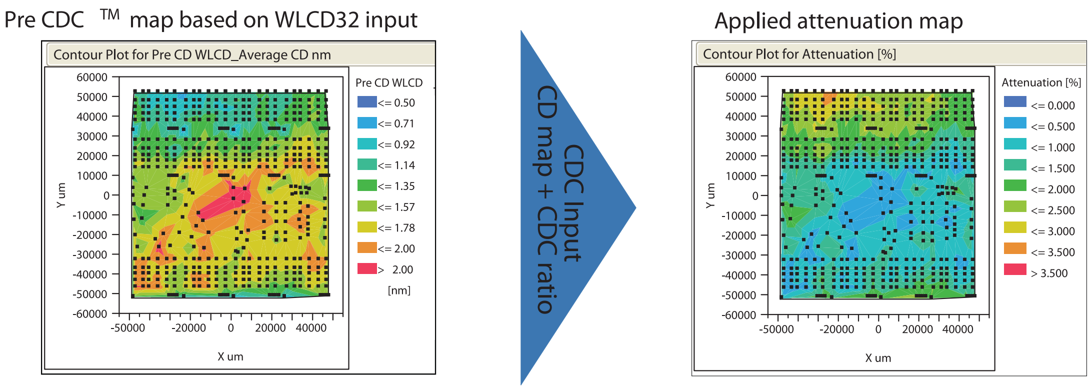


Figure 7. CD uniformity map measured by WLCD32 and applied attenuation map at CDC200™.

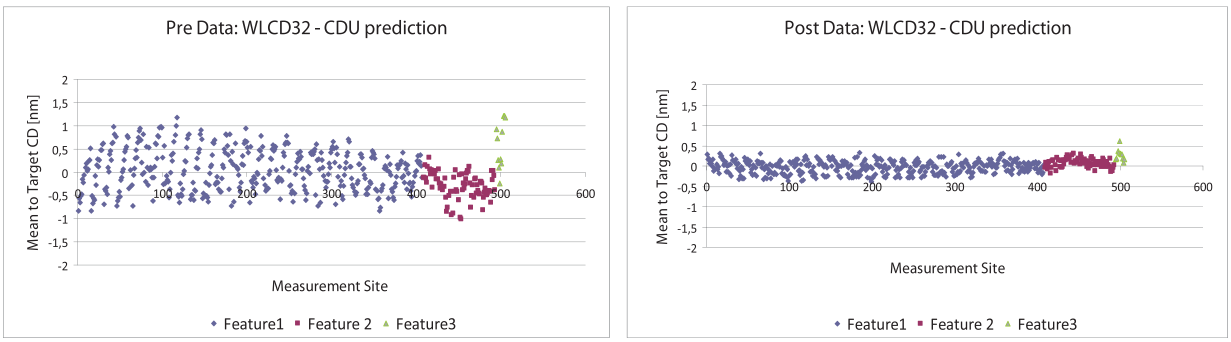


Figure 8. WLCD32 predicted CDU before (left) and after CDC process (right) shows significant CDU improvement.

in a library for future process use.

The CD uniformity correction step uses the WLCD32 reticle data scaled with the calibration factor as input for the CDC200™. The closed loop WLCD32/CDC200™ process flow it schematically shown in Figure 4. The complete process is described in more detail in an earlier paper.[6]

Figure 5 (left) shows an excellent linear correlation between WLCD32 and wafer data having a R^2 value larger than 0.85. The derived slope shows a value of 1.4 which is expected and understood because WLCD32 captures the CD in the aerial image plane and not in the resist as it the case for the wafer data. The slope of 1.4 represents mainly resist MEEF effects.

The CDC ratio representing the CD change as function of applied attenuation is shown in the right plot of Figure 5 and shows that 1% applied attenuation will lead to a CD change of about ~0.6nm.

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, which is shown in Figure 6. 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. It should be noted, that the repeatability of the wafer data is a combination of wafer process

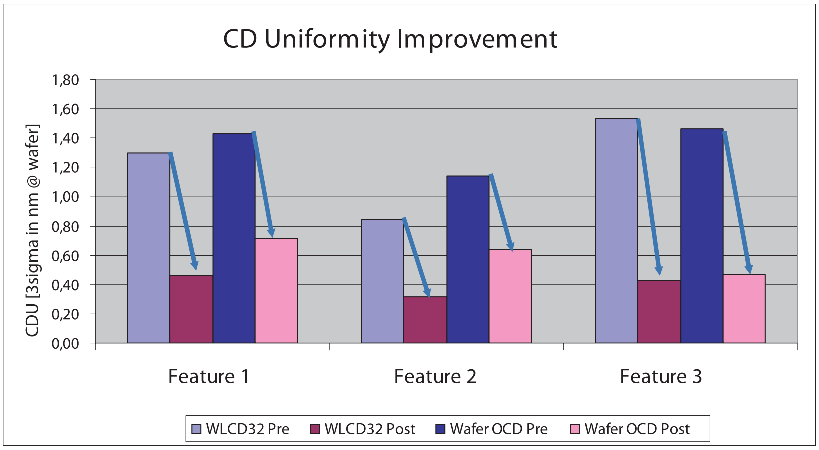


Figure 9. Validation of WLCD32 pre and post CDU data by wafer prints.

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).

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%

and metrology noise whereas the repeatability of the WLCD32 is mainly influenced by metrology noise only. The exceptional CD repeatability makes WLCD32 extremely beneficial to be used for reticle CDU qualification providing reliable input parameter and keeping the number of measurements low.

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 7).

Figure 8 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 and exactly the same measurement positions have been measured by applying optical scatterometry on wafer. The superior 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 9. Again, we like to emphasize that the CD repeatability of the wafer data is in the range of 0.67nm. This means that the CDC process did improve the CDU uniformity down to the noise level of the wafer data. The achieved CDU improvement for each feature group is about 50%. The detailed numbers for each feature group and each data set are summarized in Table 1.

The demonstrated data sets verify impressively that the closed loop process WLCD32/CDC200™ as proposed in Figure 4 can be successfully 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]

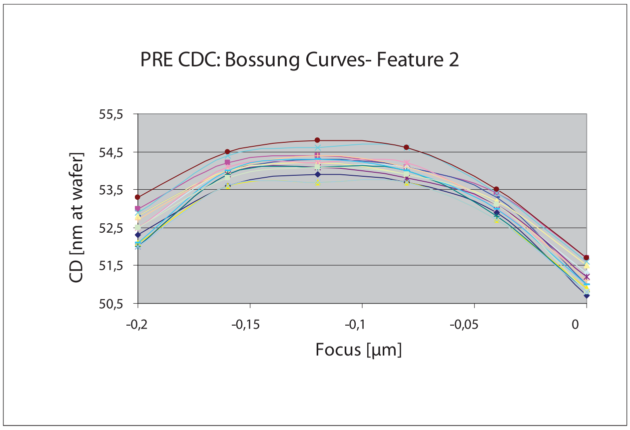
4. Process Window Investigation

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 8” flat wafers with a morphological stack of: silicon/hard mask/barc/resist/top coat have been used for the experiment.

The focus exposure matrix has been performed in dose steps (column steps) of 1mJ/cm^2 around a central dose of 14mJ/cm^2 and in focus steps (row steps) of 0.04µm around a central focus of -0.08µm.

First the Bossung plots have been investigated. For the Bossung plots totally 100 different locations have been measured covering all 3 feature groups. We concentrated on the CD distribution through focus for the different mask locations. Figure 10 shows the Bossung curves for feature group 2. Please note, that the Bossung curves have been taken at a fixed dose of 13mJ/cm^2 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. The CD variation through focus over all measurement locations has been significantly improved. This enhances the CD stability through focus and allows for a more relaxed focus control.

The improved CD variation through focus becomes even more obvious, if the 3sigma CD variation for all measurement locations is



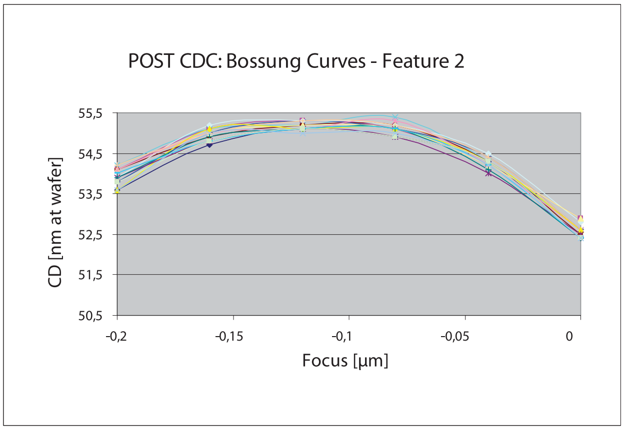


Figure 10. Bossung plots at a fixed dose of 13mJ/cm², each Bossung curve represents a different location within feature group 2. The spread in the Bossung curves is much tighter for post CDC (right) compared to pre CDC (left).

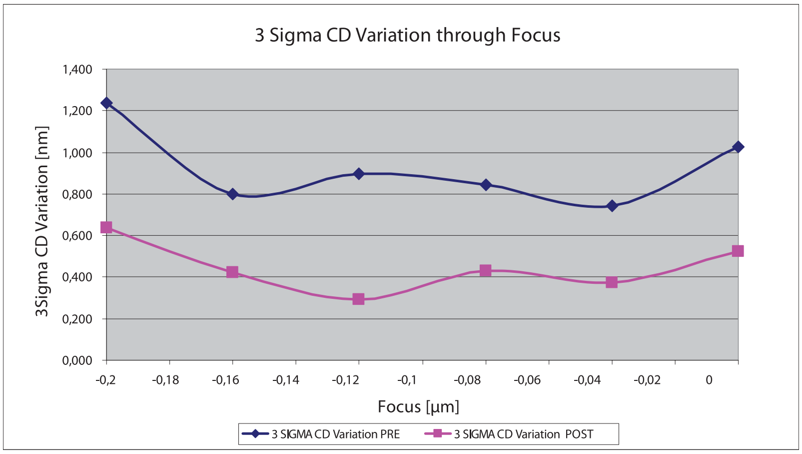


Figure 11. 3sigma CD variation through focus for all the measurement locations before and after CDC process.

plotted over focus. Figure 11 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.

Finally, we looked into the lithography process window analyzing the exposure vs. defocus behavior for all three feature groups, which is shown in Figure 12.

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 the DoF is fixed 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 for process control.

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

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 data 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 data. The final validation by wafer-prints confirms the viability of the closed loop solution WLCD32/CDC200™. This solution is optimally 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 demonstrated

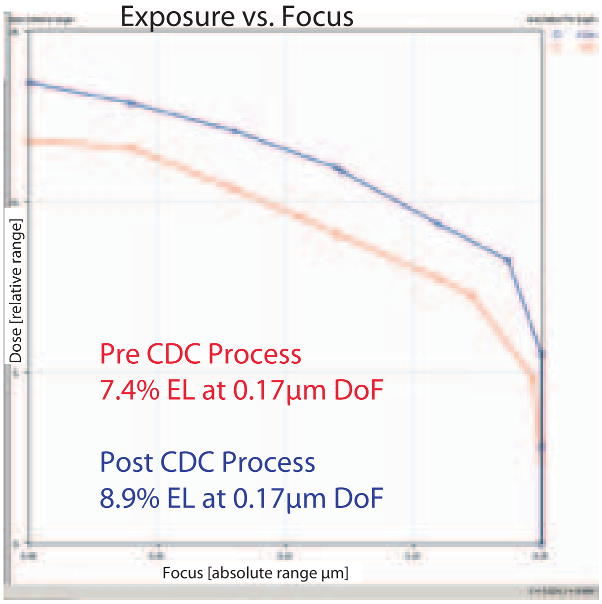


Figure 12. Lithography Process Window over all 3 features groups showing an improved process window after CDC treatment (blue curve).

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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Industry Briefs

The annual SPIE BACUS Photomask Symposium attracted more than 580 participants, up 10% over last year. Over 180 paper submissions build the basis for a 3 and a half day conference, with over 40 papers coming in from the EUV side.

Mentor CEO: Collaboration Needed in Lithography

During his keynote address at the annual SPIE Bacus mask technology conference in Monterey, Calif. on Tuesday (Sept. 20) Mentor Graphics CEO Walden Rhines insisted that the EDA industry can keep up with the computational lithography requirements for the next-generation process nodes.This is especially true for the challenges associated with extreme ultraviolet (EUV) lithography, he said. “I am optimistic that EUV will happen,” Rhines said in an interview after the presentation. “There is still some uncertainty about the schedule.” “We would like to invest in EUV,” he said. “We also have to face the possibility that EUV will slip.” As a result, Mentor must also invest R&D dollars in 193-nm lithography extensions, he said. And the EDA company must also invest in other next-generation lithography candidates, particularly multi-beam electron beam technology. Rhines said that the EDA industry must be prepared to address the growing RET requirements for EUV. He listed three major challenges in computational lithography for EUV: long range flare, 3-D mask effects, and soaring data volumes.

BACUS Panel: Is It Too Late To Panic over EUVL?

By **M. David Levenson**

The top concerns for advocates of EUV Lithography now involve the mask or its lagging infrastructure, and so it was appropriate that the 2011 SPIE Photomask Technology (BACUS) Conference concluded with a special session entitled, “Is it too late to panic? EUV is Real!” According to session organizer Frank Abboud of Intel, the purpose was to highlight how the total mask paradigm change required by the adoption of reflective EUVL masks with 1nm precision would create new opportunities for maskmakers and their suppliers. Other speakers were not so sanguine. Defect-free EUV masks will be needed for volume manufacturing in 2014, but today are impossible, they claimed.

Bill Arnold, chief scientist of ASML, spoke first at the session. According to Arnold, ASML has built six NXE:3100 1st generation EUVL scanners and has shipped three to customers. They have demonstrated useable process windows at 21nm hp, and have printed 18nm hp structures using a slow (70mJ/cm^2) inorganic resist with dipole illumination. Throughput and line edge roughness remain issues. According to Arnold, the first installed machines produce only 5-6 wph, but ASML is working with three suppliers of EUV sources to upgrade power and believes it is on track to meeting current targets.

TSMC Says Actinic EUV Mask Inspection Lagging

September 22, 2011

Extreme ultraviolet (EUV) lithography continues to make progress, but the EUV mask pattern inspection tools are still lagging behind despite recent efforts in the arena, warned a photomask manager from Taiwan Semiconductor Manufacturing Co. Ltd. (TSMC) at the at the SPIE BACUS photomask conference in Monterey, Calif. Representatives from Applied Materials, KLA-Tencor, and Zeiss gave brief updates on their companies’ EUV mask inspection tool efforts at the annual mask technology conference. Applied unveiled its Tetra EUV mask etch system earlier at the conference.

Brian Haas, vice president and general manager of KLA-Tencor’s Reticle & Photomask Inspection Division (RAPID)

Pointed out that the industry consensus was all in favor of EUVL in 2008, but the R&D decisions made recently by semiconductor manufacturers have emphasized alternatives such as multiple patterning and e-beam direct write. Haas pointed out a very clear chicken and egg conundrum: If the EUVL wafer stepper throughput stays low (and the chip yield lower), few masks will be ordered and the market for mask making tools will be tiny. Mask tool makers won’t even recover the NRE needed to develop those few unique tools and so won’t build them, he argued.

Byung-Gook Kim of Samsung was upbeat on the prospects for using EUV to make 22nm DRAMs. Kim pointed out that the phase defects all result from bumps on the substrate surface, under the multi-layer reflector, and thus they can be (in principle) polished away or hidden.

Oliver Kienzle, managing director of Carl Zeiss Semiconductor Metrology Systems, described how his company is working to solve the EUV mask defectivity problem. They are developing an EUV aerial image metrology system (AIMS). Kienzle predicted that the first tool would be shipped in 3Q2014. If defects are found to be printable, the Zeiss MeRit HR 32 repair system (which includes an in-situ AFM) can deposit or ablate the absorber to correct the problem. Even phase-shifts due to substrate bumps can be “repaired” though a compensating edge profile change, Kienzle claimed. Of course an EUV-AIMS would then be needed qualify the repaired mask.

So, the consensus appeared to be that at present it is not too late to panic, at least not about the technology. Even if EUVL is delayed again, alternative methods will take the mask making and semiconductor industries to the next node or two. EUV mask quality is improving. The economics, however, is more problematic. If defect-free EUV masks can be delivered in volume without respins in 2014, then EUVL will be competitive. If not, it will be too late to panic

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About the BACUS Group

Founded in 1980 by a group of chrome blank users wanting a single voice to interact with suppliers, BACUS has grown to become the largest and most widely known forum for the exchange of technical information of interest to photomask and reticle makers. BACUS joined SPIE in January of 1991 to expand the exchange of information with mask makers around the world.

The group sponsors an informative monthly meeting and newsletter, BACUS News. The BACUS annual Photomask Technology Symposium covers photomask technology, photomask processes, lithography, materials and resists, phase shift masks, inspection and repair, metrology, and quality and manufacturing management.

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Calendar

2012

Advanced Lithography

12-16 February 2012
San Jose Convention Center and San Jose Marriott
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SPIE Photomask Technology

10-13 September 2012
Monterey Marriott and Monterey Conference Center
Monterey, California, USA
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