Wafer Level CD Metrology on Photomasks using Aerial Imaging Technology

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ABSTRACT

Recently more and more mask designs for critical layers involve strong OPC which increases the complexity for standard CD SEM mask measurements and conclusive interpretation of results. For wafer printing the wafer level CD is the crucial measure if the mask can be successfully used in production. Recent developments in the AIMS™ software have enabled the user to use the tool for wafer level CD metrology under scanner conditions. The advantage of this methodology is that AIMS™ does see the CD with scanner eyes. All lithographic relevant effects like OPC imaging which can not be measured by other tools like mask CD SEM will be captured optically by the AIMS™ principle. Therefore, measuring the CD uniformity of the mask by using AIMS™ will lead to added value in mask metrology. With decreasing feature sizes the requirements for CD metrology do increase. In this feasibility study a new prototype algorithm for measuring the lithographically relevant AIMS™ CD with sub pixel accuracy has been tested. It will be demonstrated that by using this algorithm line edge and line width roughness can be measured accurately by an AIMS™ image. Furthermore, CD repeatability and tool matching results will be shown.

Keywords: AIMS™, CD metrology, Aerial Imaging, photomask , line edge roughness, line width roughness

1. INTRODUCTION

With the insertion of immersion lithography for the 45nm node, the quality of the photomask has become more and more crucial for achieving the required yield in the wafer fab. One reason is that the main features sizes on the mask are coming close to the wavelength of the scanner. Additionally, the mask designers have to apply more and more sophisticated OPC features in order to print small features on the wafer. These features have to be accurately controlled during the photomask manufacturing process to make sure that the desired CD is printed on the wafer. Small features or regions where the Mask Error Enhancement Factor (MEEF) is high are extremely sensitive to process variations [1]. Small process variations on the mask level can lead to large CD variations on the printed wafer. At the same time the requirements for CD uniformity (CDU) on the wafer are getting tighter by moving to smaller nodes. So, accurate control of the CDU during mask making becomes mandatory, ideally taking already into account the CD performance on wafer level after printing. Wafer level CDU is the crucial measure if the mask can be successfully used in production. Currently, the CDU is mainly measured by mask CD SEM or optical CD metrology tools. These tools are measuring the mask CD with high accuracy, but it is obvious that such methods can not take into account the lithographic performance of OPC features or MEEF which have strong impact on wafer level CDU.

Recent developments in the AIMS™ software have enabled the user to use the tool for wafer level CD metrology under scanner conditions [1 – 3]. The advantage of this methodology is that AIMS™ does see the CD with scanner eyes. All lithographic relevant effects like OPC imaging which can not be measured by other tools like mask CD SEM will be captured optically by the AIMS™ principle. Therefore, Aerial Imaging Technology is per se able to measure the wafer level CD uniformity of a mask and will lead to added value in mask metrology. However, CD metrology has different requirements than repair verification and defect disposition for which AIMS™ has be specifically developed and designed [4, 5]. Generally, CD metrology requires the ability to measure several hundreds of sites on the mask in a short time whereas for repair verification only a few sites per mask are reviewed. So, high throughput, high repeatability as well as automated job generation and tool matching are the main requirements for a CD metrology tool.

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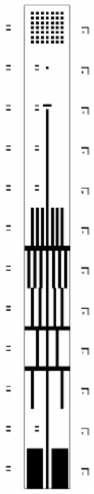
The goal of this study was to analyse the feasibility of using Aerial Imaging Technology as applied on the AIMS™45-193i platform as a bases for a wafer level CD (WLCD) metrology tool. For this purpose first the mask CD measured by a CD SEM has been compared with measurements on the same mask using an AIMS™45-193i tool. Second, a prototype algorithm has been developed to determine the CD as well as line edge roughness (LER) and line width roughness (LWR) at a given threshold with sub-pixel accuracy. This algorithm has been applied to data from 3 different AIMS™45 tools in order to study tool matching.

2. MASK CD VERSUS CD MESURED BY AERIAL IMAGING

For comparison of mask CD measured by CD SEM to AIMS™ measurements, a calibrated mask from the "Physikalisch Technische Bundesanstalt (PTB)" has been used. The PTB mask (Table 1) contains several test patterns (iso, dense lines, contacts) of several nominal CD values. These CD values have been calibrated by PTB using UV transmission microscopy, low voltage SEM and AFM measurements. The exact calibration procedure is described elsewhere [6]. In this study the CD values of the low voltage SEM have been used which represent the top CD of the mask features.

Table. 1. Description and design of the PTB CD mask standard

- 6 inch mask, Chromium on Glass (with Pellicle)
- 55 CD test structure groups with CD ranging from 100 nm to 5 µm with a pitch of 200 µm neighboring groups
- Nominal values of the CD test structures:
  - 100…500 nm, step 20 nm = 21 groups
  - 540…900 nm, step 40 nm = 10 groups
  - 1000…1600 nm, step 100 nm = 7 groups
  - 1800…5000 nm, step 200 nm = 17 groups
- Line and box structures (bright and dark)
- Mask Feature Sizes calibrated by means of UV transmission microscopy and low voltage SEM and AFM



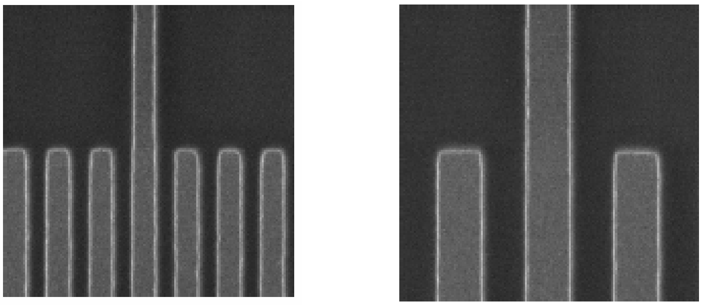


Fig. 1. SEM images 200 nm (left) and 500 nm (right) nominal size CD features on the PTB mask.

In Figure 1 CD SEM images of features of nominal 200nm and 500nm CD are shown. These features have been measured by an AIMS™45-193i. The imaging condition were NA=1.4, σ=0.98, Quasar 85%, 20° opening angle, 0°

orientation. Figure 2 shows the AIMS™ intensity plot of the iso and dense area of the 200 nm feature. On the CD SEM image in Figure 1 iso and dense areas are clearly visible and have approximately the same CD value. In Figure 2 an AIMS™ intensity plot of both 200nm iso and dense features is shown. Applying, in the aerial image a threshold for targeting 50nm at wafer level, it can be seen that the both iso and dense features would not print simultaneously. In Figure 3 the same plot is shown for the 500nm feature. Appling a threshold such that 125nm lines would print on the dense area would lead to significantly smaller CD in the iso area.

Clearly, the imaging behavior of an iso line is totally different compared to a dense line. This is a purely imaging effect on wafer level and cannot be captured by a CD SEM. A CD SEM measures the geometrical mask CD with a high resolution but is not able to capture the printing performance of a mask pattern. However, using Aerial Imaging for CD metrology would allow the mask maker to capture these effects and to measure directly the wafer level performance of the mask.

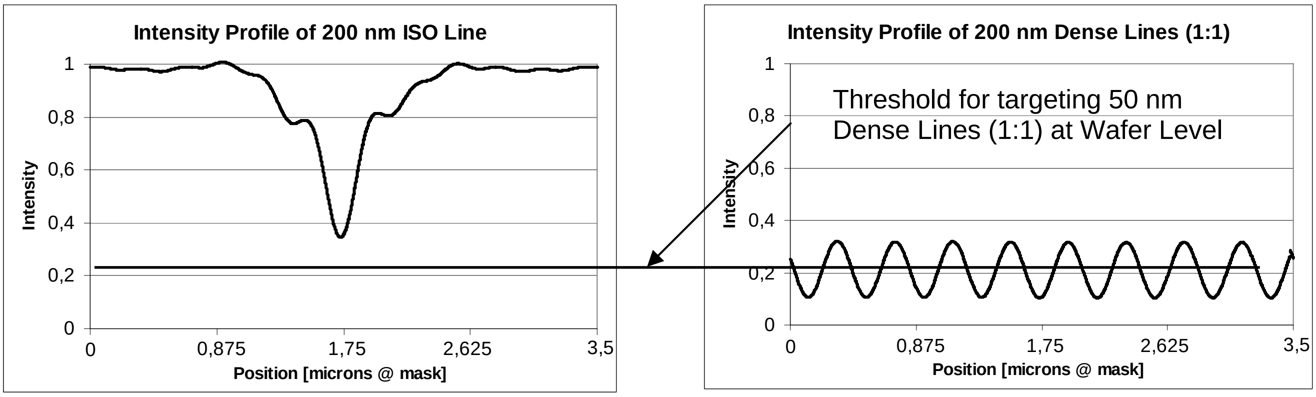


Fig. 2. AIMS™ intensity plots of the nominal 200 nm feature. Left: iso, right: dense. The dense line prints, whereas the iso line will not print.

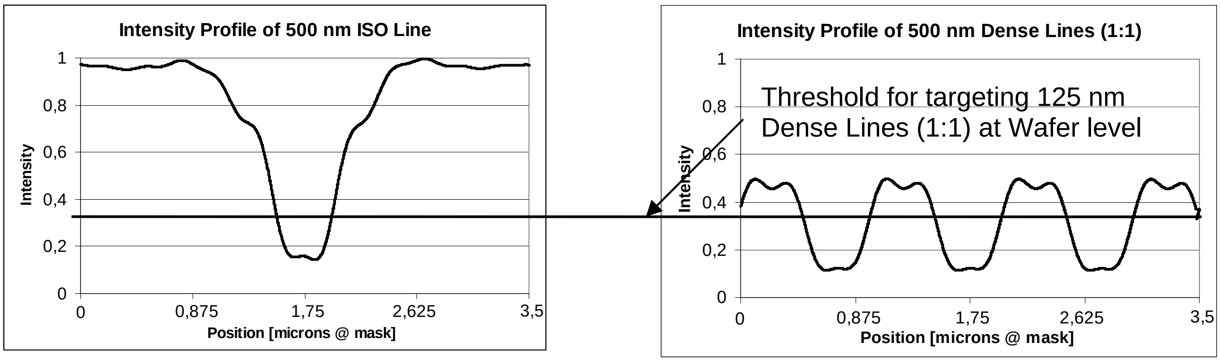


Fig. 3. AIMS™ intensity plots of the nominal 500 nm feature. Left: iso, right: dense. Dense and iso lines would print on the wafer but would have different CD which is not visible to the CD SEM.

In Figure 4 the mask CD measured by CD SEM is plotted against the AIMS™ CD for iso and dense lines as well as for iso and dense spaces. The threshold for the AIMS™ CD measurements has been determined in such a way that at 200nm the AIMS™ CD is equal to the mask CD. Then, this threshold has been applied to all other CD values. Again it can be clearly seen that the iso and dense lines have different aerial imaging CD. Hence, they will print differently on the wafer. The right graph of Figure 4 shows the same date but the AIMS™ measurements have been taken under a different setting. As a result the wafer level CD measured by AIMS™ is slightly different.

These examples illustrate that one cannot easily deduct from mask CD to wafer level CD. Wafer Level CD depends on feature size, pitch and image settings. All these effects cannot by captured by classical CD metrology on mask level. However, applying aerial imaging for CD metrology takes all these effects into account. The mask will measured with "scanner eyes" and the lithographic relevant CD can be measured. By using wafer level CD (WLCD) metrology, the wafer fab, for instance, could easily specify the mask CD using by the WLCD values to ensure that the mask performs correctly.

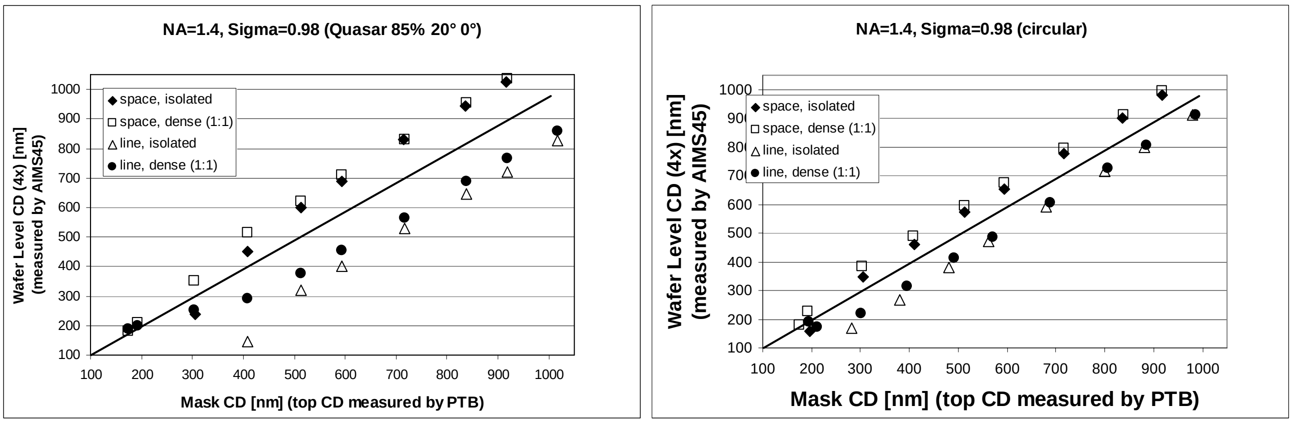


Fig.4. Comparison of mask CD measured by CD SEM versus AIMS™ CD for iso and dense lines as well as for iso and dense spaces. Left: imaging condition NA=1.4, σ=0.98, Quasar 85%, 20° opening angle, 0° orientation. Right: imaging condition NA01.4, σ=0.98, circular.

3. MEASURING LINEWIDTH AND LINE EDGE ROUGHNESS

The second step of the feasibility study it has been focused on analyzing CD repeatability as well as line edge roughness (LER) and line width roughness measurements (LWR) using Aerial Imaging Technology. For that purpose a prototype algorithm in MATLAB has been developed in order to calculate the LER and LWR along a certain line with sub-pixel accuracy at a predefined threshold in the aerial image.

The algorithm has been tested on a CoG, mask with L&S 180nm 1:1. The measurements have been taken in X and Y orientation on 3 different AIMS™45-193i tools with the following setting: NA=1.40, Dipole 60%, Sigma=0.96, unpolarized. The edges of 4 lines (Figure 5) have been detected by the new prototype algorithm at a fixed threshold of 0.245 at the best focal plane. The CD has been determined by the distance between the edges. By performing the measurements on 3 systems also tool matching has been analysed.

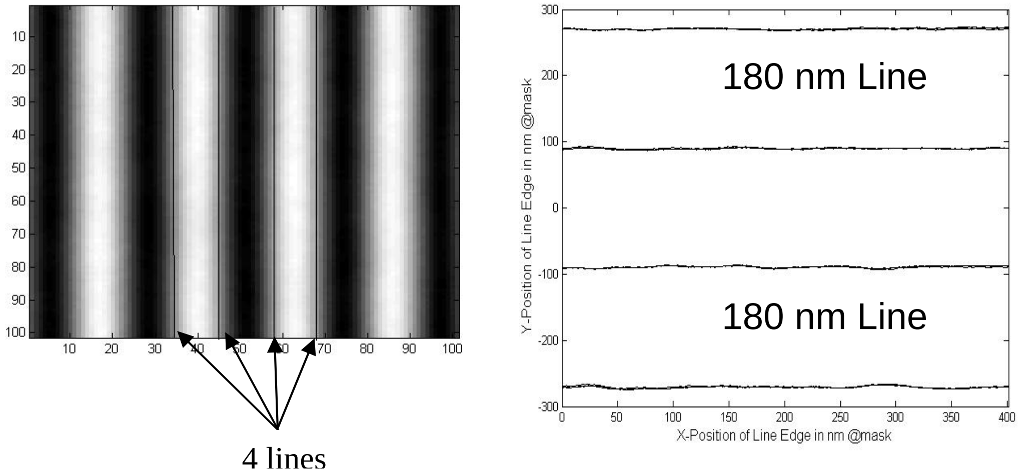


Fig.5. Left: four lines are detected with sub-pixel accuracy at a threshold of 0.245 for calculating the CD (difference between edges) and LER and LWR. Right: LER measured with 3 AIMS™45-193i tool at the same position (rotated by 90 degrees).

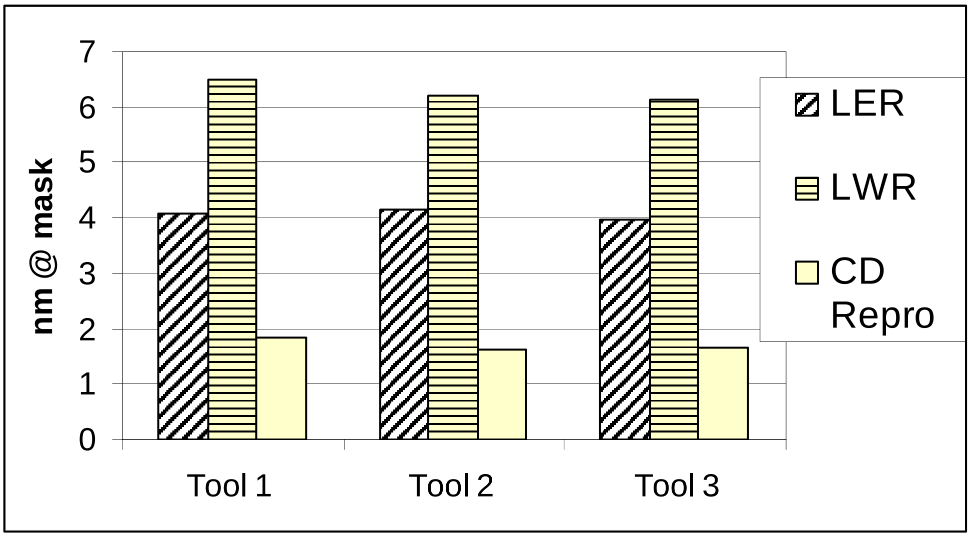


Fig.6. CD repeatability, LER, LWR measured on 3 different AIMS™45-193i tools

The measurements have been performed 5 times on the same location. This data has been used to calculate CD repeatability in terms of 3 sigma. The CD values have been averaged over 10 pixels which correspond to an Region of interest (ROI) of 180nm on mask level and is a typical AIMS™ procedure. The results are shown in Figure 6. It can be seen that the CD repeatability is well below 1.83 nm at mask level which is a quite good result. The LWR and the LER are in the range of 6.0-6.5nm and 4 nm, respectively, which is much larger than the CD repeatability. This means that the measured LWR and LER are a mask property which can be easily detected by aerial imaging and which are almost independent of the tool used.

A CD repeatability of 1.8nm gives some room for improvement as the requirements for CD metrology on mask are in the range of below 1 nm. One way to improve CD repeatability could be to average of a larger area. The pixel size at mask level of an AIMS™45 -193i tool is about 18nm. The standard averaging area in an AIMS™ measurement is 10 pixel which corresponds to 180nm. In CD metrology usually the averaging areas on line and space patterns are quite larger and in the range of several µm. Appling a larger averaging area, one would also expect that the CD repeatability of an AIMS™ is improved. In Figure 7 the CD repeatability of 3 tools as a function of 3 different averaging areas is shown (1 pixel, 10 pixel, 100 pixel). Clearly, for a 100 pixel averaging area which is 1.8 µm, the CD repeatability can be improved by 30% - 40% down to 1.2nm. .

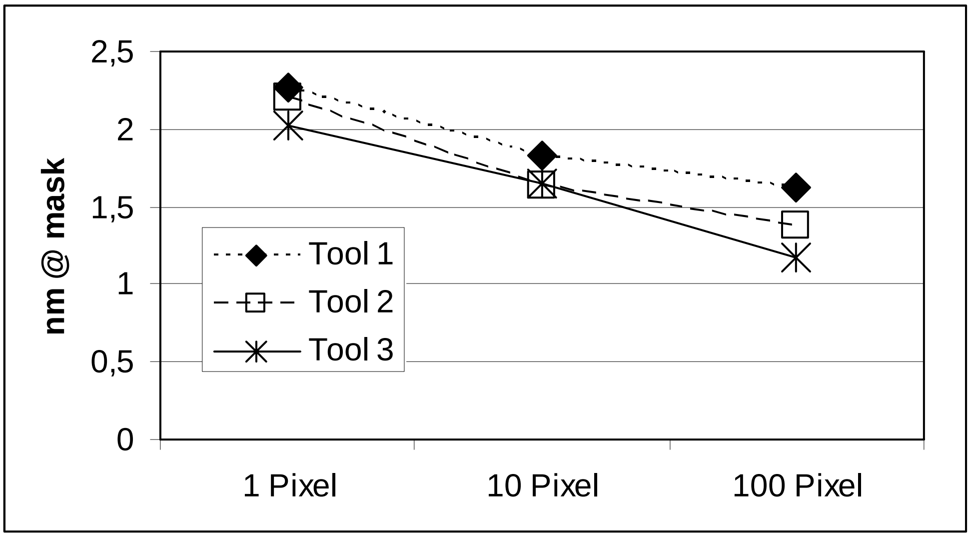


Fig.7. CD repeatability for different Tools and for different averaging areas (1 Pixel, 10 Pixel, 100 Pixel)

4. APPLICATIONS

It could be shown that Aerial Imaging is able to measure the wafer level CD on masks with high repeatability. By Wafer Level CD Metrology (WLCD) the mask can be measured with scanner eyes. All lithographic relevant data like iso-dense bias, Mask Error Enhancement Factor (MEEF), but also LER, LWR are accessible to the mask maker which opens new space for optimizing the mask process according to the desired final result at wafer (Figure 8). In the mask shop WLCD can be used for

- direct feedback to e-beam Mask and Etch Process
- optimize processes directly due to Wafer Level CD measurements and close the loop for wafer prints
- OPC verification
- Inverse Litho verification

In the wafer fab WLCD could be used for

- incoming CD inspection
- reduce wafer print costs for process qualification
- Design verification (SRAF, OPC, and Inverse Litho)

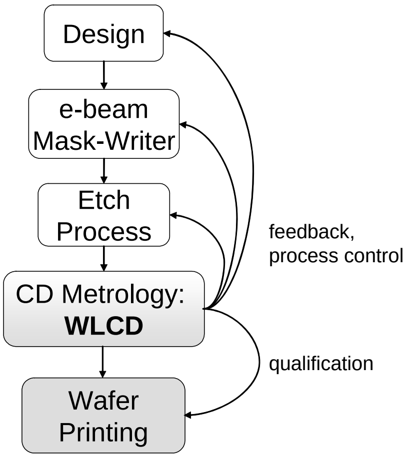


Fig.8. Wafer Level CD Metrology (WLCD) using Aerial Imaging as a standard CD Metrology method in the mask process flow to close the loop to wafer prints in the wafer fab.

5. CONCLUSIONS

In this paper it has been shown that by using aerial imaging technology wafer level CD can be measured with high repeatability. The CD measured by aerial imaging will be different to mask CD measured by CD SEM depending on feature type (iso, dense) and optical setting of the exposure tool. Aerial Imaging measures the mask with “scanner eyes” and all imaging effects are inherently captured by this method. Clearly, a concept for wafer level CD metrology (WLCD) using Aerial Imaging enables mask optimization with respect to the final result – the wafer print - already during the mask making processes. The measured CD values or CDU of WLCD are closer to wafer prints. By applying a prototype algorithm, LER and LWR as well as CD repeatability has been studied on different AIMS™45-193i tools. It has been shown that LWR and LER are clearly mask properties which can be measured by aerial imaging.

AIMS™ technology has been developed originally for repair verification. However, CD metrology has different requirements than repair verification such as extremely high throughput, excellent CD repeatability and fully automated tool operation. These demands require engineering changes and improvements both in software and hardware in order enable WLCD using aerial imaging. Therefore, Carl Zeiss SMS has put a dedicated tool on its roadmap for wafer level CD metrology using aerial imaging (“WLCD tool”) fulfilling the market requirements for CD metrology.

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