Results of an international photomask linewidth comparison of NIST and PTB

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ABSTRACT

In preparation for the international *Nano1* linewidth comparison on photomasks between nine national metrology institutes, the National Institute of Standards and Technology (NIST) and the Physikalisch-Technische Bundesanstalt (PTB), initiated a bilateral linewidth comparison in 2008, independent of and prior to the *Nano1* comparison in order to test the suitability of the mask standards and the general approach to be used for the *Nano1* comparison. This paper reports on the current status of the bilateral comparison. In particular the methods for linewidth metrology applied at NIST and PTB and its major uncertainty contributions will be discussed based on actual measurements results for both of the mask standards chosen for the bilateral comparison.

Keywords: linewidth; CD metrology; uncertainty components; Nano1; international comparison; MRA; photomask

1 INTRODUCTION

In a contribution to the BACUS SPIE conference in 2008 [1], the background and motivation of the bilateral mask linewidth comparison between NIST and PTB was described. A basic task of the national metrology institutes is to compare their standard measurement services on a regular basis by conducting international comparisons in support of the Mutual Recognition Arrangement (MRA) of national measurement standards [2]. In the area of photomask linewidth metrology, the latest international comparison dates back to 1996 [3]. The next international photomask linewidth comparison is currently under preparation, piloted by NIST and called *Nano1* with currently nine national metrology institutes (CN, DK, FR, DE, IT, JP, KR, TW, US) planning to participate. In order to test the suitability of the mask standards and the general approach to be used for the *Nano1* comparison, NIST and PTB have started a bilateral linewidth comparison in 2008, independent of and prior to the *Nano1* comparison.

The mask standards to be used for the bilateral comparison between NIST and PTB are a NIST Standard Reference Material (SRM) 2059 mask standard [4] and a mask standard of PTB design [5] which was manufactured and made available for the bilateral comparison by the Advanced Mask Technology Center (AMTC) in Dresden, Germany. AMTC is providing two nominally identical masks; one will be used for this bilateral comparison and the other for the multilateral *Nano1*. Characterizations of the masks at both metrology institutes are under way and exchange of one of the masks has been realized recently; however the complete set of measurements involving different characterization methods and subsequent analysis of results of the bilateral comparison is not yet finalized. We therefore have to restrict the discussion of the results in this paper in order to not compromise the still running bilateral comparison.

Linewidth or critical dimension (CD) measurements on the photomask standards will be carried out by a combination of different techniques, namely CD scanning atomic force microscopy (AFM), scanning electron microscopy (SEM), and ultraviolet (UV) transmission optical microscopy at NIST, and CD-SEM and UV optical transmission microscopy at PTB, supported by additional AFM characterizations at PTB. The smallest line feature sizes present on the mask standards are nominally 250 nm on the NIST SRM 2059 mask standard and nominally 40 nm on the mask standard of the PTB design. We will measure and compare the results down to the nominal 100 nm line features on the PTB mask.

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The definition of the measurands are clearly stated and defined as the width of the line at 50 % of the line feature height. For every measurement method applied, a suitable model for determination of the measurand from the microscope image has been developed and will be applied. For each of the linewidth measurement results the associated measurement uncertainty values will be specified according to accepted international guidelines [6]. The result of a linewidth measurement is not just a number, but a probability distribution of likely linewidth values. The square root of the variance of this distribution is the standard measurement uncertainty, which when multiplied by a coverage factor k becomes the expanded uncertainty usually reported [6]. National metrology institutes usually use $k = 2$ which corresponds to a 95 % probability that the true value of the measurand lies in the interval *measured value* ± *expanded uncertainty*.

2 APPROACH, TRANSFER STANDARDS AND MEASURAND DEFINITION OF THE BILATERAL PHOTOMASK COMPARISON

2.1 Approach to the bilateral comparison

Two binary chrome-on-glass (CoG) photomask standards, both of the 6025 mask format (152 mm x 152 mm x 6.35 mm), with different design and from different mask manufacturers, were chosen for the bilateral linewidth comparison. In addition, a 193 nm MoSi half-tone phase shift mask with identical format and design to one of the CoG masks is also available to be used for the comparison measurements. However, priority is on the measurements of the CoG masks.

NIST will provide an SRM 2059 CoG photomask linewidth standard; the other CoG mask as well as the phase shift mask is provided by PTB for this bilateral linewidth comparison. Both institutes will measure their respective mask standards first by the different methods applied for traceable photomask linewidth metrology. After completion of characterization of the mask standards they will be interchanged to give both institutes the opportunity to measure the other institute's mask standard. The measurement results on both masks will then independently be analyzed and documented by each institute. Afterwards the results will be compared, analyzed and reported.

Conducting this bilateral NIST-PTB photomask linewidth comparison prior to the international *Nano1* linewidth comparison has some advantages. The suitability of both types of mask standards for comparison purposes can be tested and compared, and the already prepared draft technical protocol for the *Nano1* comparison can be checked for practicability, unambiguousness and completeness.

The mask standard provided by NIST for the bilateral comparison is available from the NIST Office of Standard Reference Materials as SRM 2059. A detailed sample certificate for this type of SRM is available via [4] including a list of references (see *e.g*. [7]).

The mask standard made available by the PTB for the bilateral comparison was originally designed and developed within a project of several partners from mask industry and the PTB in Germany (see [8]). These new mask standards can be produced by the mask manufacturing companies who participated in the project, namely MZD Photronics, Dresden, and AMTC/TOPPAN, Dresden. AMTC/TOPPAN provided a CoG mask of this design for the bilateral comparison and has also provided a separate CoG mask with the same design for the *Nano1* comparison.

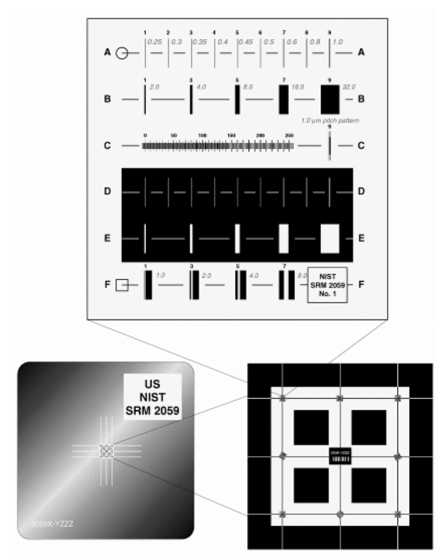


FIGURE 1 NIST SRM 2059 photomask linewidth standard.

2.2 Description of the SRM 2059 photomask standard

NIST SRM2059 is an antireflecting etched chrome binary photomask on a 152 mm x 152 mm x 6.35 mm quartz substrate. It contains calibrated isolated linewidths and spacewidths ranging from 0.25 µm to 32 µm (Fig. 1). The certified values are traceable to the definition of the meter with expanded ($k = 2$) uncertainty typically 18 nm for linewidth and spacewidth, and 6 nm for pitch (maximum uncertainty 25 nm for linewidths and spacewidths and 9 nm for pitch). It is available from the NIST Office of Standard Reference Materials [4].

2.3 Description of the PTB photomask standard

The PTB-designed 6025 quartz mask standard contains a 3 x 3 grid of 9 identical dies with 40 mm die size, see Fig. 2. Normally only structures within the central die will be calibrated. Within the 40 mm die there are 4 different areas (Fig. 2b): two quarters show the CD test structures in horizontal and in vertical orientation, within the third quarter are different pitch structures and additional 1D-grating structures for scatterometry analysis and the fourth quarter contains a larger transparent field for 100 % transmission reference calibration along with additional line and space structures in non-orthogonal orientation.

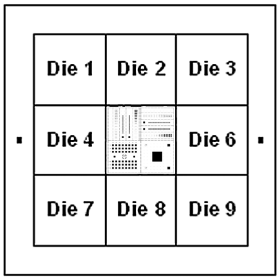


FIGURE 2A Overview of mask layout.

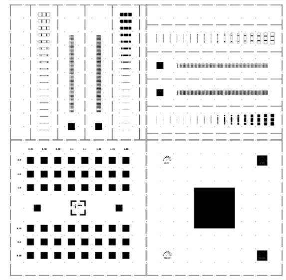


FIGURE 2B Die layout of new mask standard.

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 of the smaller test structures to be used in the comparison are shown below.

67 fine-CD test structure groups:
CD from 40 nm to 5 µm with 200 µm pitch

- 40 nm to 100 nm, step 5 nm = 12 groups
- 100 nm to 500 nm, step 20 nm = 21 groups
- 540 nm to 900 nm, step 40 nm = 10 groups
- 1000 nm to 600 nm, step100 nm = 7 groups
- 1800 nm to 5000 nm, step 200 nm = 17 groups

The basic layout of the smaller CD test structure groups is shown in Fig. 3 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 to 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.

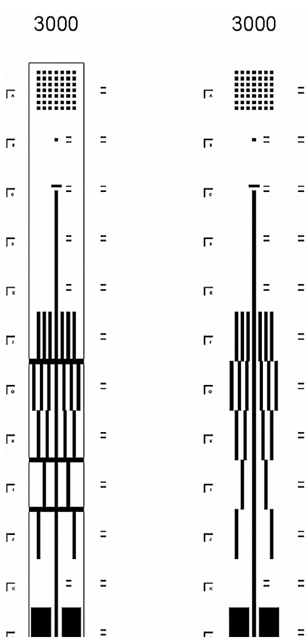


FIGURE 3 Layout of CD test structure group; (left: opaque structures, right: clear structures).

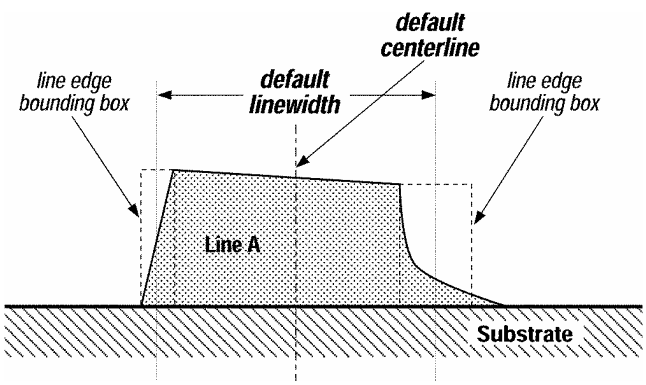
In addition to this and also for assistance during measurement, the measurement window size of 5 µm height is indicated by two auxiliary lines next to the measurement sections. The opaque line structures are conductively linked to the chromium coverage on the mask to reduce residual charging effects during e-beam measurement.

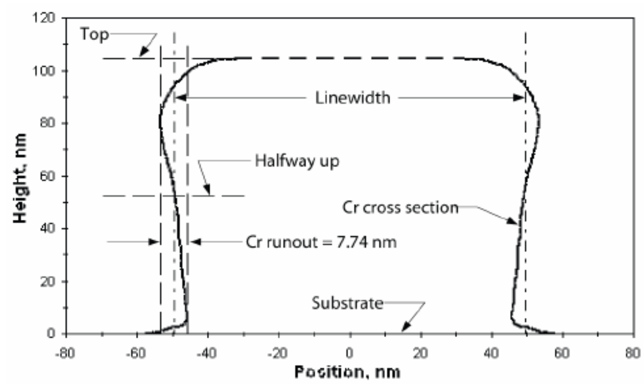
For the bilateral comparison the following features and feature sizes were chosen to be used for measurements on the mask standard of the PTB design:

- opaque line and transparent trench structures, isolated as well as 1:1 dense structures
- nominal CD values: 4000 nm, 2000 nm, 1000 nm, 780 nm, 580 nm, 500 nm, 400 nm, 300 nm, 200 nm and 100 nm

2.4 Definition of the measurand

If the linewidth of an irregular object - and line structure on photomasks are in fact non-perfect, irregular objects if imaged on the nanometer scale - is to be characterized by a single number, then a useful definition of edge is required. In practice the definition of edge will depend on the subsequent application of the artifact [9], but for this comparison a definition intrinsic to the artifact should be used because the ultimate applications of measurements are not known.


default
centerline
line edge
bounding box
default
linewidth
line edge
bounding box
Line A
Substrate


Top
Linewidth
Halfway up
Cr cross section
Cr runout = 7.74 nm
Substrate
Height, nm
Position, nm

3.1 UV transmission microscopy results on the SRM 2059 photomask standard

The features on these photomasks are measured on the NIST UV Scanning Microscope [11], a transmitted-light optical microscope used here at a wavelength of 365 nm. The support structure of this high precision measuring microscope is based on a kinematic design called the Stewart Platform. The specimen stage position is computer controlled in *x*-, *y*-, and *z*- (focusing) axes for positioning, and the stage is scanned along the *x*-axis for measurements by driving the *x*-motor at constant velocity with the stage position monitored by a laser interferometer. The illumination geometry is Köhler type.

The specimen can be measured in visible or ultraviolet transmitted light by scanning the stage, while the intensity of the magnified image is measured through a slit sampling aperture fixed on axis in the image plane and the position of the scanning stage is measured with a laser interferometer. Intensity and position data pairs are collected during the scan and saved as an array in the computer.

NIST has been using two different optical imaging models: One model uses the modal waveguide method [12], and the other uses the integral form of Maxwell's equations [13]. The microscope image data are compared with optical model images to determine the best image match and the corresponding parameters, in particular the feature width.

To obtain the highest possible accuracy the SRM 2059 calibrations were referenced to AFM measurements by using the UV Microscope in comparator mode. After completion of the instrument upgrade, the NIST UV Microscope will be better characterized, and fully independent optical feature width measurements will be possible. Major uncertainty components in descending order, determined by image library matching, are illumination NA, objective NA, Cr *n*, Cr *k*, repeatability, focus, and Cr thickness. Based on current experimental data on the SRM 2059 mask, we estimate that the expanded uncertainties ($k = 2$) for optical measurements on isolated line and spacewidth photomask features, without the use of AFM reference metrology, will be approximately 14 nm to 20 nm over a feature width range of 250 nm to 4 µm once the upgrades are completed. The repeatability of the optical linewidth measurements can be characterized by standard deviations of the mean – which typically range from 0.7 nm to 4 nm depending on the actual CD measurement structure on the mask.

3.2 Atomic force microscopy measurements on the SRM 2059 photomask standard

One of the techniques we use in this comparison is critical dimension atomic force microscopy (CD-AFM). CD-AFM is more sophisticated than conventional AFM and is based on technology that was developed by Martin and Wickramasinghe in the early 90s. [14] The most notable differences are that force sensing in CD-AFM occurs along two axes (one vertical and one lateral) and that the tool uses flared tips which allows imaging of near-vertical sidewalls such as the features found on photomasks. The specific instrument we will use for these measurements is a first generation commercial CD-AFM which is installed in our laboratory facilities at NIST. Using NIST methods and samples, we have developed this instrument into a reference measurement system (RMS) for performing traceable measurements of pitch, height, and linewidth [15-16].

Linewidth measurements on the CD-AFM have the same scale-related sources of uncertainty as pitch measurements. In addition, there are also certain classes of tip-related effects that are unique to the antisymmetric situation that occurs in linewidth metrology. The general linewidth uncertainty budget has already been presented in [1], and discussed in detail elsewhere [15-16].

The lower limit of combined standard uncertainty u_c for CD-AFM linewidth measurements on near-vertical ideal structures was determined to be: u_c (linewidth, $k = 1$) = $[(\mathrm{SD})^2 + (0.8\ \mathrm{nm})^2 + (2.2 \times 10^{-3} W)^2]^{1/2}$, with SD as the experimental standard deviation (or standard deviation of the mean, respectively) and W as the actual linewidth value. However, on realistic structures such as these, "higher order" tip effects – such as those pertaining to the flare shape, offset height, and feature sidewall profile – are not negligible but must be estimated for each individual measurement.

The measurement uncertainties for the linewidth at 50% of the feature height obtained by CD-AFM calibrations on the NIST SRM 2059 mask standard were determined as specified in the table below:

Nominal CD [µm]	0.25	0.30	0.35	0.4	0.45	0.5	0.6	0.8	1.0	2.0	4.0	8.0
Uncertainties for line features [nm, $k = 2$]	2.8	2.8	3.0	3.1	3.2	3.3	3.6	4.2	4.9	8.9	-	34.9

Uncertainties for space features [nm, $k = 2$]	3.1	3.2	3.3	3.4	3.7	3.8	4.1	4.8	5.5	9.5	18.2	35.7

Figure 5 shows the CD-AFM linewidth results – using the "middle width" (50 % height) – on the isolated line and space targets of the SRM 2059 mask. The absolute linewidth values were shifted by a constant offset to keep the comparison running blind. The non-linearity trends observed here are typical for the SRM 2059 masks.

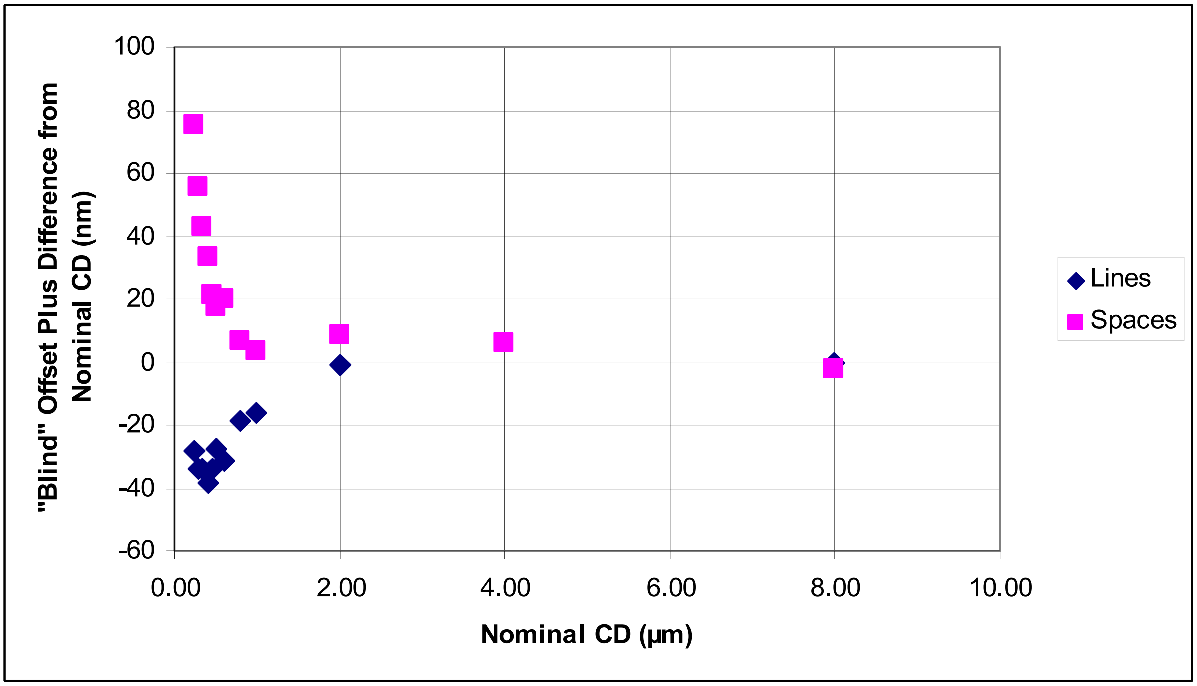


FIGURE 5 CD-AFM linewidth results (middle width) for line and space targets on SRM 2059. (Note: The indicated linewidth values were shifted by a contstant value to be close to nominal on large intervals in order to keep the comparison "blind".)

4 CHARACTERIZATIONS OF THE PTB MASK STANDARD

As already described before [1], the PTB uses two independent methods for model-based traceable linewidth metrology, namely UV transmission microscopy and scanning electron microscopy; both methods are supported by additional scanning probe microscopy measurements. In addition, NIST has already performed first CD-AFM characterizations on the PTB mask standard. We will describe the results in the following sections taking into account that the exchange of absolute CD measurement data is postponed until all measurements at both institutes are finished.

4.1 NIST CD-AFM microscopy results on the PTB mask standard

First CD-AFM results by NIST on the PTB mask standard are available and are discussed in this section. The following table shows the linewidth measurement uncertainties for top CD, middle and bottom CD as well as the sidewall slope angles. The sidewall shapes turned out to be pretty linear, so that a single sidewall angle value seems to be adequate in characterizing the feature edges.

Nominal CD [µm]	0.1	0.2	0.3	0.4	0.5	0.58	0.78	1.0	2.0	4.0
Uncertainties for space features top CD [nm, $k = 2$]	-	2.0	2.3	2.6	3.0	3.3	4.0	4.9	9.2	17.9

Uncertainties for space features middle CD [nm, $k = 2$]	-	2.5	2.8	3.0	3.4	3.6	4.3	5.2	9.3	17.9
Uncertainties for space features bottom CD [nm, $k = 2$]	-	3.2	3.4	3.6	3.9	4.1	4.8	5.5	9.5	18.0
Left sidewall angle [°]	-	87.7	88.5	88.1	88.3	87.5	88.2	88.0	86.9	86.5
Right sidewall angle [°]	-	91.3	89.2	89.1	87.5	87.5	87.3	87.6	87.9	87.9

Figure 6 shows the CD-AFM linewidth results – using the "middle width" (50 % height) – on the isolated line and space targets for the PTB mask. The absolute linewidth values were shifted by a constant offset to keep the comparison running blind. The outlier behaviour of the result on the 100 nm line target is believed to be real, but this will be confirmed subsequently. Due to tip problems, it was not possible to measure the 100 nm space target during this run.

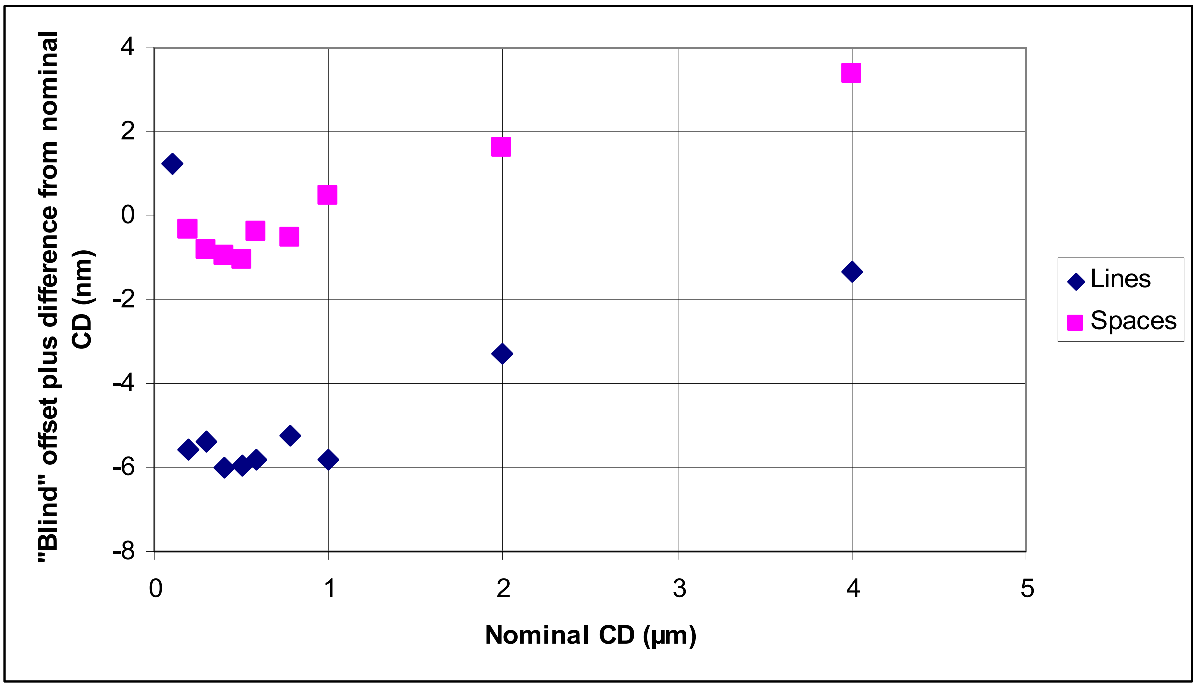


FIGURE 6 CD-AFM linewidth results (middle width) for line and space targets on PTB mask. (Note: The indicated linewidth values were shifted by a contstant value to be close to nominal on large intervals in order to keep the comparison "blind".)

4.2 Scanning electron microscopy results on the PTB mask standard

The SEM based metrology system used at PTB for CD calibration of photomasks is described in Ref. [17]. The system is called Electron Optical Metrology System (EOMS). It basically consists of a large vacuum chamber with an integrated 2D stage, which allows loading large planar measurement objects and travelling over 300 mm in both directions, and a low voltage (LV-) SEM on top of the chamber with in-lens detection capability of secondary electrons for high resolution imaging of features on the measurement objects. The calibration of scan position as well as the detection (and correction) of scan field distortions is done by means of the instrument's laser interferometer controlled 2D specimen stage. In 2006, the EOMS was upgraded with a new type of LV-SEM (Zeiss ULTRA SEM). [†]

Figure 7 shows SEM images as examples of line and space features in the iso-dense transition regions for the CoG mask standard of the PTB design used for the bilateral comparison for different CD values.

[†]Certain commercial equipment is identified in this paper to adequately describe the experimental procedure. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology nor does it imply that the equipment identified is necessarily the best available for the purpose.

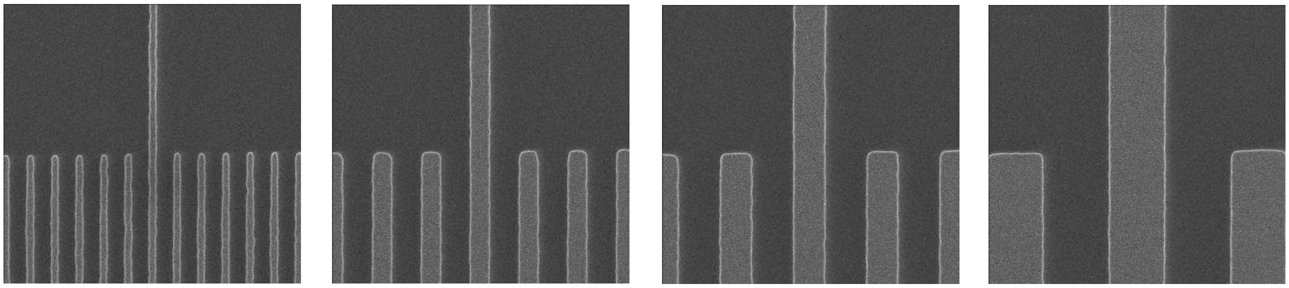


FIGURE 7 SEM images of the iso-dense transitions of the line feature measurement structures on the CoG photomask standard of the PTB design. Nominal CD values from left to right: 100 nm, 200 nm, 300 nm and 500 nm (image size: 2.5 µm).

For modelling of SEM signal profiles at micro- and nano-scale features Monte Carlo simulation methods are used. These methods allow to simulate elastic and inelastic scattering events of the primary electrons within the interaction volume in the sample features. The simulated dependence of secondary electron (SE) emission intensity in the vicinity of the primary electron impact position generally shows an exponential characteristic. This exponential increase is also present close to a feature edge and its characteristic behavior is used as the basis of a special edge operator developed at the PTB for determination of the of the top edge position of a single feature edge. By combining the information from both feature edges, the top CD, *i.e.* the linewidth of a feature at its top level can be inferred [18].

In section 2.5 the linewidth measurand was defined as the feature width at 50 % height of the feature by referring to a cross–section profile perpendicular to the direction of the line. For an ideal line feature with vanishing line edge roughness this linewidth value could be determined irrespective of the position and size of a given measurement window. For real line features however, the position and size of a measurement window have to be defined clearly to allow a meaningful comparison of different measurement methods. For this reason, the position and size of the 5 µm long measurement window are indicated by auxiliary adjustment lines on the PTB mask standard.

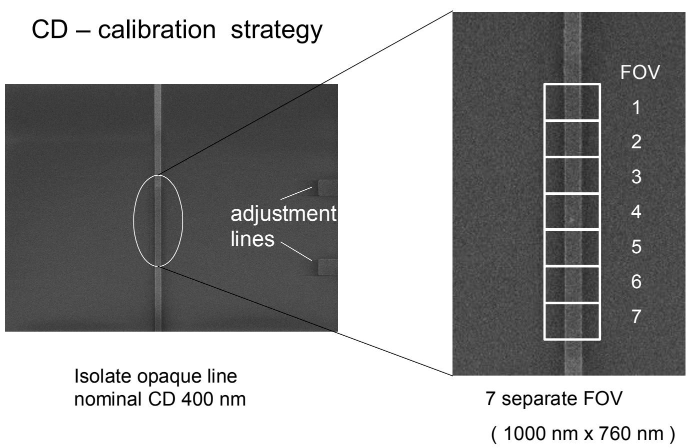


FIGURE 8 Illustration of the measurement sequence of repeated SEM images taken at different positions along the line feature.

To obtain a reliable edge position detection on measured SEM images of line features a sufficiently large number of image pixels in the edge transition region of the SEM signal should be present. In our linewidth measurements, we therefore typically chose SEM pixel sizes of about 1 nm resulting in scan areas or fields of view (FOV) of about 1 µm x 0.76 µm. The specified full evaluation window length of 5 µm along the line features thus required to subsequently position the SEM scan areas, see figure 8 for illustration of the measurement procedure.

Each measured SEM image was analyzed as follows. Line signal profiles were first calculated by averaging over 50 pixel rows, i.e. over approximately 50 nm. From these averaged signal profiles the edge positions were determined by application of suitable edge detection algorithms, like e.g. the top edge operator described above [18]. The image is then further analyzed by shifting the integration window downwards over the image with an overlap of 25 pixels to the preceding integration window. By this procedure finally 30 linewidth measurement values are determined from one SEM image. The variation of the edge position measurement values can be analyzed for linewidth (LWR) and line edge roughness (LER) of the feature of interest. This analysis is then performed over all of the 7 SEM images taken in a full measurement sequence, which results in a maximum of 210 linewidth measurement results obtained over the full measurement window size of 5 µm, provided the edge detection algorithm could reliably determine a linewidth measurement value for every integrated line profile .

Figure 9 shows the results of the top linewidth values determined by two repeated measurement sequences as described above on a nominally 190 nm line feature on the PTB mask. Please note that the indicated linewidth values are shifted by a constant offset on purpose to be close to the nominal value in order to keep the comparison “blind”, i.e. not biased by early exchange of absolute linewidth measurement results, because it is not yet finished. One can see from the graphical representation of the results that the reproducibility of the edge detection on the integrated line profiles calculated from the SEM image intensities is sufficiently good. The range of the measured linewidth values over the 5 µm evaluation length is about 17 nm and the 2σ-standard deviation of the values is about 6.5 nm for the line feature example of nominally 190 nm shown here. For the example given in fig. 9, the standard deviation of the mean top CD linewidth value over the full 5 µm evaluation length is 0.22 nm.

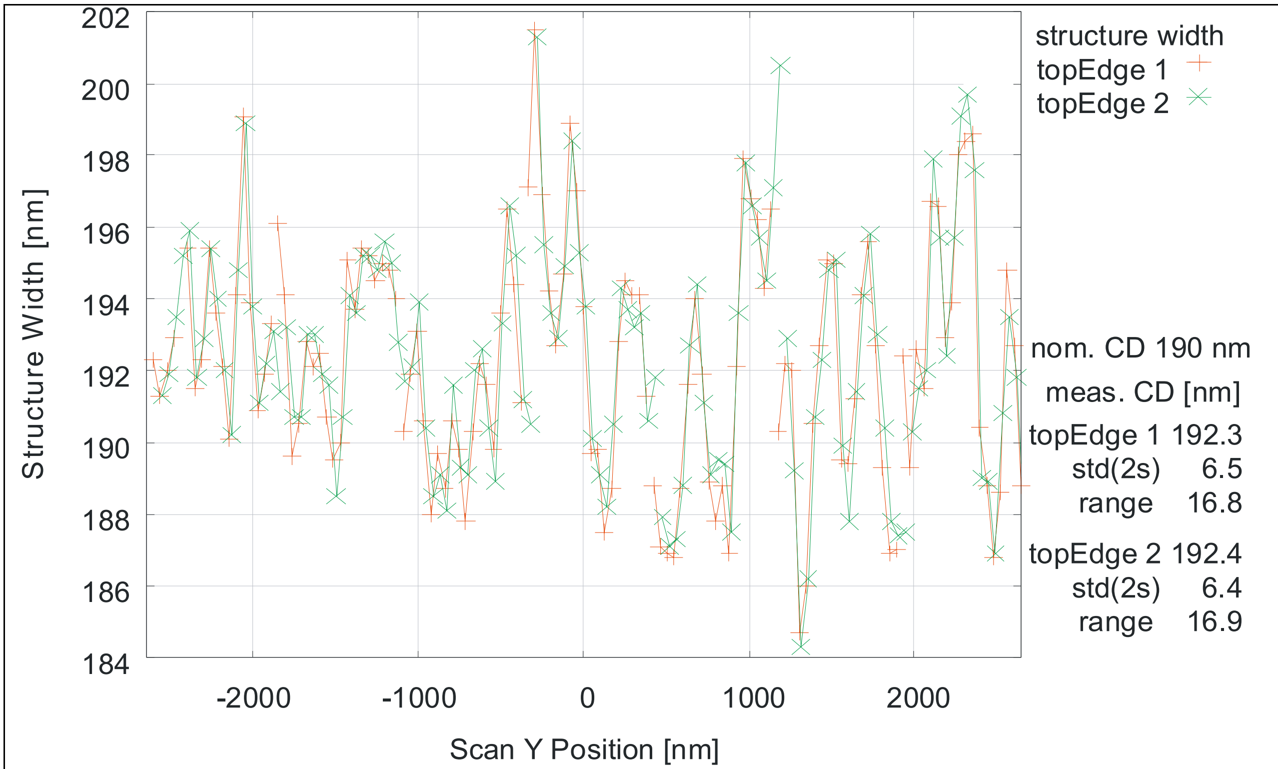


FIGURE 9 Linewidth results of two repeated measurement sequences over the 5 µm evaluation length of a nominally 190 nm line feature on the PTB mask. (Please note that the indicated linewidth values were *shifted by a constant value* to be close to the nominal values in order to keep the running comparison "blind".)

Figure 10 shows again the top CD results of measurement series 1 as in figure 9, however, in addition also the results for the CD defined by the peak positions of the SE signal and the CD at the bottom transition region of the line features are analyzed and indicated as well. Again indicated linewidth values are shifted by a constant offset on purpose to be close to the nominal value in order to keep the comparison "blind". The characteristics of the 3 different CD values are very similar, which is an indication, that within the 5 µm evaluation length, the line sidewalls seem to have a rather linear shape, i.e. can be described well by a single sidewall angle value.

The difference between the top CD and the CD values at the bottom of the line structures here is about 14 nm, which differs from the results one can deduce from the CD-AFM sidewall angle characterizations performed at NIST on the PTB photomask structures. If the thickness of the structures on the NTAR7 mask blank is assumed to be about 73 nm, the sidewall angle characterizations performed at NIST results in differences between top CD and bottom CD between 7 nm at the nominally 4 µm CD structure and between 1 nm to 2 nm at the nominally 200 nm line structure. These observed differences between top CD and bottom CD are not yet fully understood and require a more detailed discussion based on the actually measured CD-AFM sidewall shape characteristics.

According to the Guide to the Expression of Uncertainty in Measurement (GUM) [6], published by the International Organization for Standardization (ISO), the experimentally determined standard deviation of the linewidth or CD measurand enters the uncertainty budget as a so-called type A uncertainty component. The estimation of the so-called type B uncertainty components generally is a more challenging task, because here the residual uncertainties due to potentially applied systematic corrections or model-dependent influences have to be taken into account.

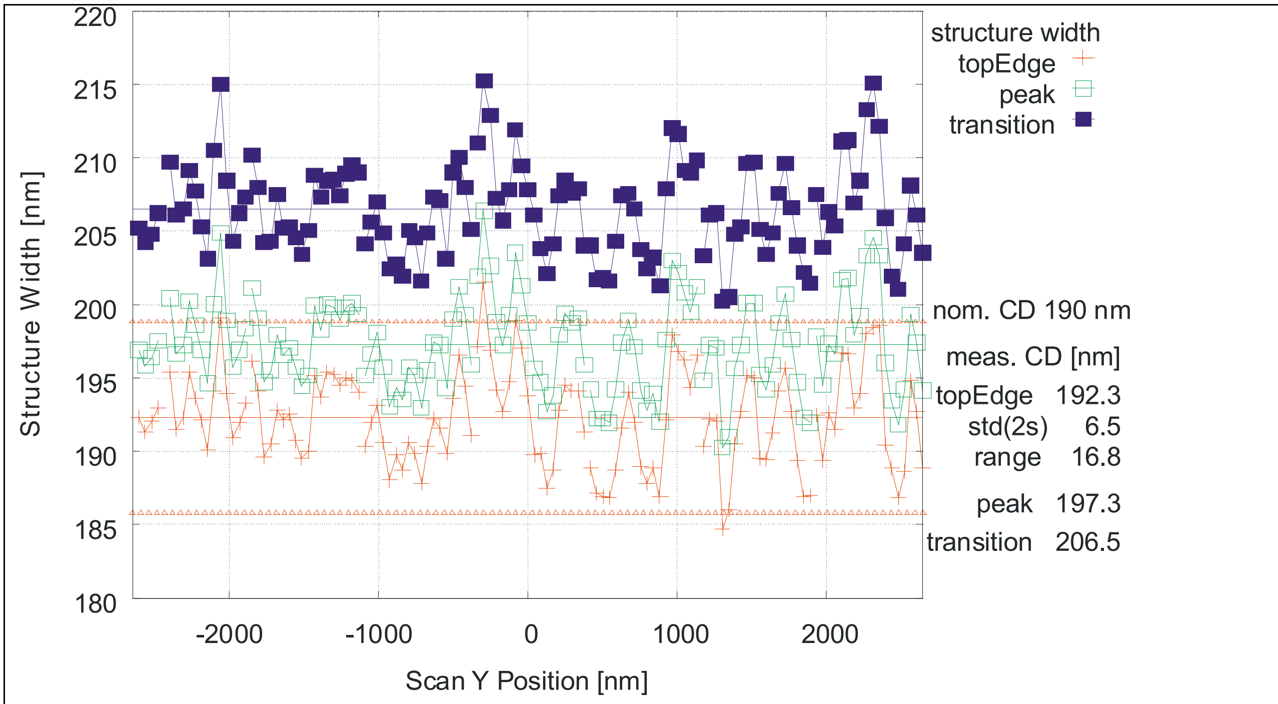


FIGURE 10 Linewidth results for top CD, CD defined by peak positions of SE signal and CD close to the transition at the bottom of a nominally 190 nm line feature on the PTB mask, characterized over 5 µm evaluation length. (Please note that the indicated linewidth values were *shifted by a constant value* to be close to the nominal values in order to keep the running comparison unbiased or “blind”.)

An example of the observed impact of SEM instrument parameters on the measured linewidth values is shown in fig. 11. In this figure the linewidth measurement results for isolated line structures on the PTB mask are shown for nominal CD values from 1000 nm down to 100 nm. In order to keep the still running comparison unbiased or “blind”, the measurement values were again all shifted by a constant offset to be close to the nominal values. By this shift, the linearity of the CD values is not altered. Figure 12 shows the results of 4 measurement series, two repeated measurements under optimum focus conditions at 1.3 keV primary energy, one series under slightly defocused conditions at the same primary energy and one series under optimum focus conditions, however at another primary energy of 700 eV.

Firstly, the two repeated measurement series at optimum focus conditions show a satisfactory reproducibility of the CD measurements. The largest differences observed over all CD results was about 0.5 nm. Secondly, the CD results of the slightly defocused measurement series are about 3 nm smaller than the CD results under optimum focus conditions, independent of the nominal CD values. It is known that the applied top CD operator shows a higher sensitivity to focus variations in comparison to other operators which work closer to the isofocal point of the SE signal profile. Thirdly, the measurement run performed at a primary energy of 700 eV results in CD values which are about 1.5 nm larger than those measured at 1300 eV. The general dependence of the characteristics of electron diffusion in solid state material and its impact on edge operators, in particular on the top CD edge operator, is well understood and has already been discussed before, see e.g. [19]. The assumption, that the increase of the SE signal in vicinity to the top edge of a line structure can be best approximated by a single exponentially increasing function is valid for smaller energies, whereas at higher energies, the changing shape of the electron diffusion cloud results in a signal increase which can be better approximated by a superposition of two different exponential functions. The energy-dependent differences are thus in principle well understood.

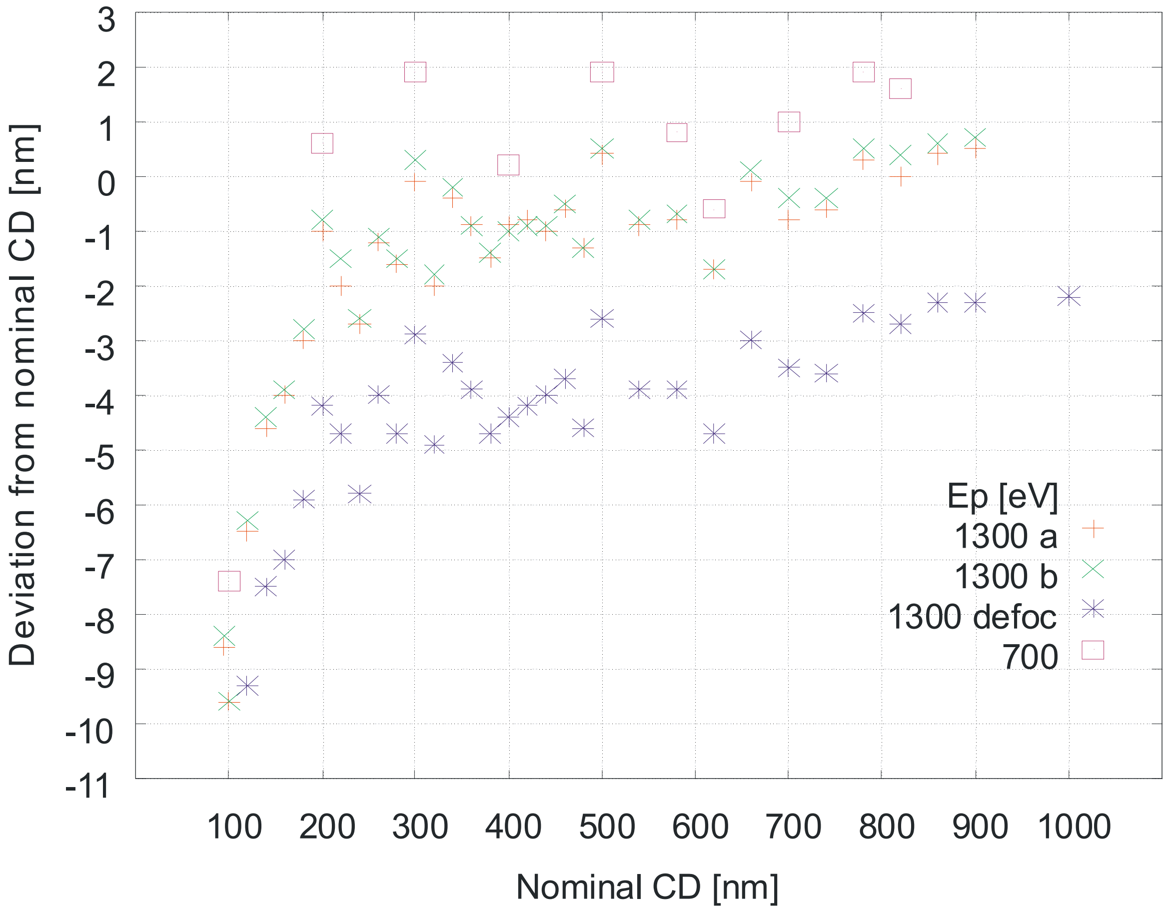


FIGURE 11 Linewidth measurement results for isolated line features on the PTB mask determined by 4 measurement series at different primary energy and different focus conditions (Please note that the indicated linewidth values were *shifted by a constant value* to be close to the nominal values in order to keep the running comparison "blind".)

The major type B uncertainty contributions to be taken into account for the SEM top CD measurements at PTB are influences from:

a) SEM image magnification and image scan nonlinearities; b) beam spot size, which broadens the SE signal profile and thus shifts the evaluated top CD position to smaller values, see influence of defocus; c) primary beam energy which changes the shape of the electron diffusion cloud and thereby also changes the details of the SE signal profile increase close to the edge; d) edge sidewall slope angle, see [18]; e) potential top corner rounding; f) additional SE material contrast due to Cr and antireflective layer influencing the SE signal profile; g) threshold values to be set for analysis of exponential increase of SE line profile; h) carbon contamination effects; i) residual charging effects.

At PTB we are currently re-estimating our uncertainty budget for SEM top CD measurements. Based on the improved experimental reproducibility, our corrections of systematic deviations can also be made with smaller uncertainties. We currently estimate our measurement uncertainty for top CD to be around 5 nm ($k = 2$) except for the smallest lines. This is a substantial improvement with respect to earlier estimations, which were mainly limited by a less mature state of experimental reproducibility. However, the validity of this revised uncertainty budget has to be confirmed by suitable comparison measurements like e.g. this bilateral NIST-PTB mask comparison with other, independent methods.

4.3 UV transmission microscopy results on the PTB mask standard

The special UV transmission microscope system used for photomask calibration at the PTB is based on a modified commercial microscope (Zeiss Axiotron) in which the sample is imaged using Koehler illumination (NA = 0.2) at a wavelength of 365 nm [20]. A slit aperture (5 µm · 45 nm in object space) placed in the image plane is imaged into the object plane by the microscope objective (magnification 122x, NA = 0.9). The linewidth measurement is based on transmitted light intensity measurement during interferometrically controlled one-dimensional movement of the sample in the focus plane. The edge position is deduced from the measured signal profile using a threshold criterion based on a suitable rigorous imaging model.

The diffraction image can be calculated with different algorithms, which solve the Maxwell equations numerically. At PTB the rigorous coupled wave analysis (RCWA) and the finite element method (FEM) are used [1]. The microscope image is computed by applying the Hopkins pupil approach: the entrance pupil is discretized and for each pupil point the electrical and/or magnetic fields of all diffracted orders within the numerical aperture of the objective are summed up. For partially coherent illumination, the intensity distributions in the image plane corresponding to each pupil point have to be summed up over all pupil points [21]. Based on a measured or assumed line topography profile information,

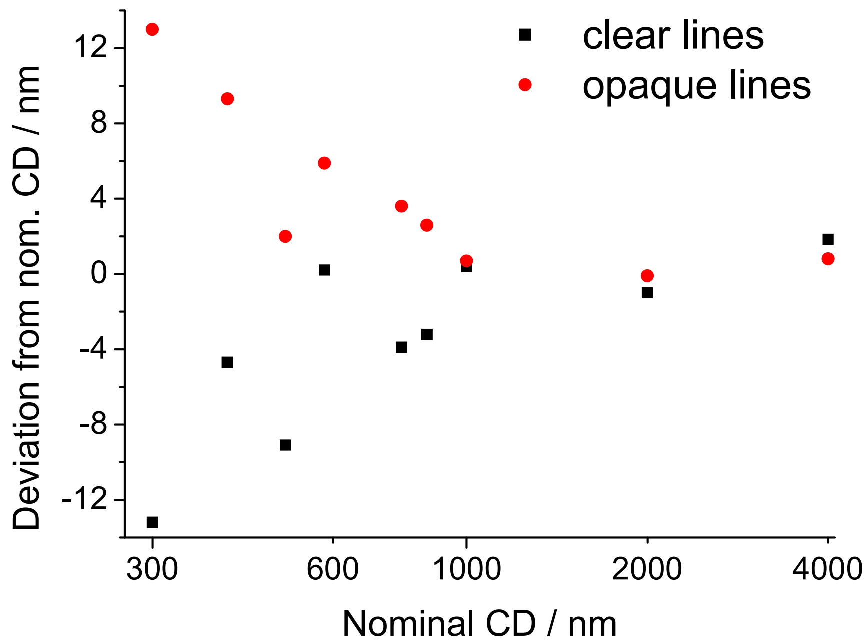


FIGURE 12 Linewidth measurement results for isolated line (opaque line) and isolated trench (clear line) features on the PTB mask determined by UV microscopy measurements (Please note that the indicated linewidth values were *shifted by different constant values* to be close to the nominal values (for linewidths > 1μm) in order to keep the running comparison "blind".)

different CD values can be deduced from a measured optical signal profile, *e.g.* the CD at 50 % height of the features. The feature height and sidewall angle information is determined by a Zeiss Veritekt scanning probe microscope, which allows characterizing sidewalls by means of a tilted cantilever system. With this system we measured feature heights of 73(1) nm and the edge angles are estimated to be ≥ 85° (edge angles above 85° cannot be measured with this Zeiss AFM due to a limited step size of 4 nm) in sufficiently good agreement both with PTB SEM and NIST AFM results.

For photomask sample features which are very close to a trapezoidal topography model, the major uncertainty components of the UV transmission microscope currently are in decreasing order of magnitude: uncertainty of microscope parameters, stray light, reproducibility and uncertainty of the optical constants of the mask materials (especially k of chrome). For the high quality line structures on the CoG masks uncertainties of 19 nm ($k = 2$, $U_{95\%}$) have been estimated.

Figure 12 shows the UV measurement results for isolated lines and trenches, both again shifted by different offsets. The observed tendency for opaque line features smaller than 1 µm in the UV transmission microscopy measurement data does not seem to be in agreement with the observed characteristics of the PTB's top CD SEM measurement data for the line features. The origin of these observed differences has to be further investigated.

5 CURRENT STATUS AND OUTLOOK

This bilateral and the planned multilateral international BIPM photomask linewidth comparisons are the first international highest-level comparisons in this field since 1996. Since then, the photomask industry has made tremendous progress and now urgently needs new high quality calibrated photomask standards with smaller linewidth structures.

National Metrology Institutes (NMIs) like NIST and PTB took up this challenge and developed advanced measurement techniques with highest resolution and accuracy, substantially improving their measurement capabilities to serve the increasing demands of mask and semiconductor industry. In addition, in combined attempts with industry, new and improved photomask standards have been developed independently in US and Europe. Hence, the two international comparisons in which advanced measurement methods and latest photomask standards will be applied are essential for support of the Mutual Recognition Arrangement signed by the NMIs. In particular, they are also an important measure for further ensuring the measurement capabilities and the reliability of linewidth calibration services offered by the NMIs.

This bilateral photomask linewidth metrology comparison will uncover any comparability issues between NIST and PTB and instill customer confidence in our measurements before *Nano1* can be completed. A serendipitous byproduct is the comparison of different measurement methods in addition to the comparison of different national metrology institutes. Actual measurements on the two transfer standards were started in 2009 in both metrology institutes on their respective mask standards. The PTB mask standard was recently sent to NIST to start with CD-AFM characterizations. In order not to bias any CD measurements still to be done in the framework of the running comparison, no absolute CD measurement values have so far been exchanged between the institutes. It is expected that the bilateral comparison measurements on both type of mask standards are finished in the beginning of 2010.

From the CD-AFM sidewall characterization results, as well as the CD-SEM results on the PTB mask standard shown in this paper, it can already be concluded that this mask standard type seems to be a suitable transfer standard to be used for the *Nano1* international comparison. *Nano1* will use a different mask (but same nominal feature patterns) and include all nine national metrology institutes. It should commence in 2010, but due to the large number of participants, logistical issues, and the large amount of data, results will not be available until 2011 at the earliest. This comparison will establish comparability among the participants via the Mutual Recognition Arrangement and refine the reference values for the features measured because of the larger number of independent measurements. Thus *Nano1* is the more valuable metrology comparison, but it will necessarily conclude at a later date than the bilateral comparison.

Suggestions regarding either of these comparisons are welcome. Send comments to harald.bosse@ptb.de or james.potzick@nist.gov .

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