Multiple Layer CD Control Treatment

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ABSTRACT

Tight control of intra-field CD variations becomes more and more important as the pattern sizes on wafer shrink. For intra-field CD uniformity improvement several techniques have been developed. A very effective method is changing the local mask blank transmittance according to measured Intra Field (IF) CD variations using Pixer's CDC™ technique. This process is irreversible. For various practical reasons it would be helpful to have the opportunity for a second or more mask blank treatments. A first application could be to improve an unsatisfying CDU post first treatment. A second application can be the switch of the mask usage to another tool group. Furthermore, the opportunity to use multiple CDC treatments would allow the splitting of the correction process for the mask and the tool separately, whereas in a first correction only the mask CDU errors will be corrected and after the mask is supplied to the customer another correction may be required to reduce the exposure tool contributions to the CDU budget.

Therefore the intention of the paper is to evaluate the opportunities of a Multiple CDC (MCDC) correction process, to determine its accuracy and the corresponding limits.

To do this two CDC tool projection lenses have been characterized, which have been developed for different focus positions. We will characterize their transmittance transfer performance, stability and sensitivities. The required multiple layer distances will be determined. The linearity of the multiple CDC treatment will be analyzed using AIMS™ measurements and wafer prints. We will present results of successful multiple CDC corrections for production masks.

Keywords: CD uniformity, CDC™, CD, AIMS™, CDC Ratio

1. INTRODUCTION TO THE CDC PROCESS

Problem description

Intra-field CD Uniformity (CDU) is a growing problem with decreasing CD design rules. The CD Uniformity problem is described in Figure 1.

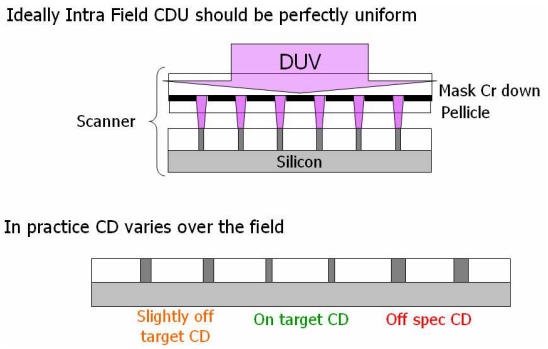

Figure 1: The intra-field CDU problem- CD non uniformity over the scan field.

The CD on wafer is a function of dose. A potential solution for controlling CD Uniformity would be to control the local dose to compensate for CD variations.

The CDC Process utilizes shading elements inside the mask bulk to attenuate the light so as to compensate for CD variations. It has been developed and is being implemented for improving CDU in various technology nodes. The basic set-up of this process is described in Figure 2.

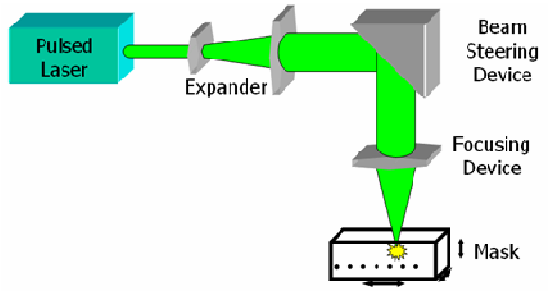

Figure 2: CDC Process: At the focal point of the laser beam a pixel is created. Quartz density is altered, and so is the local index of refraction. Each pixel acts as a scattering element.

The CDC Process creates small pixels on the order of 1µm diameter. The pixels are elongated and consist of quartz with a different morphology which creates 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 solution

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 3 shows the relevant shading elements:

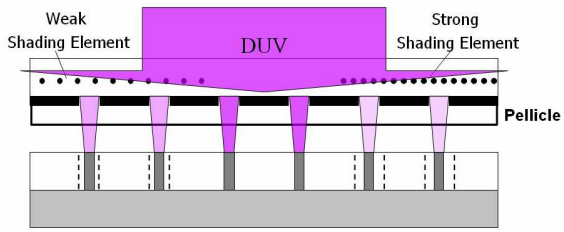

Figure 3: Applying shading elements to the mask reduces light transmission locally and effectively reduces the local dose. This causes all lines to print a CD closer to target.

CDC Ratio

Sources of CDU data for the CDC Process can include wafer CD-SEM, wafer OCD or mask Aerial Imaging.

In order to convert a CDU map to an attenuation map which should be applied to the mask a new term must be introduced. We call this term the CDC Ratio. The CDC Ratio defines the CD change in nm as a function of the attenuation in %. It is similar but not identical to the CD/dose ratio in scanners. Typical CDC Ratios are ~1.5 $^{nm}/_{\%att}$ (This means that for each 1% attenuation the CD printed on wafer will change by 1.5 nm).

The CDC Process flow

Figure 4 describes the CDC Process flow beginning with a mask and Pre CDU map, generating a job file (recipe), loading the mask to the CDC tool and processing it and measuring the Post CDU map:

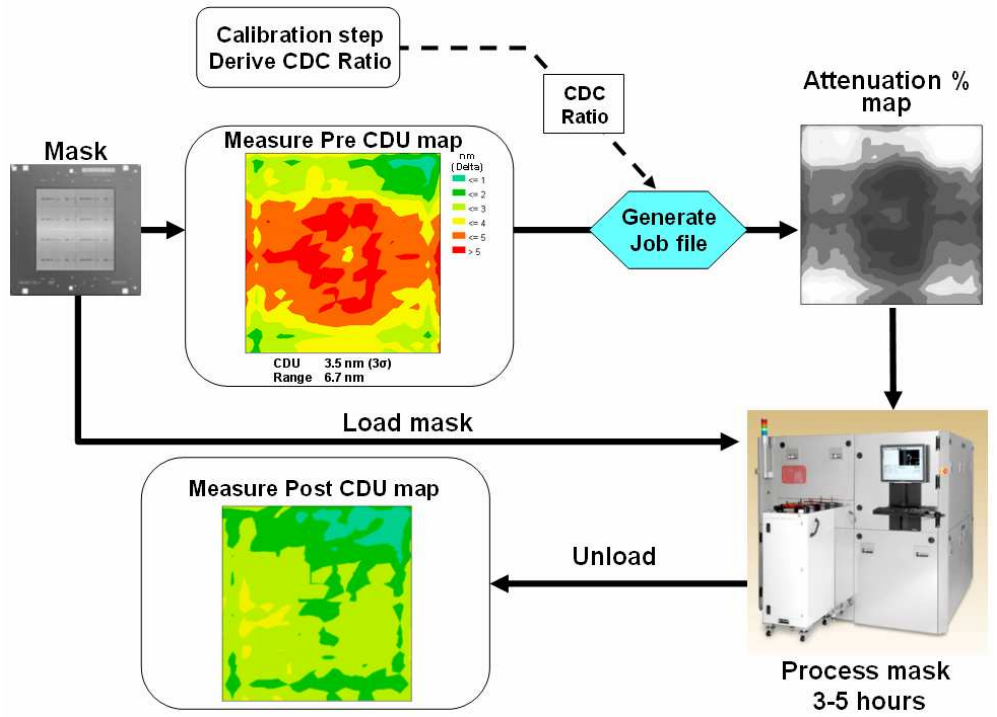

Figure 4: The CDC Process flow.

2. MOTIVATION

With respect to the explained CDC process it must be also mentioned that the CDC treatment is irreversible. That means, any deviation for a process parameter will be applied to the mask and can only be optimized by a second CDC process. For various practical reasons it is necessary to perform a second CDC treatment. For all those applications the ability to do Multiple CDC treatment is required.

The following experiments will illustrate the boundary conditions for a multiple layer CDC treatment and possible application scenarios.

3. EXPERIMENTAL RESULTS

Comparison of different objective lenses for MCDC

When attempting to create a controllable predictable and repeatable CDC shading element in the volume of the mask bulk one has to consider several variables:

1. Pixel size should be small enough in order to provide a large dynamic range of attenuation levels. For this optimal diffraction limited focusing is desired.
2. Pixel size should be very uniform. Any sources of pixel size non uniformity will contribute to attenuation non uniformity and as result to non optimal CD control.
3. Pixel size should be very stable and immune to environment sources of noise such as temperature and RH fluctuations, mechanical vibrations, laser power fluctuations etc.
4. Ease of reproducing the shading element in a multi layer scenario where the CDC process needs to be repeated (The subject of this paper).

It has been found by Pixer that in order to fulfill the above requirements the optical design needs to include the fused silica itself as an optical element in the laser beam delivery system. For this it is not sufficient to design a flat field telecentric objective, but also the focal depth needs to be compensated for by the objective. For this purpose Pixer has developed a set of special optics which provides optimal focusing at the desired writing depth.

The desired writing depth is dictated by several other requirements such as spatial resolution which dictates writing the elements close to the absorber on one hand and desire to keep the pixels out of the focal plane in order to homogenize the shading effect and eliminate printing of the pixel shade on the wafer.

For the standard CDC process window the mask center (Z=3175µm) has been chosen as the preferred depth. This paper compares among other variables the use of an optic system compensated for mask center ("new objective lens") compared to an older lens version which was compensated for Z=1500µm depth.

When planning an MCDC process one has to make sure that each layer will behave independently in order to be able to predict and control the contribution of each layer. That means each layer must be written in different z-positions. To be able to control the MCDC process for both lenses the dependency of the applied attenuation in relation to used z-position (depth) must be evaluated. For both objective lenses squares of 3x3mm on uncoated quartz blanks were created by varying the z-position at which the shading elements were written. Before the experiment the CDC tool at the AMTC was calibrated to achieve a certain attenuation level at mask center. During the experiment the tool settings were kept constant. After the CDC process the transmission was measured at the CDC treated squares.

In Figure 5 and Figure 6 the results of this experiment is illustrated for both objective lenses. The x-axis represents the z-position at which the elements were written. The red line marks the mask center (Z=3175µm). The neighbored vertical orange colored lines are indicating possible z-positions for MCDC. The y-axis shows the measured transmission on the mask after applying a certain attenuation level. The different graphs symbolize the different attenuation levels that were applied.

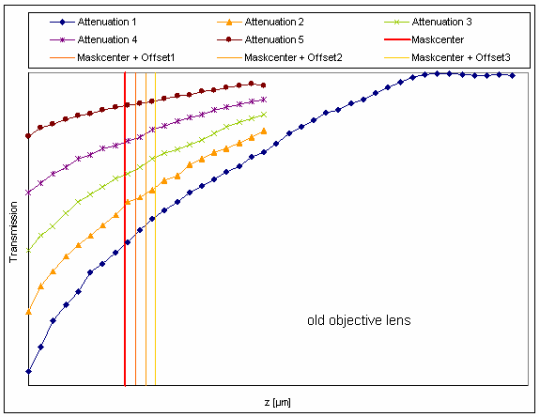

Figure 5: Dependency of applied attenuation on z-position on mask for pattern side compensated lens

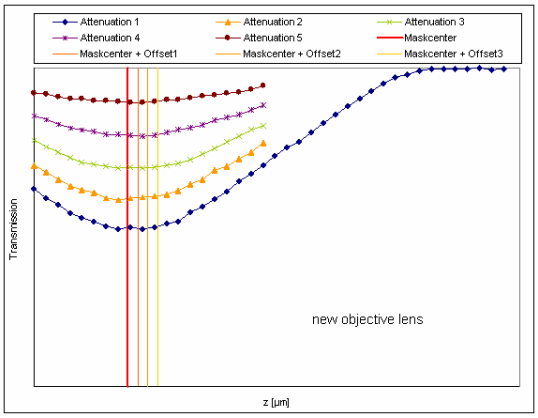

Figure 6: Dependency of applied attenuation on z-position on mask for center compensated lens

For the old objective lens (Figure 5) it is clearly visible that the measured transmission changes for different z-positions by applying the same attenuation level. If this objective lens is used for MCDC, a new calibration of the tool is needed to achieve the required attenuation level at a certain z-position. In addition, the z-calibration of the mask must be very accurate to reduce the attenuation error that is caused by this z-position dependent attenuation change.

The new objective lens (Figure 6), which is compensated for mask center, shows a different behavior compared to the old objective lens. At mask center and the z-positions that will likely be used for MCDC, the measured transmission at the mask is constant for the same applied attenuation level. That means no recalibration is needed before applying MCDC. Additionally, the influence of z-deviations on the applied attenuation is much smaller compared to the old objective lens.

In conclusion, we find that both lenses can be used for MCDC. However, dependent on the z-position at which the MCDC layers will be written, there are clear advantages in using the lens that is compensated to the appropriate z-position. That means for the standard CDC process in which the first layer is written at the mask center, the new objective lens is preferred for MCDC.

Determination of minimal distance between layers

As already explained, each layer for MCDC should behave independently, ideally as a neutral density grey scale filter and the superposition of several such filters should ideally obey the Beer-Lambert law. The Beer-Lambert law roughly states that the transmission of a stack of several independent neutral density filters should be linear to the product (not the sum) of the transmission of the filters (For example two filters with a transmission of 0.5 or 50% should together provide a transmission of 0.25 or 25%)

On the other hand one would want subsequent layers of CDC to be close to each other because of manufacturing considerations and the wish to work close to the focal plane of the focusing optics.

In order to define the optimal distance between layers we carried out an experiment to define the minimal distance in which the layers stop interacting with each other.

A base layer of 2% attenuation was written in Z= 3175µm height (mask center). 15 such base cells each 2.5x2.5mm where created. Above each base cell an additional test cell of 2% attenuation was written. The first test cell was written 1.5µm above the first base cell. The 2nd test cell was written 3µm above the second base cell and so on until 22.5µm distance between the last test cell and its base cell.

All CDC writing was done with a Pixer CDC200™ and DUV attenuation measurements were performed with a Galileo™ transmission measurement set up, both in Pixer demo lab in Israel. The experiment was performed on a photomask production quality quartz uncoated blank.

Figure 7 describes the design of this experiment from side view of the mask.

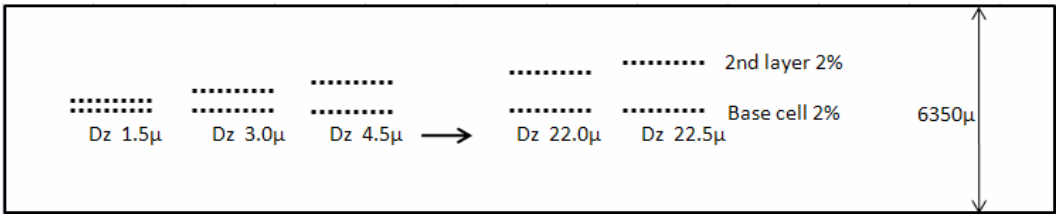

Figure 7: Arrangement of base cells and second layer test cells in the minimum distance between layers experiment.

It was found that there is a variable interaction between the layers at close distances from 1.5 to 13µm between the layers. At 16.5µm distance and above the attenuation value of the 2nd layer settles down to approximately 2% which is the target attenuation value. Figure 8 shows the results of this experiment.

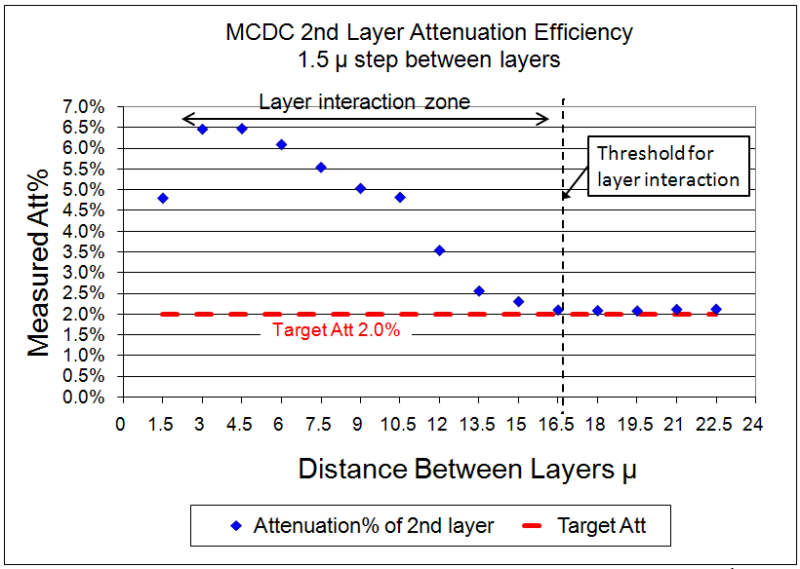

Figure 8: Effect of distance between two layers on the attenuation of the 2nd layer.

In conclusion of this experiment the minimal distance between layers has been defined as 16.5µm. However to provide a safety factor to account for position errors in Z a recommended minimum distance between layers was defined as 30µm.

Attenuation effect of multiple layers

Assuming that repeat CDC processes will be needed in some circumstances, there is no reason to limit the number of cycles to two. We therefore set out to test the combined effect of up to 4 additional layers over several attenuation values.

A base layer of 8 cells, 2.5x2.5mm size with variable attenuation from 0.5% up to 4.0% with steps of 0.5% was written at Z= 3175µm (mask center). Above each base cell 4 additional layers of 1.0% attenuation each were written. The distance between each layer was Z=50µm. After the first layer and after each additional layer the attenuation was measured. All CDC writing was done with Pixer CDC200 and DUV attenuation measurements were performed with a Galileo™ transmission measurement set up, both in Pixer demo lab in Israel. The experiment was performed on a photomask production quality quartz uncoated blank.

Figure 9 describes the design of this experiment from side view of the mask.

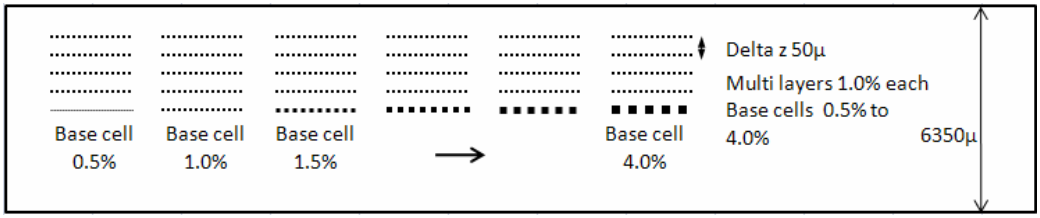

Figure 9: DOE of combined multiple layers attenuation effect. A series of base cells with attenuation of 0.5% to 4.0% are written at mask center. 4 additional layers of 1.0% attenuation each are written in steps of 50µm between layers. Attenuation was measured after writing of each layer.

We found a very linear and predictable combined attenuation for each additional layer for all tested base cell layers from 0.5 to 4.0% attenuation. This means that multiple layers with a distance of 50µm between layers can be used with high accuracy and predictability and no interaction could be identified between the layers over the whole usable attenuation range of 0.0 to 4.0%.

An interesting and yet unexplained finding is that the measured result deviates from the theoretical Beer law by approximately 0.1% for each additional layer.

Figure 10 shows the results in graphical form. It can be seen that the measured trend line for each series is very linear (R^2 >0.998), indicating a high predictability of attenuation of additional layers. The dashed lines show the theoretical value.

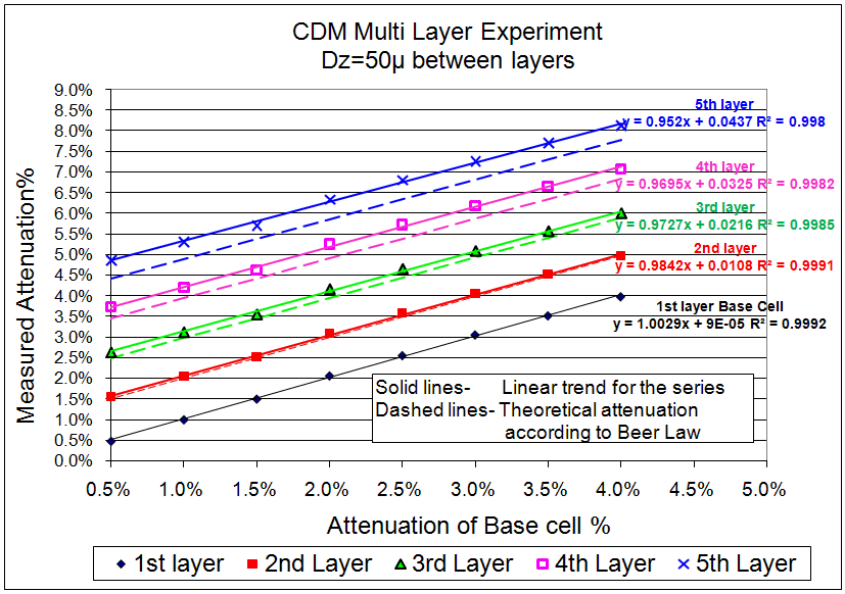

Figure 10: Total attenuation of multiple layers over variable base cell attenuations from 0.5% to 4.0%. Result shows very linear behavior over all base attenuations up to 4 additional layers. A bias of higher attenuation compared to the theoretical value (dashed line) can be seen in all layers.

In conclusion of the combined attenuation multiple layer experiment we can state that adding up to 5 CDC layers will provide a highly predictable attenuation level and that each layer behaves independently. Each additional CDC process will behave independently of the previous CDC process, and therefore up to at least 5 layers can be performed without risk of wrong CD correction.

Optimization of a non-optimal CDC process

The most important parameter for an optimal CDC treatment is the CDCR. If this parameter is not chosen correctly an under or over correction is the consequence. The following experiment will show the outcome of a non-optimal chosen CDCR.

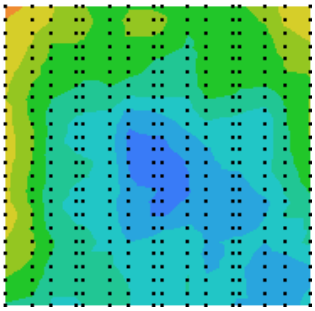

Figure 11: Intra-field wafer CD map before CDC treatment

Based on an intra-field wafer CD map (see Figure 11) for a mask with a known CDCR two CDC treatments were applied each with doubled CDCR. The consequence of a doubled CDCR is that the applied attenuation is cut in half and so an under correction for the first CDC treatment is expected.

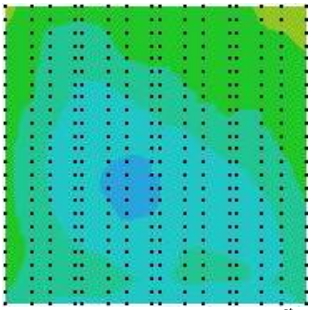

Figure 12: Intra-field wafer CD map after 1st CDC treatment

In Figure 12 you can see the intra-field wafer CD map after the 1st CD treatment was applied. Compared to Figure 11, it can be seen that the CD range has decreased but the signature is still visible. That means the expected under correction could be provoked. By calculating the CDCR for the 1st CDC treatment based on the Delta CD (1st Post CD – Pre CD) the correct CDCR can be determined. That means in case of a wrong chosen CDCR for a production mask the correct CDCR can be determined based on the performed CDC treatment.

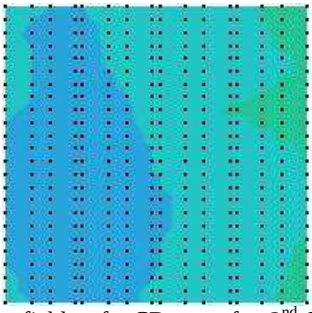

Figure 13: Intra-field wafer CD map after 2nd CDC treatment

In this experiment the same attenuation map from the first CDC treatment was applied for the second CDC treatment. In Figure 13 the intra-field wafer CD map after the 2nd CDC treatment is visible. You can recognize that while the full CD range was corrected to almost zero, the Pre CD signature was eliminated. To achieve an optimal treatment with a second layer it is recommended to use the Post CD data and the calculated CDCR from the first CDC treatment.

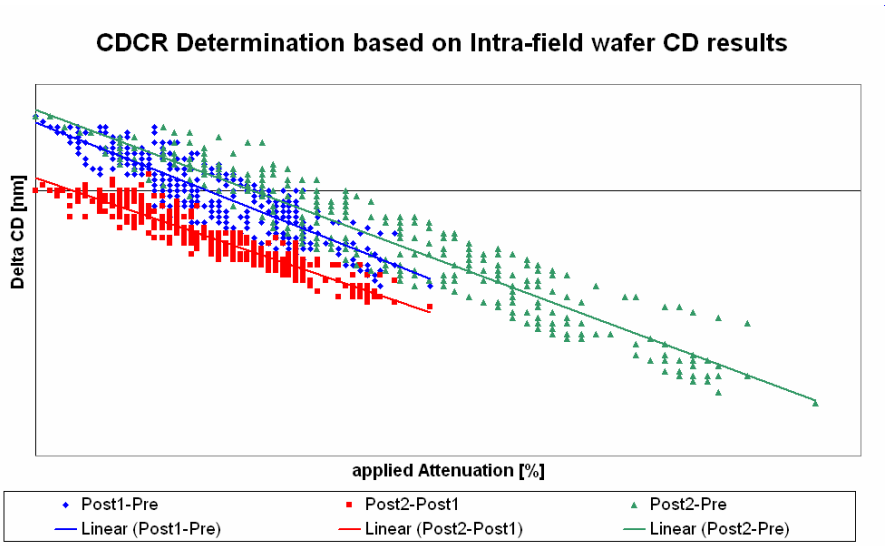

Figure 14: Calculation of CDCR based on intra-field wafer CD results

In Figure 14 you can see the differences in intra-field wafer CD for the 2 treatments over the applied attenuation. From this chart the CDCR can be determined by the slope of the linear interpolation of each graph. It is clearly visible that the slopes of the three graphs (Delta CD from 1st and 2nd treatment and total CD difference) are almost equal. The applied attenuation for both CDC treatments together (green graph) are determined by the multiplication of the applied transmissions.

Conclusion of this experiment is that the intra-field wafer CD results can be used for the determination of the optimal CDCR. In case of a non-optimally chosen CDCR, it is possible to apply a second CDC treatment. For this additional treatment it is recommended to use the intra-field wafer CD map after the first CDC treatment with the new determined CDCR.

Optimization of non-optimal CDC process based on tool instabilities

To get an optimal CDC treatment a lot of parameters must be chosen correctly. It is also very important that the CDC tool is optimally calibrated. This first experiment shall show the effect of laser instabilities during the CDC process, the ability to detect such a tool fluctuation with the available tool parameter and the possibility to compensate this non-optimal CDC treatment.

In Figure 15 you can see the top part (along Y axis of the field) of the intra-field wafer signature which was used for the CDC treatment. The parameters for the CDC treatment were optimally chosen, to be able to determine only the influence of the laser instability.

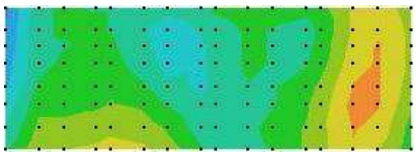

Figure 15: Intra-field wafer CD map before CDC treatment.

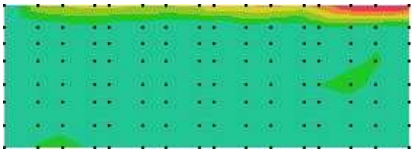

Figure 16: DUV result map (msr. att. – target. att.) of 1st CDC treatment.

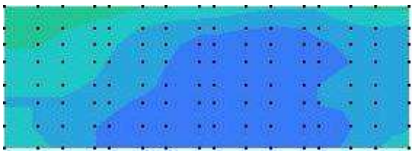

Figure 17: Intra-field wafer CD map after 1st CDC treatment.

During the experiment the laser showed a stable behavior but at the end of the CDC process the laser drifted downwards (see blue line in Figure 18). To verify this laser drift a transmission measurement with the internal DUV

measurement system was performed. In Figure 16 you can see the attenuation deviation (measured attenuation – target attenuation) as an X-Y-map. In the last top row the deviation from target attenuation increased (yellow red horizontal line in Figure 16). The DUV dots in Figure 18 show the same attenuation deviation but in this case in relation to the y-position on the mask. The blue line shows one of the laser parameter of the CDC tool at the corresponding y-position on the mask. Between the last two rows the laser started to drift. This laser change caused a decrease in the applied attenuation which is visible in the negative attenuation deviation for the last row. The range for the attenuation deviation of the last row is bigger compared to the other rows, which is caused by the continuous drift of the laser during the CDC process of the last row. Figure 16 confirms this phenomenon because the attenuation deviation becomes worse for increased x position which is equal to the CDC write process.

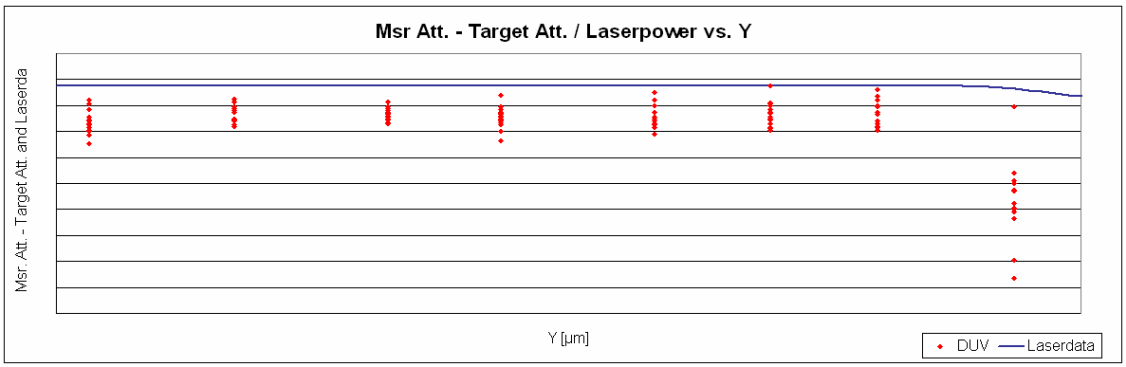

Figure 18: Correlation between attenuation deviation (measured attenuation – target attenuation) and corresponding laser value at a certain y position on mask.

In Figure 17 you can see an under correction in the upper area of the intra-field wafer CD signature after this non-optimal CDC treatment. The comparison of the DUV result map (Figure 16) and the PostCDC wafer CD map (Figure 17) illustrates that the effect of laser instability is more visible in the transmission measurement which is related to the applied CDC Ratio. For a CDC Ratio > $1^{nm}/_{\%att.}$ the impact on wafer CD is smaller compared to the impact on the applied attenuation on the mask.

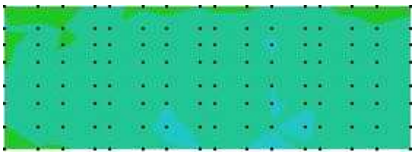

Figure 19: DUV result map (msr. att. – target att.) of 2nd CDC treatment.

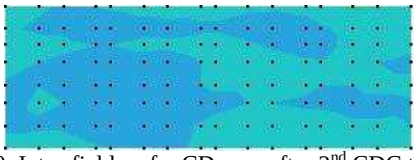

Figure 20: Intra-field wafer CD map after 2nd CDC treatment.

The intra-field CD map after the first CDC treatment (see Figure 17) was taken as a basis for a second correction to compensate for the tool fluctuation induced signature. For this second CDC treatment all parameters were chosen optimally. Figure 19 shows the DUV Transmission map post 2nd CDC treatment and Figure 20 shows the corresponding wafer CDU map post 2nd treatment. It can be seen that both DUV Transmission and wafer CD have significantly improved following the 2nd correction which was applied to the area were the laser drift and attenuation error were identified.

Switch of mask usage to different scanner

The opportunity to change the attenuation distribution of a mask blank in a second CDC run allows the user to swap the usage of a corrected mask from one tool to another with a theoretical option of a perfect CD control. This might be needed in case a concerning tool has not been considered for the first mask correction due to changing production-organizational circumstances. The typical process of mask correction for multi-tool usage is to balance the tool performance differences by using mean CDU data of the corresponding tools. Figure 21 shows the wafer CDU of two 193nm scanners for the same mask and its difference pre and post "Dose Mapper"™ application. After "Dose Mapper"™ application the CDU fingerprint becomes very similar. The CDU difference of the tools drops down by a factor of 2 (3s values); the CD range is almost unchanged. A perfect correction for one tool would result in a larger IF

CD range for the other. In case of a perfect correction to the mean CDU of both tools half of this range would remain. In case such a value would be still too large, a succeeding correction process for the tool of choice would be needed and possible.

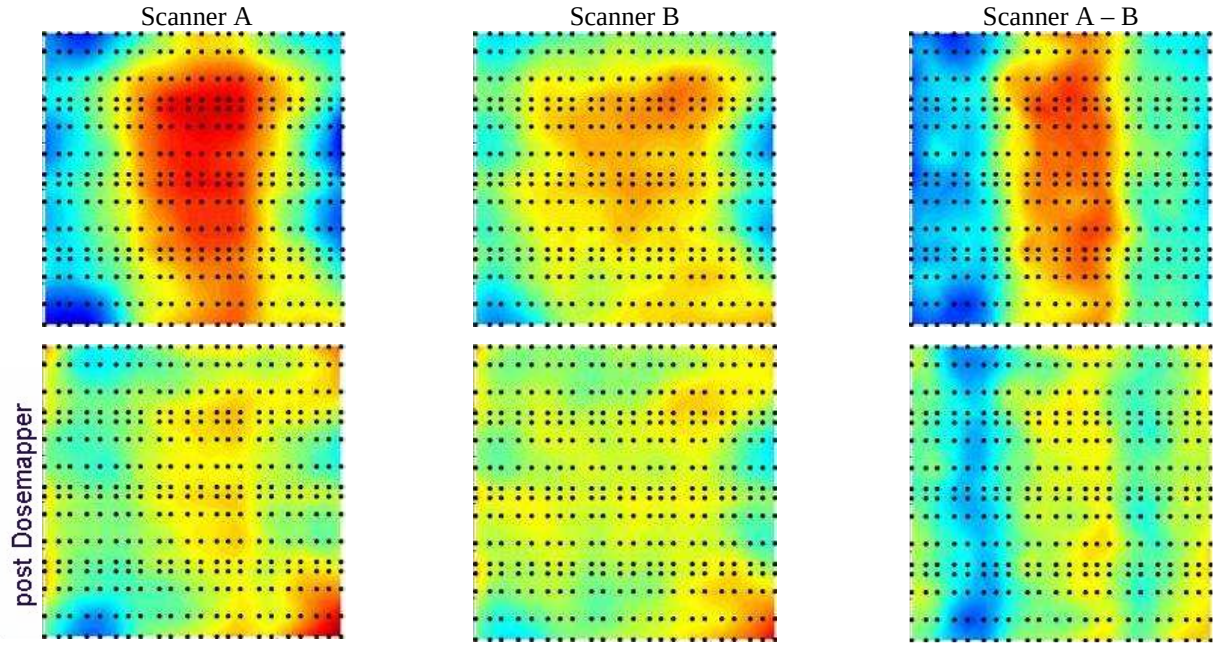

Figure 21: Intra-field CD Map for different scanners

Separate correction for mask and exposure tool signature

Another way of applying CDC treatment is to separate the correction of the mask CD signature from the correction of the exposure tool signature. The advantage of this application is that the first CDC treatment can be done directly after the mask was built. In case of a sufficient correction the mask can immediately be used in the wafer fab. If it is necessary to further improve the wafer CDU map after this first CDC treatment a second CDC treatment can be applied based on the wafer CDU map. An experiment was done to prove applicability of this approach. In addition to determination of CDU from a printed wafer, an aerial image based CDU was determined for a mask using the AIMS45i^{TM} tool. In a first step, CDC treatment was applied to achieve a flat aerial image CDU. The correction was verified using AIMS measurements. After this correction the mask was printed on wafer again in order to determine the residual wafer CDU which was then compensated by a second application of CDC.

In Figure 22 the aerial image based CDU before and after CDC treatment is shown. The CDC treatment reduced the signature by more than 50% to a value of less than 1nm (range).

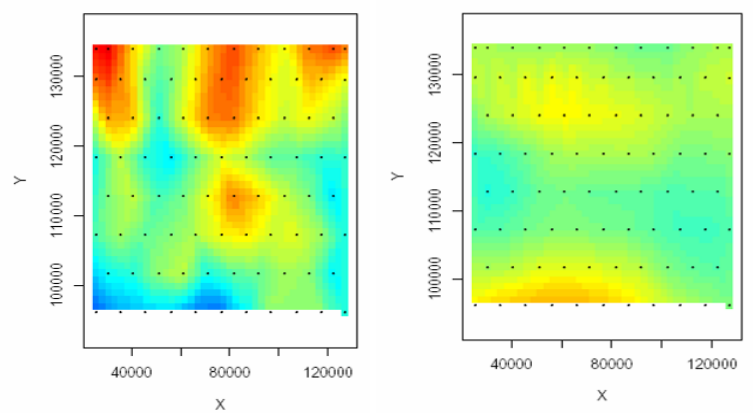

Figure 22: Aerial image CDU before (left) and after (right) CDC treatment.

In Figure 23 the printed wafer CDU of the mask is shown before any CDC treatment, after the CDC treatment used for compensation of the aerial image CD signature and after a second treatment using the wafer CD data after the first treatment.

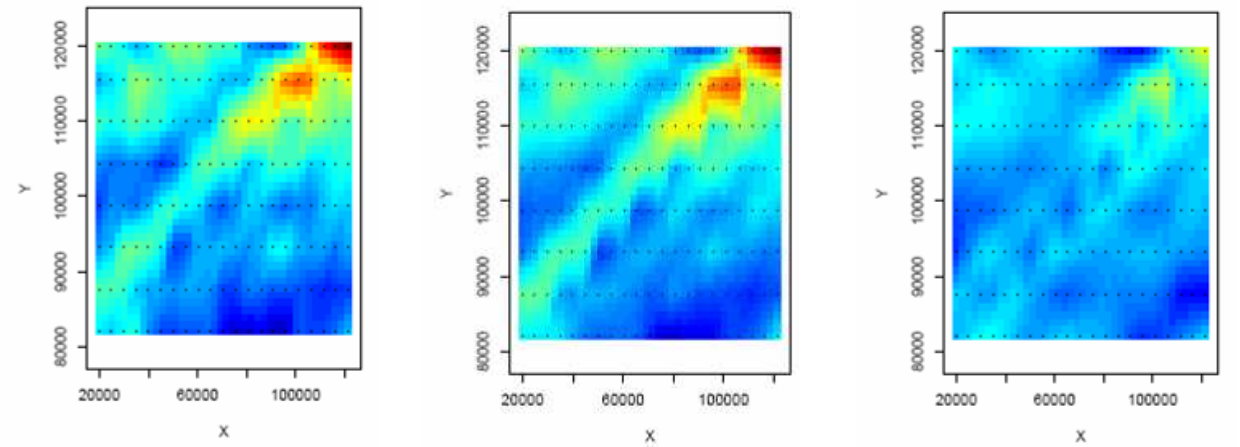

Figure 23: Wafer CDU before CDC treatment (left), after 1st (middle) and after 2nd CDC treatment (right). All plots are done using the same color scale.

One finds that the aerial image based CD compensation (although successful based on AIMS measurements) has not yielded a significant improvement of the wafer CDU. In numbers: the AIMS based compensation reduced the wafer CDU range by 10% whereas the wafer based CDC treatment yielded more than 50% improvement.

The reason for this difference in improvement is that the aerial image CDU in this particular case was not well correlated with the wafer CDU, probably because scanner contribution to CD error was more significant than mask contribution. This can be seen by comparing the CD signatures measured by AIMS tool and on wafer before the CDC treatment. In Figure 24 the correlation of SEM measurements of the mask structures with the AIMS CDs is shown as well as the correlation of the CDs measured on wafer with AIMS measured CDs. Whereas the aerial image signature is well correlated with the structure sizes on the mask measured by SEM the wafer CD is not well correlated with the aerial image signature. Hence, the AIMS can well characterize the mask structures but is not sufficient to predict the printed wafer signature. This means that the exposure process adds a significant contribution to the wafer CDU that is not predictable by AIMS (and SEM) measurements of the mask.

In conclusion, an AIMS based CDC treatment is possible and yields signature reductions comparable to those corrections based on wafer data. However, pure aerial image based signature compensation might not be sufficient as contributions to the wafer CDU arising during wafer exposure process are not captured. The actual CDU improvement of AIMS based corrections depends on the specific contribution of the mask and the scanner to the CD error budget in each

specific mask- scanner combination. It is worth noting that other cases where mask contribution to wafer intrafield CD error as high as 40% have been seen. In such cases where mask signature is relatively high and the scanner signature is relatively flat, correcting CD based on AIMS may be sufficient to bring the process CDU into spec.

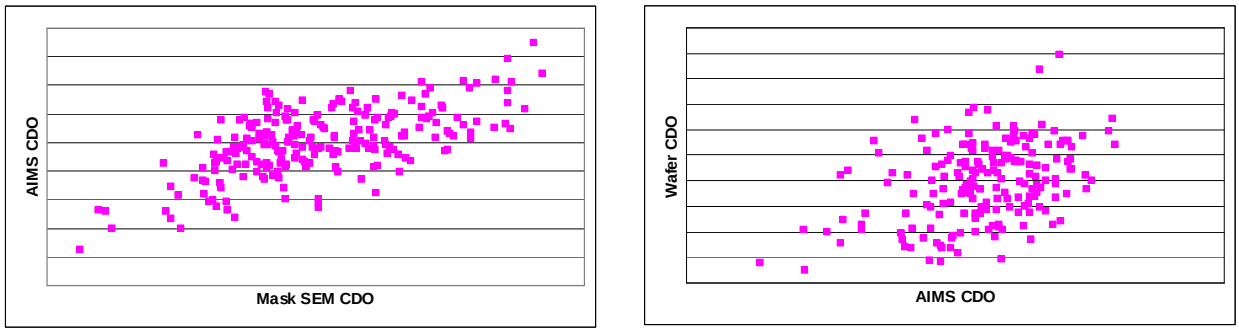

Figure 24: Correlation of AIMS CDU vs. mask-SEM CDU(left) and wafer CDU vs. AIMS CDU (right)

4. SUMMARY AND CONCLUSIONS

A multi-layer CDC correction process has been developed and its successful application by wafer prints demonstrated. For this a specifically optimized new lens was characterized regarding attenuation change versus depth within the quartz bulk. It gives a much more stable performance for position variations around the optimum focus position. The minimum distance between the pixel layers have been determined and the linearity of superposition of the attenuations has been demonstrated by tool transmittance measurements and wafer prints. The applicability of the multi-layer CDC has been discussed for multi-scanner correction, AIMS or mask CD based pre-correction and failure of the CDC tool during the pixel writing process. Based on the obtained results it can be concluded the multi-layer CDC is possible and can be applied with success for various practical circumstances.

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