Development and characterization of new CD mask standards: a status report

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Abstract

We report on the current status of a project on development and characterization of CD photomasks with 6025 format to be used as reference standards for different type of CD metrology instruments. The project consortium consists of mask suppliers, manufacturers of CD metrology instruments, users of such instruments and calibration laboratories. Different type of CD metrology instrumentation, namely optical CD microscopes, CD-SEM, and AFM will be applied for investigation and measurement of microstructures, additionally supported by AIMS tool. We will describe the basic design criteria of the mask standard and first measurement results gained with different metrology tools on the prototype mask standards.

1 Introduction

The CD metrology tasks on wafer and mask level were identified in the ITRS [1] as big challenges already today and in future development of lithography, too. In particular requirements are described with respect to factory level and company wide metrology integration for *in situ* and inline metrology tools and further development of microscopy tools for critical dimension measurement, also taking into account side wall shape. The current ITRS specifications for the 130 nm node at mask level are 10 nm for CD tolerances and 2 nm for the corresponding metrology precision. If these CD metrology specifications are interpreted in terms of achievable reproducibility of measurement results from a specific metrology tool or in terms of matching precision between different metrology tools, they can be met. If, however, these specifications are understood in terms of measurement results which have to be traceable to the definition of length in the SI system of units, they can hardly be met today. This is because the measurement uncertainties which have to be associated to the CD measurement results according to the guide for expression of uncertainty in measurement (GUM) [2] are larger than the above mentioned metrology precision. To obtain traceable measurement results, one needs to either use a calibrated CD standard with specified measurement uncertainties to transfer the length unit to the instrument used or one has to properly set up a physical model to analyze the measurement profiles of the instrument correctly in the meaning of metrological traceability. The latter procedure usually is applied by metrology institutes, which disseminate the length unit to industry by means of calibrated standards.

Photomask CD standards were already developed in the past and still are in use today. Namely, there were 5 inch standards available from the NIST [3] and the BCR [4]. They consisted of AR chromium films on 5009 quartz blanks with etched line patterns with CDs down to 0,5 µm or 0,3 µm. The smallest measurement uncertainties were given as 20 nm (k=2). However, to our knowledge, currently these calibrated CD mask standards are no longer available and new types of standard are not yet on the market.

In this contribution we will describe a project which is aiming at the development and calibration of new photomask CD standards. Within the project, mask manufacturers, manufacturers of mask metrology equipment and calibration laboratories from Germany are cooperating.

The basic characteristics of the new standards are:

6025 mask format, AR chromium blank, Chrome on quartz as well as attenuated PSM masks, CDs down to 0,2 µm (design is prepared down to nominally 0,1 µm, suitable for further nodes), lines and contacts, isolated and dense structures, opaque and clear structures, x- and y-orientation and additional pitch structures, all structures positioned in a regular die pattern for easy automated measurements. Measurement uncertainties targeted at are below 15 nm for CD (k=2). The principal design of the standard mask was defined and first prototype masks were manufactured. These prototypes were investigated by different metrology tools with respect to smallest resolved features, line edge roughness, edge slope, details in edge transition region, CD linearity, corner rounding and other characteristics. We will describe the present status and future activities of the project.

2 Layout of mask standards

2.1 Overall layout

On the 6025 mask, a 3x3 grid of 9 identical dies with 40 mm die size was chosen. For alignment purposes NIKON fiducials were used, and an additional regular pattern of auxiliary alignment crosses was placed near the mask edges, see Fig. 1.

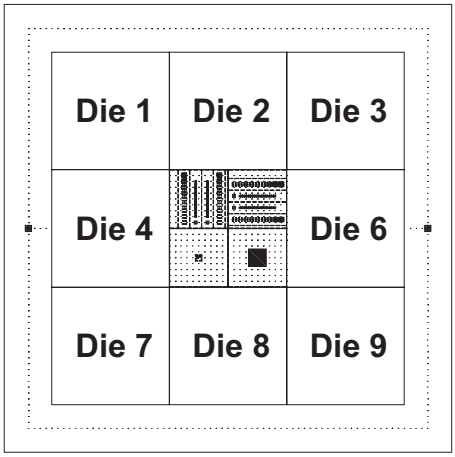

Fig. 1 Overview of mask layout.

During prototype development all 9 dies served for variation of process parameters to obtain information for optimized structure quality. On final masks, only structures within the central die will be calibrated. The other dies can be used to transfer measurement results for everyday calibration purposes or they can be calibrated later if e.g. the central die has been damaged.

2.2 Die layout

Within the 40 mm die there are 4 different areas: two quarters show the CD test structures in horizontal and in vertical orientation, within the third quarter are different pitch structures and the fourth quarter contains a larger transparent field for transmission 100 % reference calibration. The pitch structures each consist of 26 lines and spaces (1:1) with the following nominal pitch values: 10 µm, 4 µm, 2 µm, 1 µm, and 0,4 µm. Within each of the two quadrants containing the CD test structures, there are two blocks of structures, one for smallest CDs up to 5 µm and one for larger CDs up to 500 µm. The CD steps are as follows:

55 fine-CD test structure groups:
CD from 100 nm to 5 µm with 200 µm pitch

- 100 ... 500 nm, step 20 nm = 21 groups
- 540 ... 900 nm, step 40 nm = 10 groups
- 1000 ... 1600 nm, step100 nm = 7 groups
- 1800 ... 5000 nm, step 200 nm= 17 groups

18 coarse-CD test structure groups:
CD from 5 µm to 500 µm with 1 mm pitch

- 6 ... 10 µm, step 1 µm = 5 groups
- 20… 50 µm, step 10 µm = 4 groups
- 100 …500 µm, step 50 µm = 9 groups

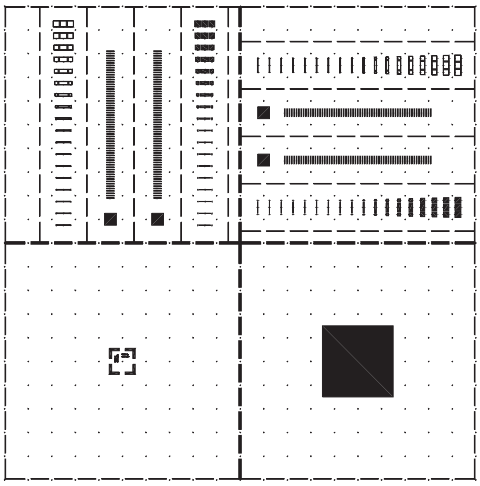

Fig. 2 Die layout of new mask standard.

The basic layout of the smaller CD test structure groups is shown in Fig. 3 below exemplarily by means of the nominal 3 µm structure group. It consists of a main line structure in isolated as well as differently dense environments (1:1…1:5) and a square pattern, again isolated as well as grouped. Each of the 12 structure elements uses an area of 50 µm x 50 µm. The structures are identified by label fields (A-L) and alignment L-bars at the left. In addition to this and also for assistance during measurement, the measurement window size of 5 µm height is indicated by two auxiliary lines next to the measurement sections.
The opaque line structures are conductively linked to the chromium coverage on the mask to reduce residual charging effects during e-beam measurement. For this, additional Cr lines are arranged horizontally to realize electrical contact of the opaque measurement line structures with the surrounding chromium film, see Fig. 3 on the left side.

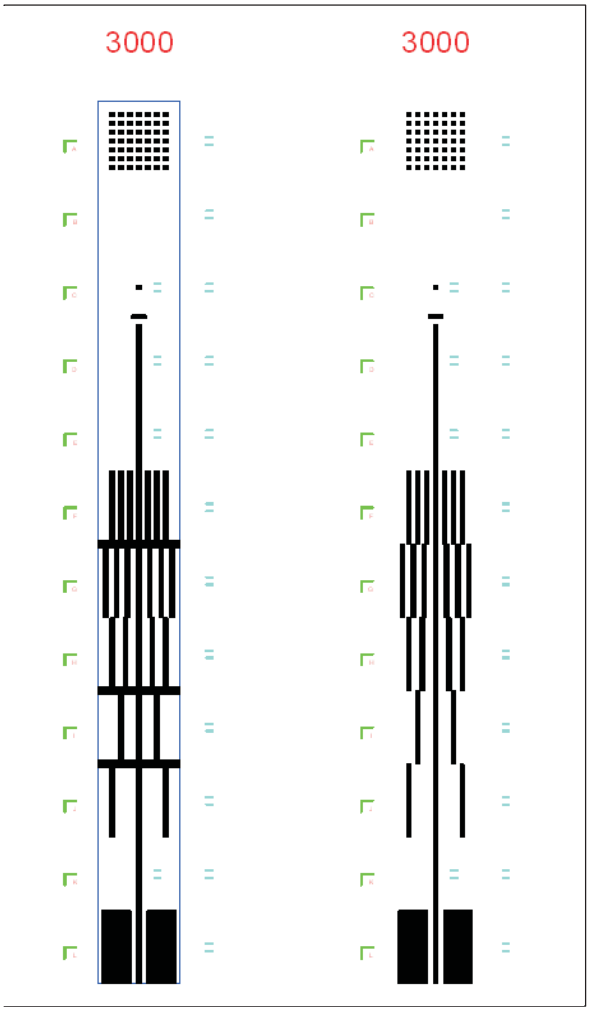

Fig. 3 Layout of CD test structure group, see text (left: opaque structures, right: clear structures).

3 Production of mask standards

Two different mask blank suppliers were chosen to provide 6025 blanks with antireflective chromium layers. The layer thickness of blanks was 70 nm and 80 nm respectively. We used one of the blanks for first tests (*test mask*) and the other for production of an improved *prototype mask*. In addition to the COG masks, also attenuated phase shift masks were produced (MoSi with 6 % transmission).
The patterning of the masks was performed by different electron shaped beam writing tools, working with 20 keV or 50 keV primary electron energy. The mask shops either used their standard data fractioning/ preparation and writing schemes or they used the 9 different dies on the mask layout for process optimization. Typical e-beam writing times of the full pattern are about 6-7 hours.

3.1 Mask blank investigation

The mask AR chromium thin films were characterized by means of depth-resolved XPS analysis to investigate their composition profile. It is known, that the AR layer of chromium and the chromium itself can show different dry etching rates, which may result in a fine structure within the edge transition region. It is therefore important to get information on the AR chromium film composition.

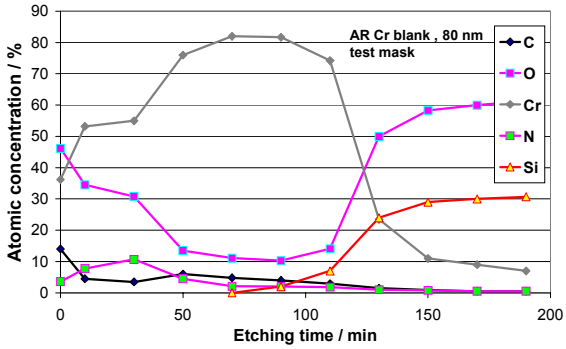

Fig. 4 XPS depth composition analysis of the first test AR COG mask (80 nm layer thickness).

Fig. 4 shows the result of an XPS depth composition measurement of the first test mask blank with 80 nm nominal thickness. One can recognize a change in the gradient of the oxygen contribution at about 10 min and again at about 40 min etching time (≈ 0,8 nm /min.), which corresponds to etching depths of about 5-10 nm and about 30-35 nm respectively. In comparison to these results, Fig. 5 shows the depth composition profile of the other COG AR blank, now with 70 nm nominal chromium thickness.

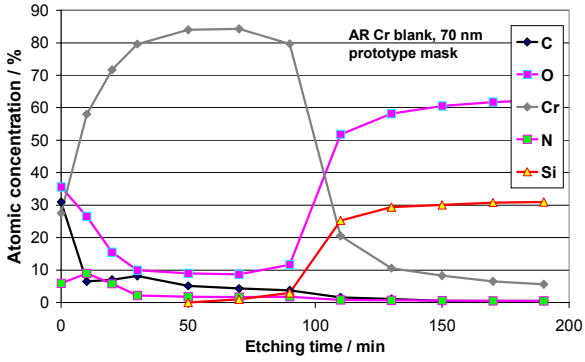

Fig. 5 XPS depth composition analysis of the prototype AR COG mask (70 nm layer thickness).

In this case, a gradual increase of the chromium content is observed, without any obvious discontinuity as for the test mask shown in Fig. 4. In chapter 4 these differences of composition profile and their possible impact on edge profile will be further discussed.
The different mask blanks were also characterized by means of spectral reflectometry. The results are given in Fig. 6. Whereas the test mask blank reveals its minimum in reflectivity at about 450 nm, the prototype mask is designed to show low reflectivity down to below 200 nm and can therefore also be used in 193 nm lithography.

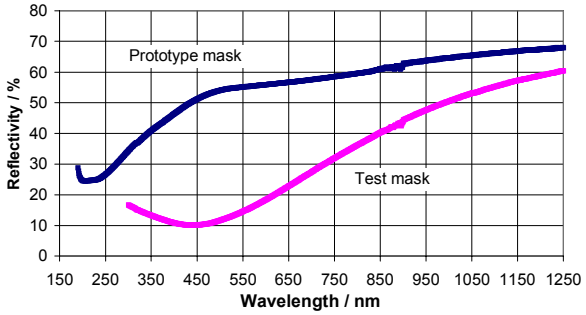

Fig. 6 Spectral reflectivity of the AR chromium films on the test mask blank and the prototype mask blank.

4 Characterization of test and prototype masks

The test mask and the prototype masks were processed and afterwards inspected and analyzed by means of different metrology tools. Questions concerning the following measurement quantities should be answered by the outcome of the analysis: slope and details within edge transition region, line edge roughness, smallest resolved features, iso-dense bias at smallest features, CD linearity and CD off-target.
The better the edge will be physically defined, the easier would be the agreement of the results from different metrology tools to be achieved.

4.1 Investigation of edge transitions

Ideally, the edge profile should have a rectangular shape, like it is e.g. assumed in scalar diffraction theory of optical microscopy [5]. Realistically, however, one normally observes a line edge shape similar to a trapezoidal profile with more or less steep edge slopes, see e.g. the corresponding SEMI P35 standard on line CD metrology [6]. If the edge flanks can be approximated by a linear function (for geometric shape as well as the relevant material properties), the physical modeling of the interaction between probe and sample is easier than for more complex edge shapes. It is thus crucial to get more reliable information on the details of the edge transition region.

4.11 Results on first test mask

For this, AFM measurements on a set of characteristic lines as well as contact squares were performed on the masks. It was decided to perform measurements on the structures with nominal dimensions of 1 µm, 0,5 µm and 0,3 µm. For AFM imaging, intermittent contact or tapping mode was used with artificially grown sharp carbon contamination needles (EBD tips) as probing elements.

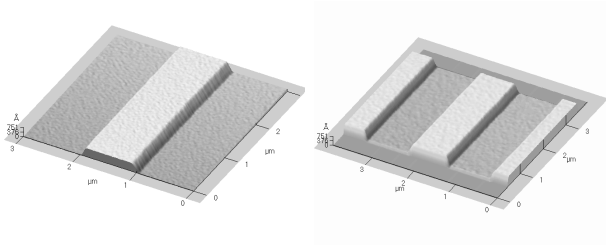

Fig. 7 AFM profiles of single and dense lines with 1 µm nominal (0,89 µm actual) CD on the test mask.

Fig. 7 shows AFM imaging results on the test mask at the 1 µm nominal line structures, whereas in Fig. 8 measurement results on the 500 nm line and space structures are compared.

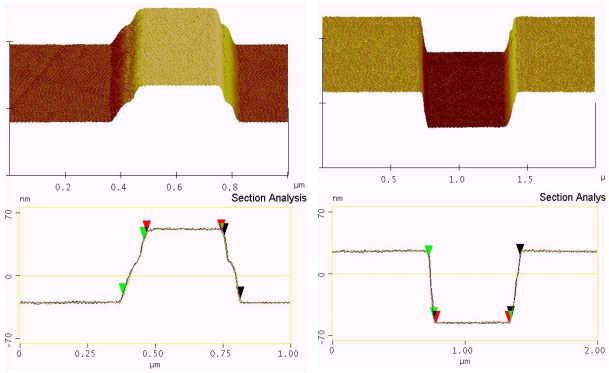

Fig. 8 AFM profiles of nominally 500 nm line (measured 400 nm) and space (measured 610 nm) structures on the test mask.

Obviously, the groove does show a sharper edge transition with a better defined slope compared to the line structure, which also exhibits a discontinuity in its edge. This behaviour may result from etch loading effects and is more clearly visualized in Fig. 9.

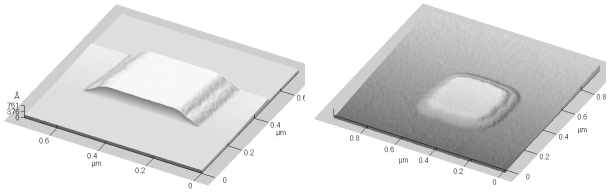

Fig. 9 AFM profiles of nominally 500 nm line and dot structures on the first test mask.

In Fig. 9 one can clearly observe a fine structure in the edge transition region, which is caused by a change of slope. We attribute these different edge slopes to different etching rates on the layers of the AR chromium film which we had to deal with on the first test mask, see Fig. 4. The imaging results shown in Fig. 10 on the 300 nm line structures support this assumption.

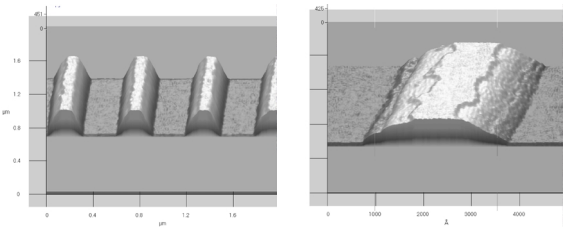

Fig. 10 AFM profiles of dense opaque lines with 300 nm nominal CD on the test mask.

In the enlarged view on the right image, a very thin top layer on the chromium line and a second discontinuity on the flanks were observed in agreement with the discontinuities which are visible in the composition profile in Fig. 4.

4.12 Results on prototype mask

The AFM edge investigations were also conducted on the prototype mask. This mask, whose composition profile is shown in Fig. 5, was produced in another process as the first test mask. Figure 11 shows typical AFM line images.

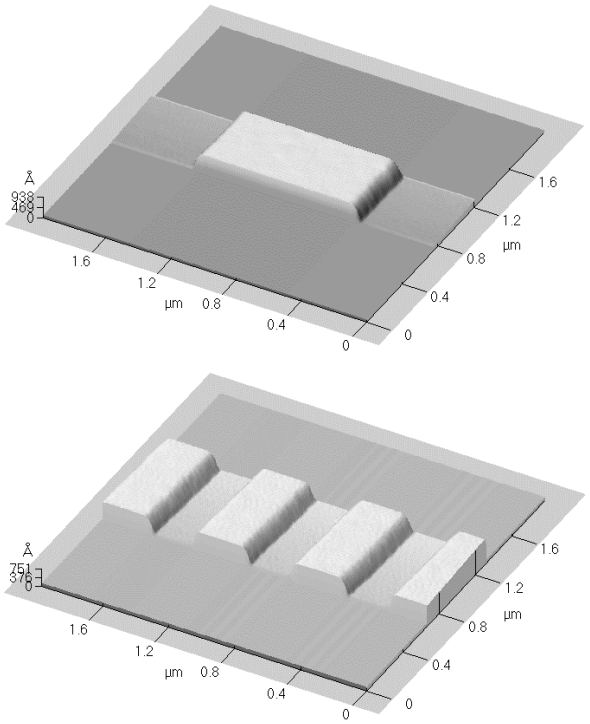

Fig. 11 AFM profiles of a single line with 1 µm nominal and 0,9 µm measured CD (top) and a group of dense lines with 300 nm nominal and 210 nm measured CD (bottom) on the prototype mask.

On the prototype mask the dense line structures down to 120 nm nominal CD could be resolved with reasonable line quality, see Fig. 12 as an example.

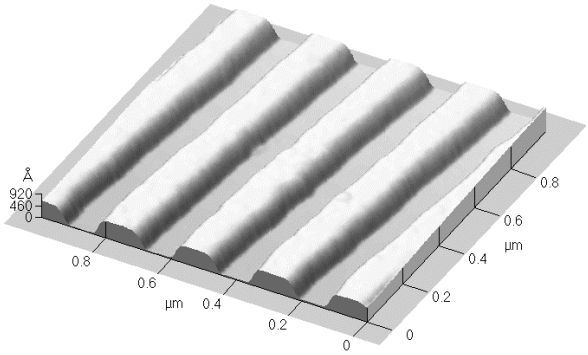

Fig. 12 AFM profiles of the group of dense lines with 120 nm nominal CD on the prototype mask.

4.13 Edge angle measurements

On both mask types, the edge angles were determined by means of AFM measurements with the e-beam deposited (EBD) sharp carbon needle tips. The EBD-tip geometry is specified by the supplier with a half cone angle smaller than 5 ° and a tip radius smaller than 10 nm, thus edge flanks up to 85 ° should in principle be measurable. Table 1 summarizes our edge angle characterizations. The steepest edge flanks are close to 70 ° on the prototype mask. Re-calibrations of edge angles with another type of AFM and EBD tip showed values even above 70 °.

Edge angle [°]	line / space	test mask	prototype mask
@ CD 500 nm	line	42	64
@ CD 500 nm	space	47	68
@ CD 300 nm	line	43	67
@ CD 300 nm	space	-	57

Table 1 Edge angles within dense line structures determined on the two different types of masks.

The AFM investigations clearly showed the differences in edge angle and profiles of the two masks. These findings were supported by corresponding top view SEM measurements, which also clearly revealed the discontinuity within the line edge region on the test mask, see Fig. 13.

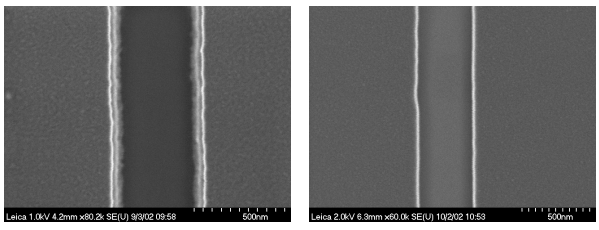

Fig. 13 Low voltage SEM top view images of nominally 320 nm clear lines on the test mask (left, 1 keV) and the prototype mask (right, 2 keV).

4.14 Line edge roughness

Measurements of line edge roughness (LER) were performed by different metrology tools, namely AFM, SEM and optical microscopes. The resolution of the latter class of instruments is diffraction limited and does not allow to detect high frequency LER components with wavelengths smaller than about λ/2. On the other hand, the AFM method offers high resolution but its measurement time is comparatively large, and it therefore might have drift problems which interfere with high precision LER measurements. CD-SEM measurements are a suitable alternative method, however, LER qualifications require good signal to noise ratio and this normally raises the problem of e-beam induced contamination on the sample. Figure 14 shows examples of LER characterization on the two masks by means of optical microscopy with visible light. The variation of the line edge roughness shows dominant components with a characteristic period of about 2,5 µm which might be attributable to the stitching of individual exposure areas applied during e-beam writing. This characteristic edge position variation is more pronounced in the case of the prototype mask with its improved edge slope. These optical LER results were confirmed by CD-SEM characterizations. The 3σ-RMS LER values were found to be between 5 nm and 8 nm on the lines.

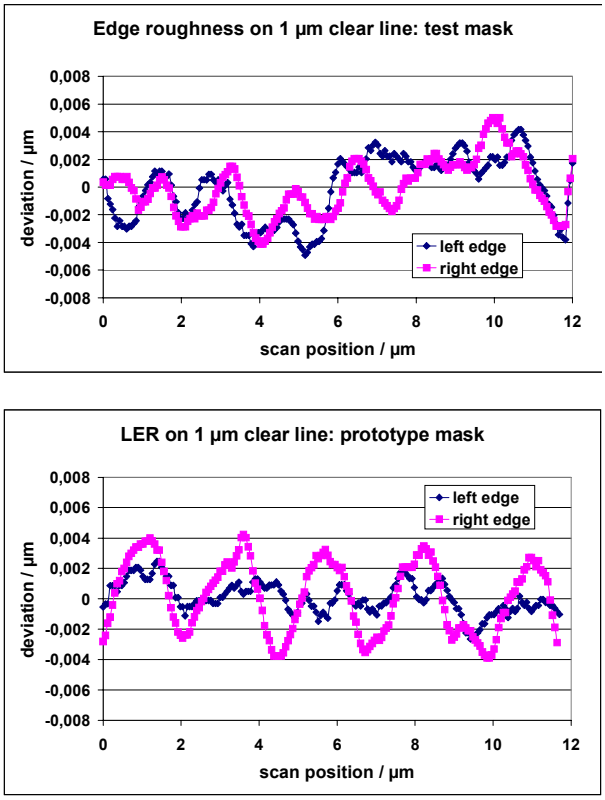

Fig. 14 LER profiles determined by optical microscopy with visible light on both types of mask.

4.15 Corner rounding

The contact and dot structures were also used for characterization of corner rounding. Fig. 15 shows an AFM image of a 500 nm dot structure. Typical values for corner rounding radius at nominally 1 µm square structures were 150 nm and for nominally 0,5 µm structures we found 100 nm on both type of masks. However, a standardized definition of corner rounding radius determination is not yet available. This defintion is prepared in a SEMI task force on photomask qualification terminology [7].

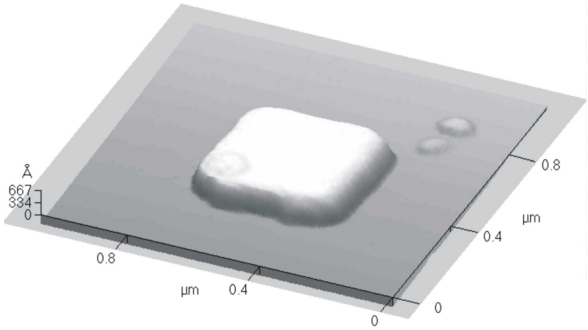

Fig. 15 AFM image of a nominally 500 nm dot structure on the prototype mask.

5 CD measurements on test and prototype masks

On both mask types CD comparison measurements were performed by means of different microscopy methods. Optical as well as CD-SEM instruments were applied in this comparative study. The applied commercially available optical CD metrology tools (MueTec M5k (248 nm) [8, 9], Leica LWM250UV (365 nm) and LWM270DUV (248 nm)) all used a CCD camera detection for analysis of the transmitted light intensity. They were operated in automated measurement mode with several measurement runs and achieved repeatabilities < 1 nm up to 3 nm, depending on the structure size and geometry. The PTB (German metrology institute) uses transmission microscopy with object scanning and slit detection of i-line radiation, which allows to achieve measurement uncertainties of 20 nm (k=2) on line structures [5]. The instrumentation used for SEM characterization was a Hitachi S4700 in one case and the PTB used a special metrology low voltage SEM, see e.g. [10].
Both of the DUV commercial optical metrology tools were only basically calibrated for image magnification by pitch measurements, but no customized CD calibration was applied. The CD values in these cases were determined using a 50 % threshold. For a comparative analysis we therefore decided to refer all CD measurement results to the result of the PTB optical transmission measurement result at the 1 µm nominal line structures. This offset was corrected for all measurement results on line structures.

The pitch reference structures on the masks which were used for calibration of image magnification were also checked by means of LMS IPRO and LMS 2020 pitch calibrations. As expected, pitch deviations of the gratings are very small: $< 10^{-4}$ for the 1 µm graduation and $< 5*10^{-6}$ for the 10 µm graduation.

5.1 CD measurements on test mask

In Figure 16, the original measurement values before offset correction from different metrology tools on isolated clear line structures on the test mask are shown for comparison. The SEM results are based on application of a 50 % edge threshold whereas the AFM CD value is based on the measured width of the space at the chromium/quartz interface.

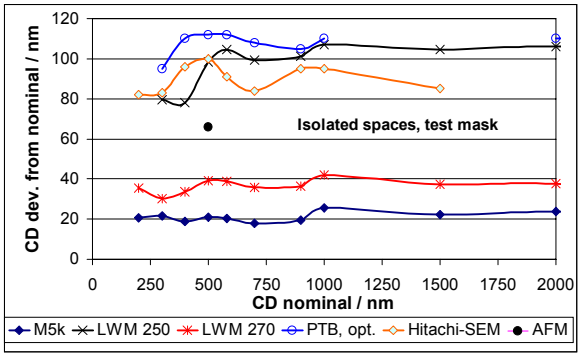

Fig. 16 CD measurement results of different metrology tools on isolated clear lines on the test mask *before offset correction*.

In Figures 17-20 the results of CD measurements on the test mask with all values referred to the PTB optical transmission result at 1 µm are shown.

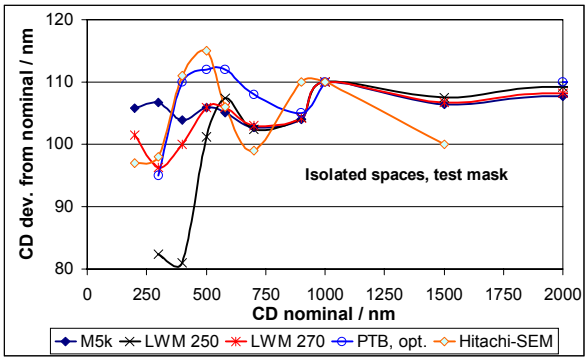

Fig. 17 CD measurement results of different metrology tools on isolated clear lines on the test mask.

The test mask showed a comparatively large CD off-target of 110 nm. Spaces are larger and lines are smaller than the nominal values by this amount at 1 µm width. The CD linearity is within 10 nm, apart from the smallest structures. For the isolated clear structures, there is a deviation of the LWM250UV results compared to the other systems. This was expected since the CD linearity range for this measurement system is specified down to 0,45 µm (resp. 0,35 µm for LWM250DUV). In case, structures smaller than this limit are measured, a specific point-to-point calibration is recommended.

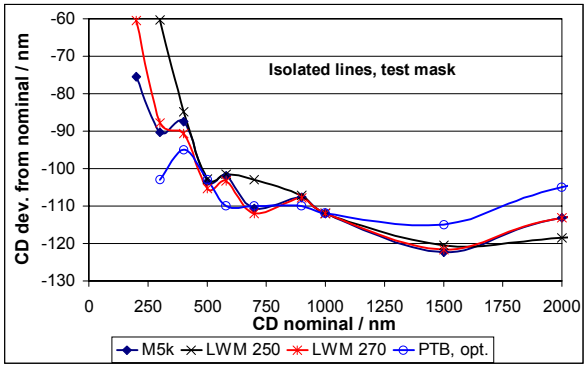

Fig. 18 CD measurement results of different metrology tools on isolated opaque lines on the test mask.

The following graphs show the measurement results on the dense transparent space and opaque line test structures.

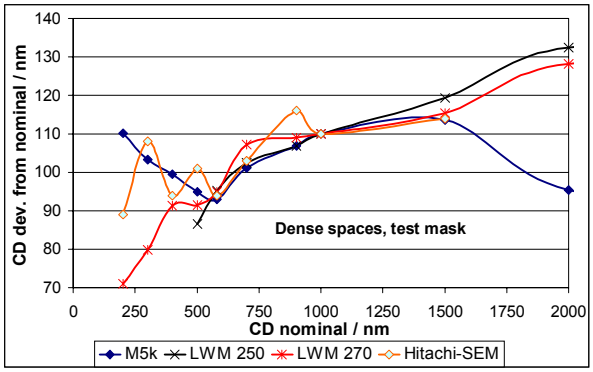

Fig. 19 CD measurement results of different metrology tools on dense clear lines on the test mask.

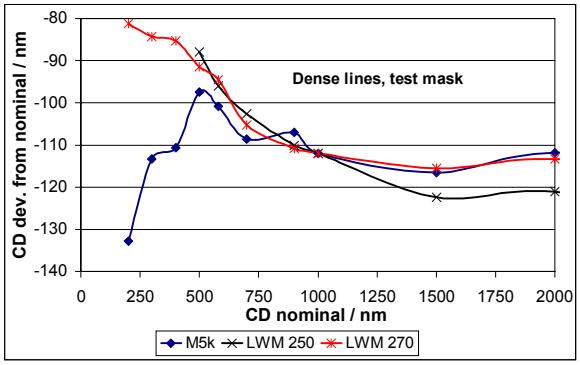

Fig. 20 CD measurement results of different metrology tools on dense opaque lines on the test mask.

In the case of dense structures, the differences between the optical tools are increasing for actual space widths smaller than 400 nm and for actual opaque line widths smaller than 300 nm. Furthermore, also the CD linearity of the dense transparent structures on the test mask seems to be slightly deteriorated compared to the situation for single spaces.

5.2 CD measurements on prototype mask

We present the CD comparison measurement results analogous to the preceding section 5.1, starting with the results for the isolated or single line structures.

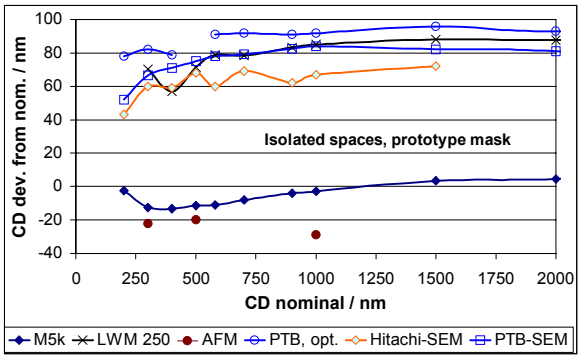

Fig. 21 CD measurement results of different metrology tools on isolated clear lines on prototype mask *before offset correction*.

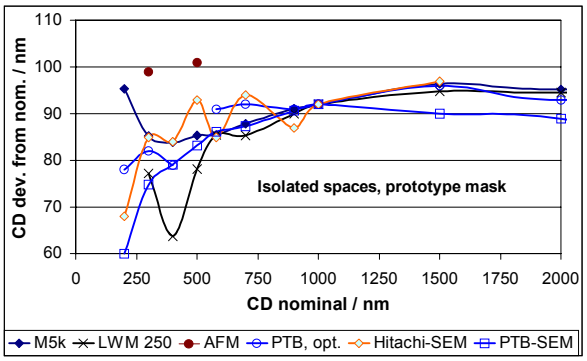

Fig. 22 CD measurement results of different metrology tools on isolated clear lines on prototype mask.

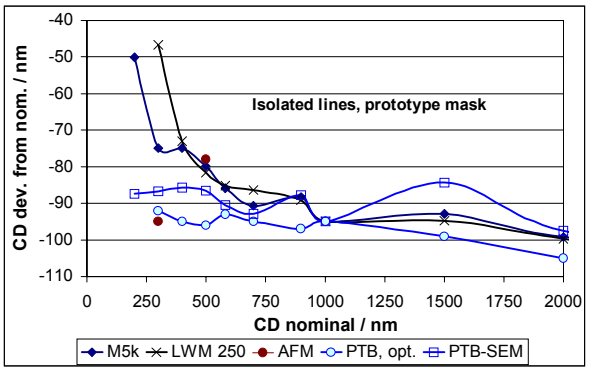

Fig. 23 CD measurement results of different metrology tools on isolated opaque lines on prototype mask.

Also in case of the prototype mask we observed a comparatively large CD off-target value of 90 nm, spaces again were enlarged and opaque lines were too small compared to nominal values. CD linearity on the isolated features is within 10 nm with a slight decrease for smaller CD for the clear structures. On the dense structures, CD linearity is on the order of 30 nm.

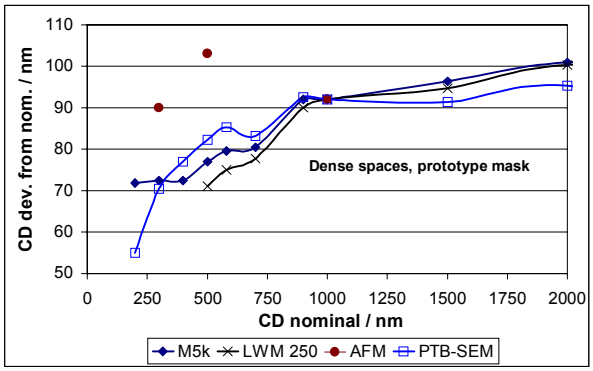

Fig. 24 CD measurement results of different metrology tools on dense clear lines on prototype mask.

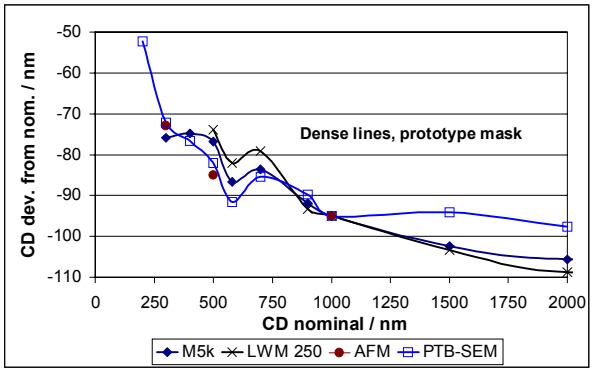

Fig. 25 CD measurement results of different metrology tools on dense opaque lines on prototype mask.

If we compare Fig. 17 and 18 on the isolated features with their corresponding figures 22 and 23, we can recognize some similarities. That is, the characteristic behaviour of the optical CD measurement results seems to be primarily due to instrument response functions and only to a small degree dependent on the edge details of the two different masks, which showed stronger differences.

Because with some of the instruments, very small nominal CDs down to or even smaller than actually 200 nm were characterized, in the following SEM images the iso-dense transition region for the smaller clear structures on the prototype mask are shown.

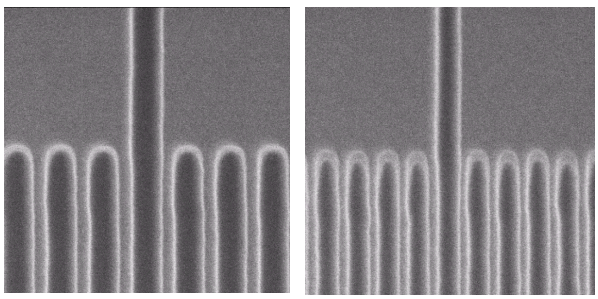

Fig. 26 SEM images of iso-dense transition regions for two clear structures with nominal CD of 200 nm (left) and 140 nm (right) on the prototype mask.

Whereas the nominal 200 nm features (actually about 260 nm) are well resolved, on the nominally 140 nm

features a decrease of edge slope in the line end is observed. For further studies we will also use an aerial image measurement system (AIMSfab 193) to qualify if smallest structures are well resolved, or if bridging or other defects have occurred. This system will also be applied for characterization of the attenuated 193 nm MoSi phase shift mask, developed within the project.

6 Conclusion and Outlook

We described the basic layout of a mask which should serve as a new CD standard for line and square features. A first test mask and an improved prototype mask were produced and characterized by different measuring instruments. We quantified important parameters like line edge roughness, edge slope, edge geometry details, resolution of patterns, corner rounding, CD linearity and CD off-target.
From the edge inspection results on the first test mask, we got important information about mask blank properties, too.
The prototype mask on the other side showed improved edge quality and already revealed very promising characteristics, but there is still room for further optimization. This especially holds for even better edge slope and smaller CD off-target results.
The first masks with the new design are already used by the partners within the project for qualification of different CD instrumentation and measurement processes. It is planned to produce some more prototype masks to achieve the above mentioned goals in the very near future. After this optimization process, we will be ready to offer the calibrated standards to interested third parties.

7 Acknowledgements

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8 Literature

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Description of table of images shown on the next two pages to illustrate the 12 elements of the fine CD test structure groups. The SEM images were made on the transparent structures with 780 nm nominal CD on the prototype mask:

	Description of element
A	Array of squares (contacts, holes), 1:1
B	free (=> can be used for single squares)
C	single squares (=> can be used for line end)
D	isolated or single line
E	isolated or single line
F	dense lines/spaces 1:1
G	dense lines/spaces 1:1,5
H	dense lines/spaces 1:3
I	dense lines/spaces 1:5
J	dense lines/spaces 1:2
K	isolated or single line
L	line/space within inverse environment