Performance comparison of techniques for intra-field CD control improvement

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ABSTRACT

Intra-field CD variation is a main contributor to the total CD variation budget in IC manufacturing. It is essentially caused by mask CD variations and imperfections of the exposure tool. Techniques to reduce the IF CD error will be introduced. Tool and mask based CDU improvement techniques will be compared. Their CDU improvement potential and their correction accuracy will be analyzed. The correction methodology will be discussed, specifically none-wafer based CD measurement techniques as correction data input. Implementation efforts of the techniques will be compared.

Keywords: CD control, IF CDU, DoseMapper, shading elements, femto laser, photomask, AIMS, CDC

1. Introduction

Projections system based optical lithography has succeeded to match the requirements of the semiconductor industry since more than 25 years. The feature size shrink in this period was accompanied by a comparable shrink of the specifications of the lithographic parameters. This was specifically valid for the control of the feature width. Figure 1 shows a forecast of the ITRS roadmap 2006 how the minimum half pitch and the CD control will change over time for DRAMs. To meet the future CD control specifications, improvements along the whole litho chain are needed including tool, material and process.

A key component of the CDU budget for memory devices is the Intra-field CD Uniformity (IF CDU). Main contributors to this parameter are mask and scanner projection system performance. Since DRAMs and Flash devices are manufactured hard at the resolution edge, i.e. imaged at k_1 factors of about 0.3 or even less, large ME²F values will convert small mask CD variations to significant contributions to the total CD control budget.

Although scanner manufacturers have steadily improved the performance of the projection systems, such as aberration level, homogeneity of IF intensity and IF light ellipticity, and the dose reproducibility, the increasing variety of custom illumination schemes and specifically the introduction of polarized light have resulted in new challenges to tool design and adjustment.

The introduction of polarized light has lead to a new specification for mask blanks (birefringence) to control contributions from across field varying Degree of Polarization (DoP) to the IF CDU.

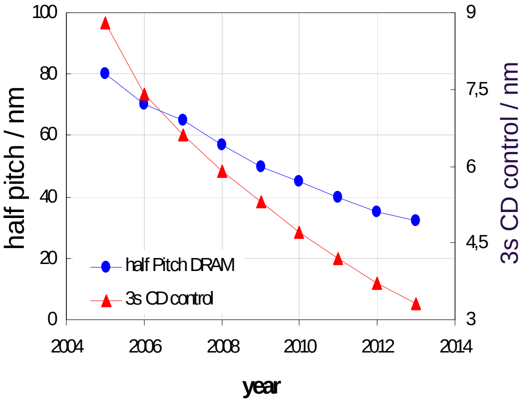


Figure 1: Half pitch and 3s CD control specifications according to ITRS roadmap 2006

This is the technical background why tool suppliers and lithographers have been searching for methods to improve IF CDU at given tool and mask performance. Meanwhile some techniques have been successfully introduced.

2. Techniques for intra-field CD control

There are basically 2 groups of techniques to improve IF CDU: exposure tool based and mask based techniques.

The exposure tool based techniques apply an on-scan dose tuning combined with an intra-slit intensity profiling [1] [2]. Dose tuning during the stage movement – typically performed by wafer and mask stage speed control - allows a change of the CD in scan direction. The change of the CD vertically to the scan direction is performed by optical filters within the illumination system or by a local along-slit variation of the slit height. Currently there is no option to change the slit intensity profile during the scan, i.e. only a mean slit profile can be applied per field. The local dose correction is determined based on CD-vs-dose gradient and IF CDU measurements. The tool based technique will be further denoted as DoseMapper^{TM} technique, since it has been introduced first under this trade mark.

Another group of techniques is based on changes of the optical properties of the mask blank. Since these techniques vary the intensity at mask absorber level, they can be grouped as intensity mapping techniques (IMT). One of these techniques applies 180° phase shifting pattern at the backside of the mask blank [3]. A part of the light of the incident rays is diffracted at such diffraction pattern into higher diffraction orders. Therefore the zero order diffracted beam, which represents the original incident light beam path, is attenuated. Consequently the intensity of the light, which is building the mask pattern image, is reduced. The desired across field intensity (and therefore dose) correction is obtained by varying the local phase pattern density.

Another technique is based on a layer of light shading elements (LSE) within the mask glass bulk [4]. Each shading element consists of an array of so-called pixels, i.e. small dots of slightly modified glass properties. The pixels are created by focusing an ultra-short laser pulse (femto laser) inside the glass bulk. The laser pulse energy causes a so-called optical breakdown, which creates a very small plasma dot. After plasma cooling a small needle shaped dot with slightly varying refractive index compared to the glass bulk is created. DUV radiation is scattered and partially absorbed by these dots, hence the transmitted light ray is attenuated. The density and size of these dots define the light attenuation. Typically the attenuation of the light is controlled by varying the pixel density across the mask area at fixed pixel size.

As the dose mapping technique both intensity mapping techniques require reliable CD measurements of the intra-field CD uniformity and the CD-vs-dose gradient. Furthermore a correlation of pixel density, respectively phase pattern density, and light attenuation is required.

Instead of changing the optical properties of the glass blank, the properties of a pellicle like glass plate can be varied. This glass plate is placed above the glass side of the mask. The required light intensity variation is built in this glass plate. This technique has a basic flexibility advantage in comparison to the described mask blank based techniques.

Intention of the paper is to compare the CD control improvement potential of the two major techniques of IF CD control improvement, the DoseMapper of ASML and the light shading elements technique of Pixer, and to elaborate on their resolution and accuracy. Furthermore we will discuss aspects of the correction process and the implementation efforts for the techniques.

3. CD control accuracy

3.1. Dose mapping

General considerations

Compared to the intensity mapping techniques the DoseMapper technique has a specific intrinsic advantage. Besides an intra-field CD correction it allows a field-by-field dose correction across the wafer. This across-wafer function of the dose mapping technique is indispensable for an advanced CD control in manufacturing of front end semiconductors. The intra-slit profile can be varied also field-by-field (not across field), but at the expense of a large productivity penalty [2].

The CD correction within an image field has limitations which depend from the considered DoseMapper model. For the intra-slit CD control exposure tools can be supplied with an attenuation filter system allowing a parabolic profile along the main axis of the slit as the main option (2nd or 6th order functions depending from the model); alternatively a linear profile can be chosen. This profile is kept constant during the scan, i.e. deviations from this (mean) profile result in CD correction residuals. Along the scan a 4th order function dose profile can be fitted (for the latest model at the most advanced systems a 6th order profile fit is available). As a consequence the CD correction potential depends strongly from the actual CD distribution across the field.

To get a more detailed insight into the correctability of IF CDU distributions, some basic CDU shapes have been defined, which are described in Figure 2: parabolic and rectangular distributions, wedges, and distributions with rotational symmetry.

A combination of these shapes might allow a reasonable representation of typical IF CD distributions. Assuming the same maximum CD variation range of 4nm within the field for all distributions, the remaining maximum variation range and 3s CD variation after a simulated DoseMapper correction has been determined. This was done assuming a parabolic slit attenuation filter profile. The values are summarized in Table 1. Very good CD correction can be obtained for cases a conveniently profiled slit filter is available.

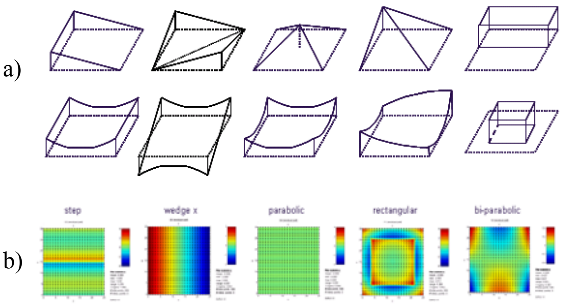


Figure 2: Basic CDU distribution shapes (a) and post correction CDU distributions (b)

Bad CD control is observed for CD distributions for which the intra-slit CD profile varies in scan direction. For some distributions even no improvement can be obtained. Switching from 4th order to 6th order fit functions will not significantly improve the CDU for the considered cases.

Experimental data

Figure 3a and Figure 3b show CDU data before and after applying the DoseMapper as examples of a large and a small improvement. A parabolic filter has been used for this experiment. Consequently the good result is achieved for a parabolic like IS CD variation (Fig. 3a). For the wedge x like CD variation shape - as expected - only a very small improvement is obtained. Note, that TPS fitted data [6] have been used for this demonstration.

In Figure 4 the theoretical and experimental CDU improvement by DoseMapper for masks of various nodes is compared.

Shape	3s, post	Range, post
wedge y	0,0	0,0
wedge x	3,6	4,0
double wedge	2,6	4,0
pyramide	1,4	2,0
asym. Pyramide	2,2	4,0
step	2,0	3,3
parabolic y	0,0	0,0
parabolic x	0,0	0,0
bi-parabolic minus	0,8	1,6
bi-parabolic plus	0,4	0,8
shifted parabolic	2,4	5,2
rectangular	3,7	5,3

Table 1: 3s and ranges of CDU after correction

Theoretically every mask shows improvement potential. The largest theoretically possible improvement is 49 percent, the worst 18 percent. This improvement potential is - as expected - not always achieved experimentally. For some cases the experimentally received improvement is even better than expected. This might be caused by a slightly changing tool intra-field performance or by a not fully optimized data collection or treatment. There is some trend of improvement of the pre-correction CDU with reducing node indicating improved mask and/or scanner imaging performance.

In Figure 5 the improvement of the CDU by a transition to the latest DoseMapper model is demonstrated. For both models a clear reduction of the 3s CDU values is achieved. The transition from a 2nd- 4th order fit (old model) to a 6th – 6th order fit (orders indicate the intra-slit fit and intra-scan fit) gives only marginal improvement for the investigated CDU distribution.

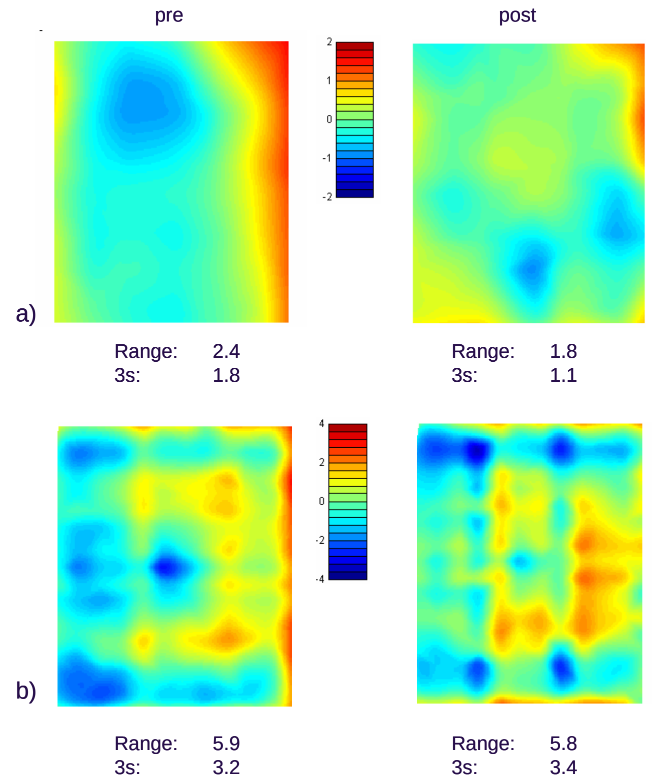


Figure 3: CDU (in nm) pre and post DoseMapper for 2 masks (a and b)

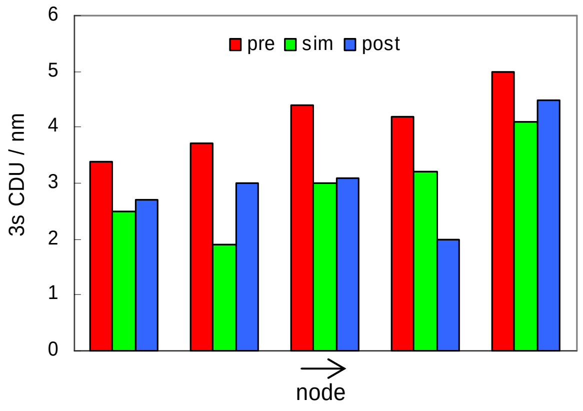


Figure 4: Improvement of 3s CDU using DoseMapper (pre, post simulated, post experimental)

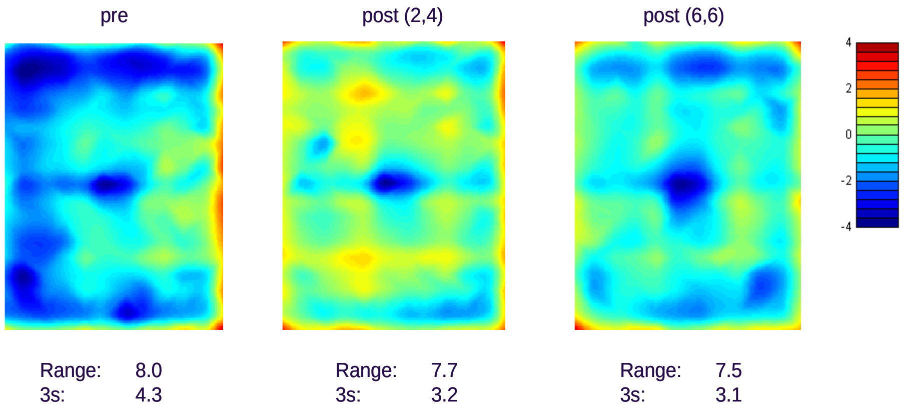


Figure 5: IF CDU (in nm) pre and post DoseMapper for two fit

3.2. Mask blank transmittance control

General considerations

Also the intensity mapping techniques based on mask blank transmittance control have a specific intrinsic advantage over the dose mapping technique: the intensity attenuation increment can be chosen very small and arbitrary correction functions can be adapted well in slit and scan direction. There is no need to fit attenuation functions within the limits of a specific mathematical model. Very small elements can be used in the actuation layer, the glass side of the mask or the plane of the light shading elements.

Limitations of the IMT result from semi-shadow superposition effects. Assuming - for simplification - a spot like dipole illumination as light source, then the pole beams cause core and semi-shadow regions of the shading element as shown in Figure 6. The attenuation of a shading element has a major impact on the intensity at the corresponding mask region underneath only there is (some) core shadow. A core shadow is obtained in case

$$B \geq R = 2T*\tan \alpha^{\text{glass}} \approx (2*T*\beta/n)*s*NA .$$

α^{glass} is the incident angle of the light beam in the glass, B the width of the shading element, T the distance between absorber and shading element, n the refractive index of the glass blank, β the magnification, s the position of the illumination source point in the illumination pupil, and NA the numerical aperture of the lens. This size can be understood as a sort of resolution value, which has impact on the correction precision. The more vertical the angle of the impinging rays is, the smaller is the semi-shadow and the better is the local attenuation resolution. Therefore the LSE technique has an advantage compared to the phase-shifting technique. It allows a placement of the attenuation plane up to 500µm close to the absorber [5]. For standard 6” masks (thickness 6.35mm) the resolution of the phase-shifting technique is therefore about 12 times worse. This difference will become even larger in case a quartz-like pellicle as described above will be used.

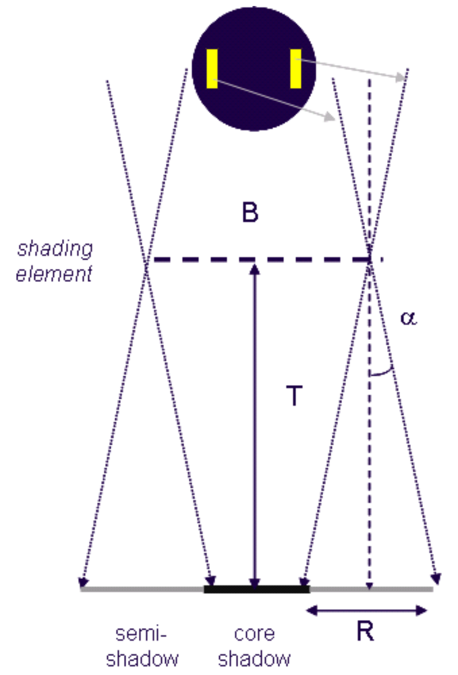


Figure 6: Geometrical conditions at light shading

Figure 7 shows R versus T and the product (s*NA). In case the shading element layer is placed in the center of the mask blank a resolution of 730µm is obtained for s*NA=0.75. For the phase-shifter approach R becomes 1570µm. For the pellicle-like approach the resolution is even worse (2030µm). For a distance T of 500µm even for a (s*NA) value of 1 good resolution of 165nm can be achieved. This number corresponds to an impinging angle of the light ray in case the illumination is optimized for a half pitch of about 45nm.

In the semi-shadow region - defined as the region where the light of two neighboring shading elements superposes – the attenuation is given by the mean value of both attenuations. For very large off-axis angles or large distances T the shadow of neighboring elements will even not superpose. For such cases an appropriate convolution method has to be applied to determine the optimum attenuation of the shading elements.

The most straightforward way is an appropriate choice of the absorber-shading element distance.

The above consideration is based on the assumption a point source is used. This is practically never the case. A precise consideration will have to take the real source distribution into account. It can vary between circular, annular, quasar, cross-pole, dipole or even specific custom illumination. In addition the sources have a finite extension (which can vary too).

Due to the analogy of the basic functionality limits and the resolution drawback of the phase-shifting technique the discussion will further focus on the performance of the LSE technique of Pixer Ltd. When this technique is applied to the hypothetical CDU distributions described in Figure 2, all distributions will perfectly be corrected except the examples with CD jumps. For these cases a stripe like variation along the CD function edge will remain. The remaining CD amplitude and extension is dependent from the source and chosen shading layer distance.

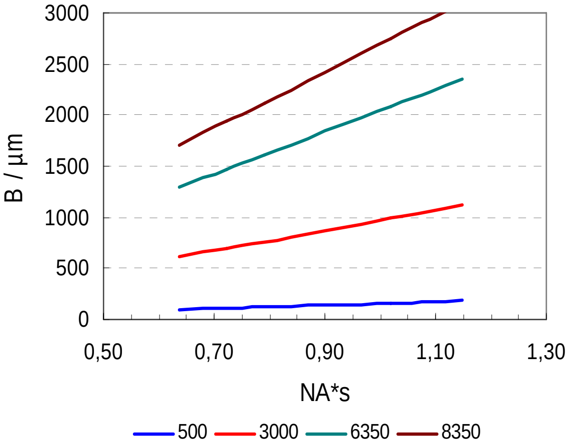


Figure 7: Resolution versus (NA*s) for various distances shading element - absorber

Experimental results

The correction steps of the Pixer technique is essentially comparable to the ones applied for the DoseMapper: CDU input data measurement, CD-vs-dose gradient determination, calculation of the attenuation across mask, application of the attenuation irradiation, tool internal measurement of the obtained transmittance change, and finally verification of the achieved IF CDU by mask printing and CDU determination. In addition to the DoseMapper procedure the determination of the relationship of the pixel density (at given pixel size) and attenuation is needed. Since the obtained mask blank transmittance change is measured pre and post laser irradiation by an internal transmittance measurement tool, in practice the obtained wafer CD change is related to the tool internally measured mask transmittance change. The ingoing CDU data are derived by TPS fit [6] from the raw CDU data. Per image field point several measurements are applied. The resultant raw data run in addition a significance validity check to detect flyers. To qualify the correction success the post correction CDU data are typically described as TPS fitted data too.

Figure 8 shows IF CDU data before and after correction based on raw data and TPS fitted data. The raw data – determined from 3 measurements per field point - scatter much more than the TPS fitted data. The CD range and 3-sigma values are also larger than the corresponding values of the fitted data. Considering the fitted data, which have been used for correction, an improvement of the IF CDU by a factor of 4 for the 3s value and almost 7 for the range has been obtained. It verifies that almost perfect correction is feasible.

Figure 9 gives an overview of the achieved CDU improvement – defined by the ratio of the 3s values of post and pre correction - for various nodes. The ratio varies between 0.25 and 0.5, i.e. it is as expected clearly superior to corresponding DoseMapper results.

As for the DoseMapper also for the Pixer technique the IF CD correction can be applied to any feature of the layout or to several features as group. For multiple

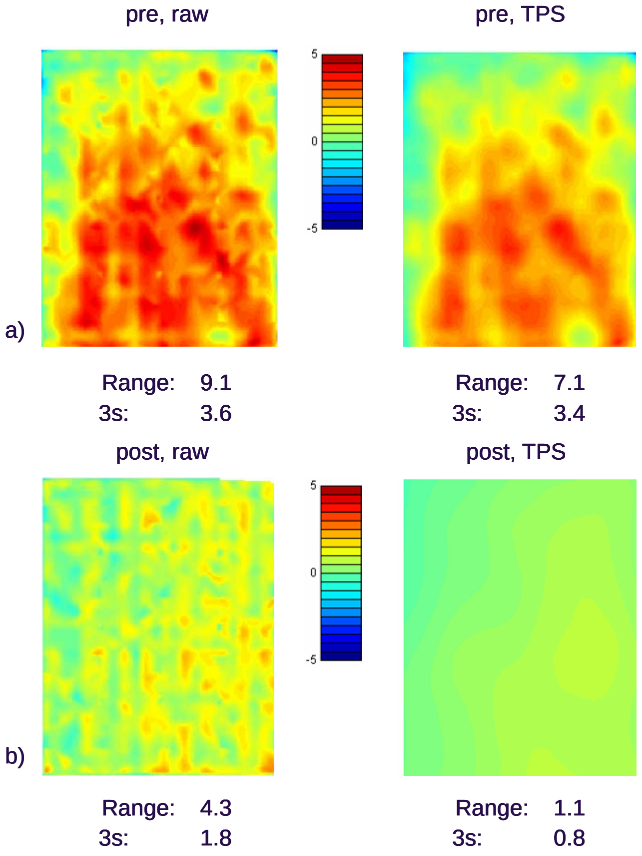


Figure 8: IF CDU (in nm) pre (a) and post (b) Pixer correction

feature corrections the corresponding CD data can be prepared and treated as weighted mean values. The correction will than be done based on these data. On the other hand, for line like resolution critical layers of advanced memory devices the pattern density of array and periphery regions at the mask is about comparable since typically SRAFs are placed close to the isolated main features.

In case a mask has to be used at more than one exposure system, pre CDU data sets from the corresponding systems can be taken and weighted, respectively. In this case no perfect correction per system can be obtained since every scanner contributes its system CDU fingerprint to the final CDU. This is a drawback compared to the DoseMapper, which allows a tool individual correction.

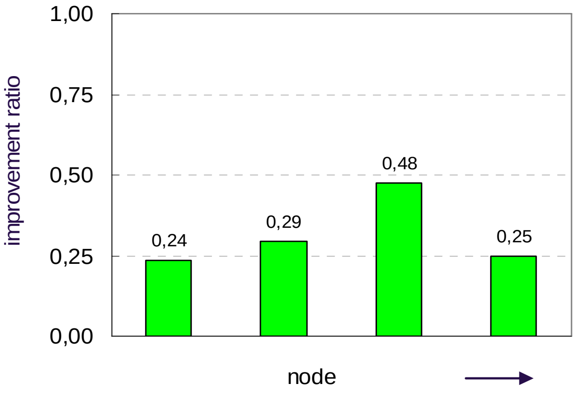


Figure 9: CDU improvement factor by Pixer correction vs. node

Figure 10a shows the mean IF CDU distribution of two scanners. Figures 10b, c give the resultant IF CDU graphs for both systems for the case a perfect correction to the mean CDs has been applied. The resultant CDU distributions show small CD tilts x (along the slit) with inversed sign. They highlight residuals of the scanner projection system performance. In scan direction the CD is very stable.

Basically there is the option to use both, Pixer and DM correction in combination. The improvement potential using the DM post Pixer correction assuming a parabolic density filter is shown in Figure 11. The graph shows improvement potential up to 1.3nm. The mean improvement is about 0.5nm, i.e. rather negligible. In the reversed case, i.e. Pixer correction after DoseMapper correction, the improvement potential is about 3nm.

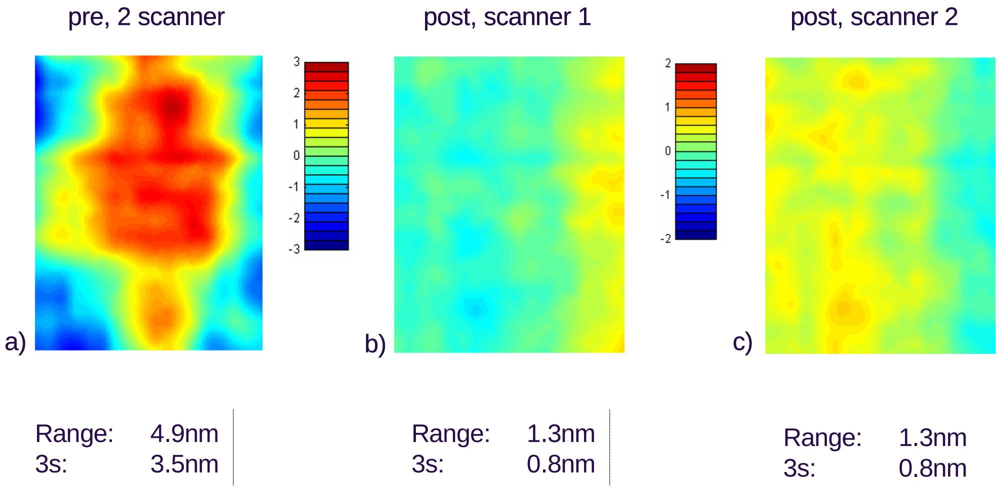


Figure 10: CDU of array lines, (a) based on mean value of 2 scanners, (b) of scanner 1 post correction, and (c) for scanner 2 post correction

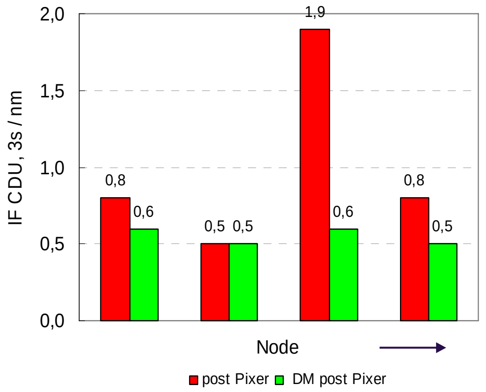


Figure 11:
CDU improvement potential for DoseMapper after Pixer correction versus node

4. Correction strategy

General considerations

To achieve the results discussed above resist CD measurements have been used as pre correction data. But wafer CD measurements are time consuming and expensive. To save productive tool time and costs, and in view of organizational simplifications it is worth to evaluate, whether there are alternatives to generate the data needed as input for corrections of the IF CDU. This statement holds true for all discussed CDU improvement approaches. Mask CD SEM measurements would be an obvious option, since they have to be performed in the mask manufacturing process anyway. Alternatively scatterometry based CD measurements [7] could be considered. Another candidate is AIMS CD measurements [8]. AIMS CD measurements appear very attractive, since they could be used also for a (in-mask house) verification of the correction success of the mask blank attenuation. Both other discussed techniques do not allow this.

Goal of the next chapter is to discuss results of investigations to replace wafer CD measurement as input data by SEM or AIMS measurements.

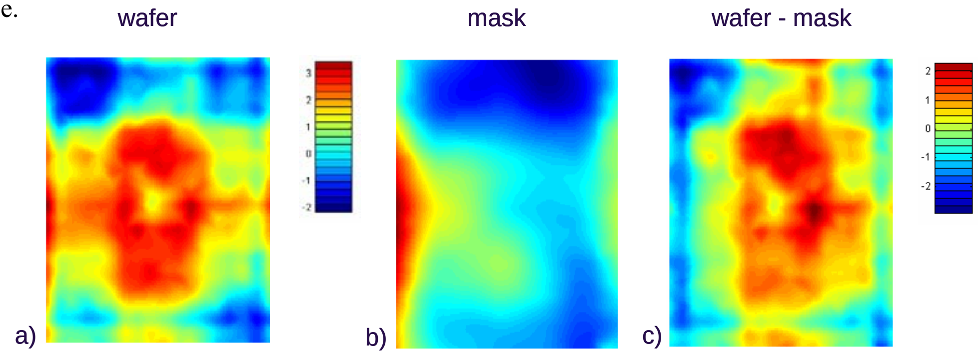
Results

The experimental conditions for doing this evaluation have been the following: SEM measurements have been done using an AMAT Reticle NanoSem 3. For the mask CD measurements the mask house standard measurement procedure (regarding measurement point distribution and data analysis mode) has been used. Alternatively a recipe adapting the intra-field positions of the wafer CD measurements has been applied. For the CD measurements a mode comparable to the macro CD measurements on wafers (averaging of measurement at 4 lines) has been used.

For the AIMS measurements the latest Zeiss model AIMS45-193i has been applied. The imaging conditions (NA, illumination source) have been adapted to the scanner imaging conditions. For the wafer processing the wafer production environment has been used. Wafer CD measurements of densely packed pattern have been done using a macro CD approach (AMAT Verity).

To evaluate the usability of the standard SEM CD measurement procedure for CDU correction, the CDU graphs of mask and wafer CD measurements can be compared. Figures 12a and 12b show the corresponding IF CDU graphs, which give the local CD difference to the mean CD. Some similarities of the CDU distributions are obvious: at the left and right part of the field larger CDs are observed. Also the regions of small CD are comparable. But, there is a ring shaped area of large CD at the wafer CDU graph, which is not observed in the mask SEM data. Figure 12c shows the difference between both graphs. To determine this difference, the mask CD variation has been converted to wafer CD variation applying the ME^{2}F as factor. This CD difference between wafer and mask converted CD (range 5.2nm, 3s 3nm) would appear as not correctable residual error in case, only the mask related errors would be corrected. It is too large for the tight uniformity requirements of the most CD critical layers of advanced DRAMs.

For the advanced SEM CD measurement approach the CDU graph is shown in Figure 13a. The fingerprint analogies to the wafer CDU (Figure 12a) are more pronounced as for the standard measurement approach. This holds true specifically for the ring shaped CD variation. The difference between both CD distributions – calculated as for Figure 12c - is given by Figure 13b. Although the visual similarities of wafer and mask CDU distributions are more pronounced, the range and 3s values are only 10 percent better as for the standard SEM measurement approach. Mask CD measurement data are obviously not well suited as reference for the correction of CD critical layers. The main contributor to these residuals is (most probably) the projection system of the scanner. Therefore wafer CD measurements as input have an intrinsic advantage.



Range: 5.45nm
3s: 3.54nm

Range: 6.05nm
3s: 3.42nm

Range: 5.23nm
3s: 3.01nm

Figure 12a-c: IF CDU of printed resist features (a), determined by a standard SEM mask CD measurements recipe (b), and calculated CD difference of both (c)

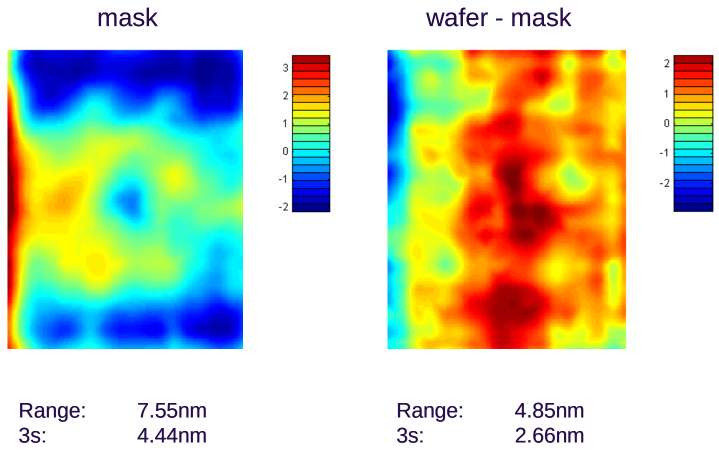


Figure 13a, b:
IF CDU determined by an advanced SEM measurement procedure (a), CDU difference mask – wafer (b)

The AIMS CD measurements have been done using the same NA and illumination as the scanner. Through-focus aerial image scan data have been used to determine the CD at best focus. An in-house software has been applied to determine the CD data. The CDU measurement point distribution has been chosen in analogy to the wafer CD measurements. After every 40 measurements a clear image calibration has been performed.

Figure 14 compares the CDU of wafer (a) and AIMS (b) CD measurements for another mask and wafer patterning process. The mismatch of the CDU results is obvious. The CD range and 3s value of the AIMS measurement is about 4 times smaller than the values obtained by wafer CD measurements. Also the CDU fingerprints are quite different. Note, that we compare TPS fitted CDU data. But, also the raw data CDU distributions show still a difference by a factor of 2 (not shown here); the CDU fingerprint differences remain. A repetition of the AIMS CD measurement with a reduced clear image cycle (10 measurements per cycle) did not result in significant different fingerprint results. Therefore it has to be concluded that AIMS based CD measurements are not well suited as direct input for CDU corrections. To understand better what the origin of this mismatch is, also for this mask comprehensive mask CD measurements have been done. The corresponding fingerprint is shown in Figure 14c. The comparison to the AIMS CDU shows more similarities as the wafer CDU. Several low and large CD hot spots positions are comparable. Note, that the SEM measurements give also about two times larger CD ranges and 3s values than the AIMS measurement. The origin of this difference might be the averaging of much more lines and line edges of mask features compared to SEM measurements, which suppresses residual mask feature roughness, and may be larger signal noise for the SEM measurements.

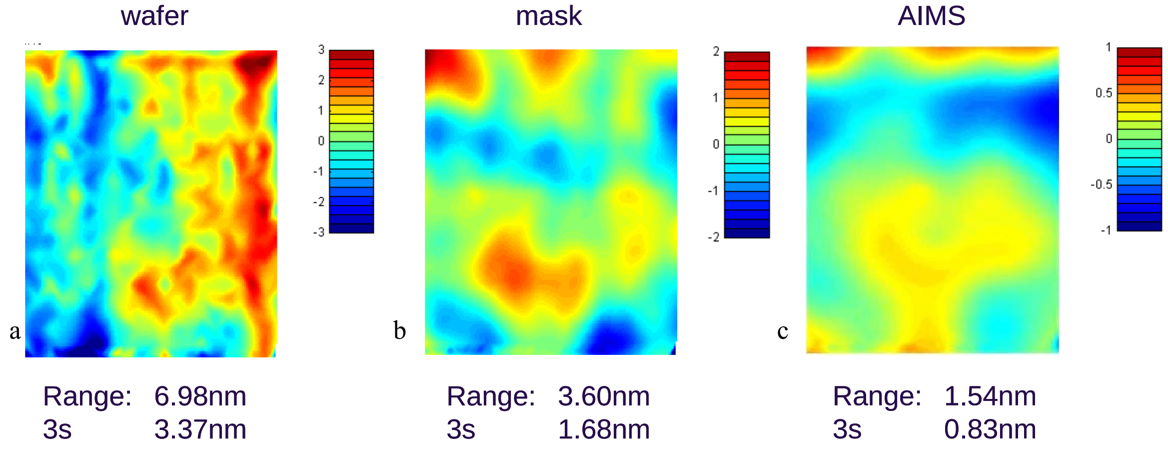


Figure 14: IF CDU of printed resist pattern (a), mask SEM CD (b), and AIMS CD measurements (c)

As discussed before another potential field of application of the AIMS is its usage for verification of the correctness of the programmed blank transmittance changes of the Pixer process. To check this, programmed attenuation wedges have been written in a mask blank. Before and after applying these wedges the CD has been measured at printed wafers and by AIMS. Figure 15 shows the correlation of the measured CD changes. It is linear. The curve slope (=0.71) deviates from 1. It indicates the difference of the exposure latitude between pure aerial imaging and pattern print. The correlation factor is 0.98. Based on the fitted curve the deviation of the measurement points to the curve has been determined to 0.45nm (3s).

Note that the curve slope depends somewhat from the chosen intensity threshold value for the AIMS CD determination. It can be concluded that AIMS measurements are well suited to control the attenuation change induced by the Pixer process. This has been demonstrated also by Ben Zvi et.al. [9], [10].

5. Summary and conclusions

Exposure tool and mask based techniques for IF CD control improvements have been analyzed. Their limitations have been discussed. The Pixer technique of generating shading elements in the mask blank bulk by femto laser irradiation shows the best improvement potential. A CDU improvement up to a factor of 4 has been achieved. The correction methodology has been discussed. At the current state of investigations SEM and AIMS measurements seem not be suited well to replace the wafer CD measurements as input data for the CD control requirements of the most critical litho layers.

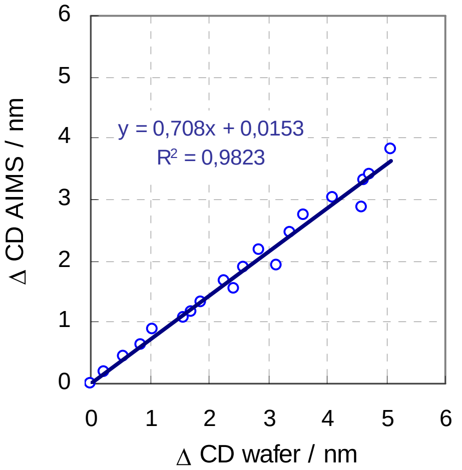


Figure 15: CD change correlation of wafer and AIMS CD for transmittance wedge

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