# Towards traceable bidirectional optical size measurements for optical coordinate measuring machine metrology

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## Abstract

Bidirectional measurements are to be performed for the calibrations and the reverification of the performance of optical coordinate measurement machines (CMMs). The national metrology institutes are challenged to provide internationally recognized calibrations of suitable standards at the required uncertainty level of 100 nm. Furthermore most users are not aware of the specific difficulties of these measurements. Because the optical image formation process is based on interference and diffraction the measurements depend on all of their influence parameters. The first requisite is the use of the correct threshold value, which usually needs to be determined by a simulation of the microscopic image. A comparison of optical linewidth measurements, which are one example of bidirectional measurements, and scanning electron linewidth measurement agreed down to the nanometer level. These results validate the proposed measurement procedure and the related uncertainty calculations. The experience obtained within the accreditation process of industrial labs shows that, in order to be able to achieve the desired measurement uncertainties of about 100 nm, the imaging system needs to have a a monochromatic Koehler illumination, numerical aperture lager than 0.6, a magnification greater than 50 and the ability to control the deviation of the focus position to better than 100 nm.

## 1 Introduction

Optical coordinate measurement machines with vision systems are preferred over other types of CMMs if sensitive work pieces or small details with a large number of measurement points have to be characterized. The related Standard for Geometrical Product Specifications Acceptance and Reverification tests for CMMs [1] requires bidirectional measurements to be performed for the calibration of the CMM or the verification of its performance.

Examples for bidirectional measurements are the width of a feature or the diameter of a hole. The distance of two features on the other hand represents a unidirectional measurement. While the influence of the structure localization sensor cancels out almost completely in the case of unidirectional measurements it directly enters into the result of a bidirectional measurement. Therefore, for these measurements, the image formation process of the optical microscope needs to be considered.

Although, according to [1], bidirectional measurements are required for the acceptance and reverification test the national metrology institutes are not yet able to offer internationally recognized bidirectional calibrations, which are covered by the Mutual Recognition agreement (MRA [2]) and documented in the key comparison database [3]. Furthermore there has been just one bilateral comparison on linewidth measurements [4] about 15 years ago. However, according to the list of calibration and measurement capabilities [5] three national metrology institutes, the National Institute of Standards and Technology (NIST, USA), the National Physical Laboratory (NPL, UK) and the Physikalisch-Technische Bundesanstalt (PTB, Germany) do offer optical linewidth calibrations. While NIST and NPL do provide this service just for photomasks, the PTB performs linewidth calibrations on suitable user-supplied samples, including line scales, as well.

The information gathered from calibration inquiries of the customers at PTB show that a measurement uncertainty of 100 nm ($k$=2) is sufficient in most cases. Unfortunately these communications reveal often that the customers are not aware of the specific problems of optical bidirectional measurements.

The aim of this contribution is to provide an in-depth discussion of the scientific background, which will reveal the difficulties of the measurement leading to this situation, to show that despite these difficulties optical linewidth measurements can be performed with measurement uncertainties down to 20 nm, to explain how this status has been reached and to offer a solution to the problem of bidirectional measurements by means of optical CMMs.

## 2 Optical linewidth measurements at the PTB

As already mentioned the PTB does offer optical linewidth calibrations. These serve throughout the paper as one example of bidirectional measurements. We start this section by revisiting the image formation process of the optical microscope. Then we will discuss the need of the simulation of microscopic images and their role in the determination of the measurement uncertainty of linewidth measurements as well as the main factors affecting the measurements. In the following subsection we will report on the linewidth microscope currently used for the calibrations and an internal linewidth comparison, which demonstrate that an expanded uncertainty of 20 nm is feasible. Finally we will propose a solution of the bidirectional measurement issue for optical CMMs.

### 2.1 Image formation of an optical microscope

The image formation process of an optical microscope was first described by Ernst Abbe in [6]. It can be described as the interference of the light diffracted by the sample. The process is illustrated in figure 1.

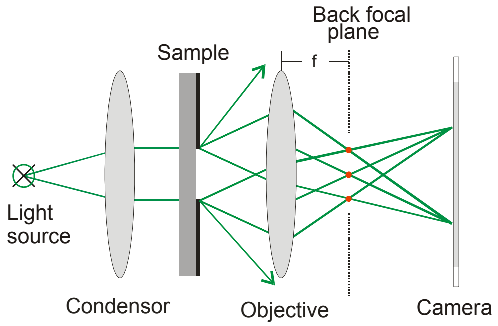



*Figure 1: Image formation of an optical microscope*

The incoming light beam gets diffracted at the slit structure at the top surface of the sample. Here, for the sake of simplicity, only the incoming rays, which hit the edges of the slit, and three diffracted beams, which result from the interaction of these incoming beams with the sample are traced. The diffracted rays which exhibit an angle within the numerical aperture of the objective form a diffraction pattern in the back focal plane of the objective. From there the light propagates to the image plane where the image is formed by the interference of the rays of the different diffraction orders. Here it can be observed on a screen or by a camera. As the slit structure in the object plane gets smaller the diffraction angles get larger. The resolution limit is reached if the diffraction angle of the first diffraction order is larger than the numerical aperture of the objective so that the related rays do not enter the microscope anymore.

Because the image formation process is based on diffraction and interference of the microscope light it is clear that all factors on which they depend will influence optical linewidth measurements. Additional influences arise from the optics and the image detector. The influence factors can be divided in four groups:

- **Illumination**
  Homogeneity, coherence, wavelength, spectrum, polarisation
- **Object**

Shape, size, optical constants, edge angle, edge profile, roughness

- **Imaging optics**
  Numerical aperture, magnification, aberrations, alignment, stray light, defocus
- **Image detector**
  CCD: pixel size, pixel's position deviations, linearity, noise
  Slit: size, bandwidth and noise of photo detector

Here defocus denotes the deviation of the separation between the objective and the object from the nominal value.

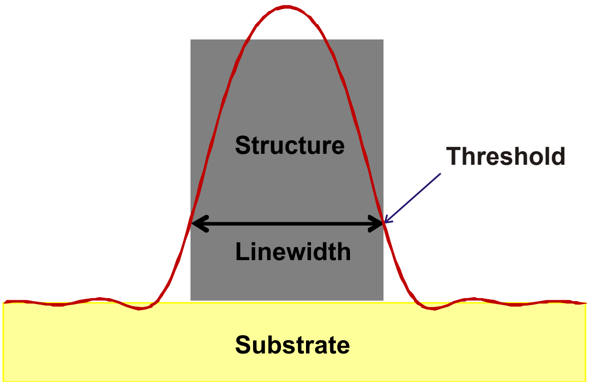



*Figure 2: Profile of a high reflecting line structure on a low reflecting substrate obtained by a reflection type microscope, the line edge is assumed to have ideally sharp edges, i. e. edges with an edge slope of 90°*

Figure 2 shows a line structure together with the related profile of the line structure obtained from a microscopic image. Here the consequences of the imaging process become obvious. The profile obtained for a line edge is broadened due to diffraction and it contains roundings. In addition, the edge profile of the image coincides with the edge position of the structure at one point. The intensity value at this distinguished point is called threshold value. It is usually given as percentage of the difference of the maximum and minimum intensity. If a linewidth or any other bidirectional measurement is to be performed the threshold value needs to be known. As will be shown later in detail, this threshold value is not constant but depends on all of the aforementioned influence factors of the image formation. Thus, a simple and constant threshold like e. g. 50% cannot be employed. Such an assumption would lead often right away on its own to deviations, which are larger than 100 nm.

Under some circumstances, as discussed later in the paper, the threshold value can be obtained by a calibration. In most cases it needs to be obtained from a simulation of the microscopic image.

## 2.2 Simulation of microscopic images

Up to about ten years ago, the simulation of microscopic images has been an art rather than a science. Meanwhile software packages for this task are commercially available [7, 8, 9]. Methods based on scalar diffraction appear to be not suitable due to the rather large numerical aperture required to achieve the desired uncertainty level of 100 nm. Similar results are to be expected if optical design programs, which are based on ray-tracing, are used to calculate the optical image, because these are unable to incorporate diffraction effects.

Instead, to reach an uncertainty level of well below 100 nm, the application of so-called rigorous diffraction calculation methods have to be applied, which take into account both the vector properties of the light waves and the three dimensionality of the imaged structures. There are several methods which are in principle suitable for this application. At PTB, two different widely used rigorous methods are applied, the Rigorous Coupled Waveguide Analysis (RCWA) and the Finite Element (FEM) methods, which are implemented in the software tools *Microsim* [7] and *JCMwave* [8, 9], respectively. We like to mention here that most simulation programs assume a Koehler illumination to be used.

Figure 3 shows two geometrical representations of the cross-section of a trapezoidal shaped line structure used as input for the two simulation programs used at the PTB. In both cases for the simulation of the image the geometrical parameters and the optical constants (refractive- and

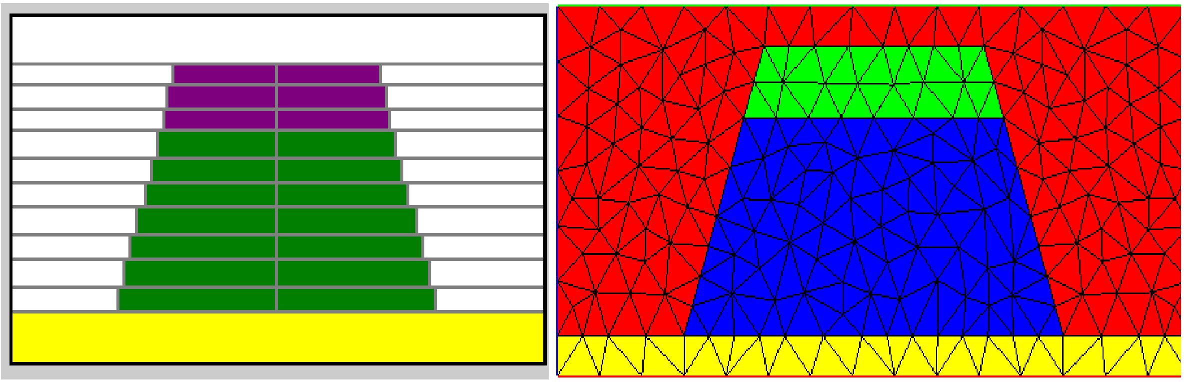


*Figure 3: Input of Microsim (left image) and JCM-Wave (right image)*

absorption index) are required. It is located on a substrate (yellow), contains an antireflection coating (violet in the left and green in the right diagram) and is surrounded by air. While Microsim (left diagram) requires to specify the properties of the structure layer by layer, JCM-Wave (right diagram) divides the structure into triangles. The FEM based methods have the advantage that they can deal with arbitrary geometries. In addition for large structures (width larger than 10 µm) the RCWA based methods require to use a lot of eigenwaves if accurate calculations are to be performed, which in turn leads to large computing times.

Comparisons of the results of the simulation programs used at PTB for the same structures showed a relative good agreement with remaining differences of ≤ 1 % in the intensity profiles and ≤ 0.3 % in the corresponding threshold values [10]. However, comparisons with other commercially available simulation tools have partially shown significantly larger deviations.

The simulations of the microscopic image are not only used to determine the threshold value. They are also used to determine the uncertainty contributions of input parameters that cannot be varied experimentally in controlled manner like the edge angle of the structures or the numerical aperture of the objective.

## 2.3 Main influence parameters of linewidth measurements

Not all parameters influence the measurements to the same extent. In this subsection we provide simulations and experimental examples to demonstrate the magnitude of the most important factors.

### 2.3.1 Numerical aperture

Figure 4 shows a comparison of images of the same line taken with the same microscope using two objectives exhibiting NA values of 0.3 and 0.75. The edge in the image of the low NA image appears

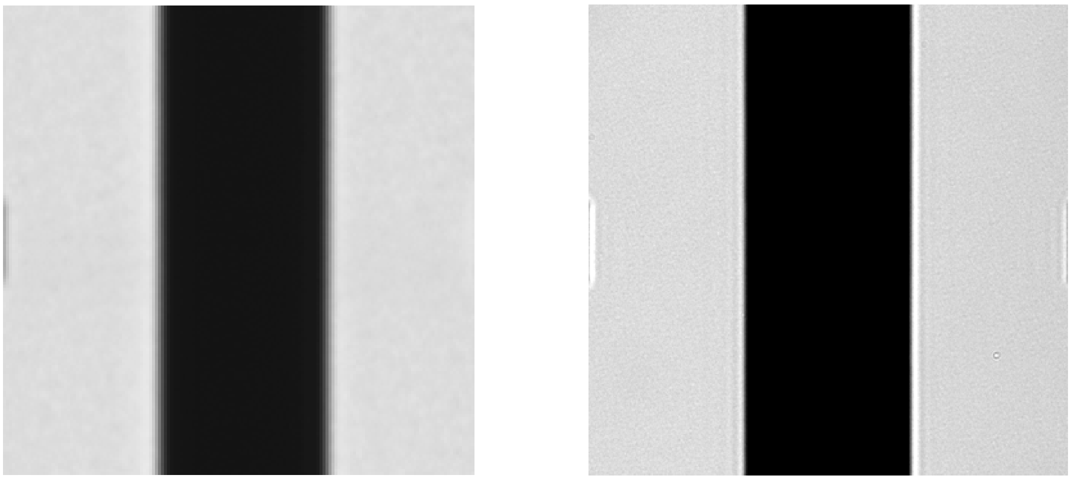


*Figure 4: Images of a 10 µm wide line taken by the same microscope using objectives with a numerical aperture of 0.3 (left) and 0.75 (right). The microscope operates in transmission mode.*

to be blurred while in the higher NA image the edge transition regime is obviously much smaller. To allow a quantitative interpretation, profiles of the right edges of both images together with their simulated counterparts are plotted in the diagram of figure 5. There is a considerable difference in the slope of the profile at the threshold value. Because the threshold value can only be determined with a finite uncertainty a certain edge slope is required to achieve a predetermined uncertainty value. Here an error of 1 % of the threshold (in the measurement or the simulation) would lead to a deviation of 20 nm and 8 nm in the linewidth for numerical apertures of NA = 0.3 and NA = 0.75, respectively. Usually the threshold has an uncertainty of several percent. In addition the difference of two profiles at the 50% value is shown: while the evaluation of the high NA measurement would lead to a deviation of 70 nm of the apparent to the real edge position, for the low NA measurement this deviation is even increased to about 210 nm deviation of the position of the right edge demonstrating again that the application of this widely used constant value is not appropriate. The threshold value for this setup is for both NA values about 25%. These results demonstrate that an objective of sufficiently high NA and the correct threshold values have to be used.

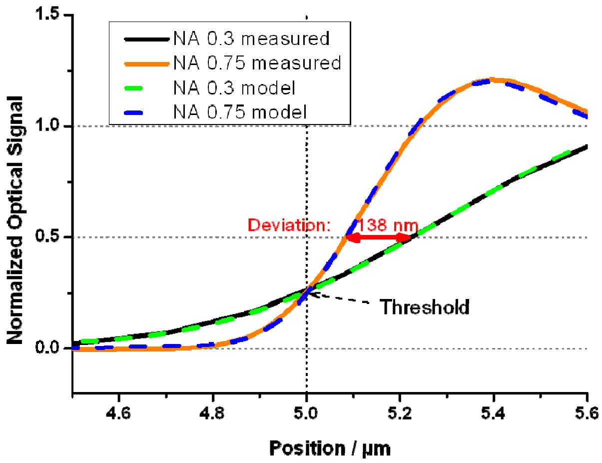



*Figure 5: Simulated and image profiles taken from the images in figure 4 of the right edges.*

We like to mention here that the NA values of objectives are typically uncertain to about 0.04. The results of the simulations performed to determine the resulting uncertainty of the threshold value are shown in the right diagram of figure 6. Marked by the green lines are values for the current line width calibration microscope ($NA_{Illumination}$ = 0.2, $NA_{Objective}$ = 0.9) discussed below. According to the right

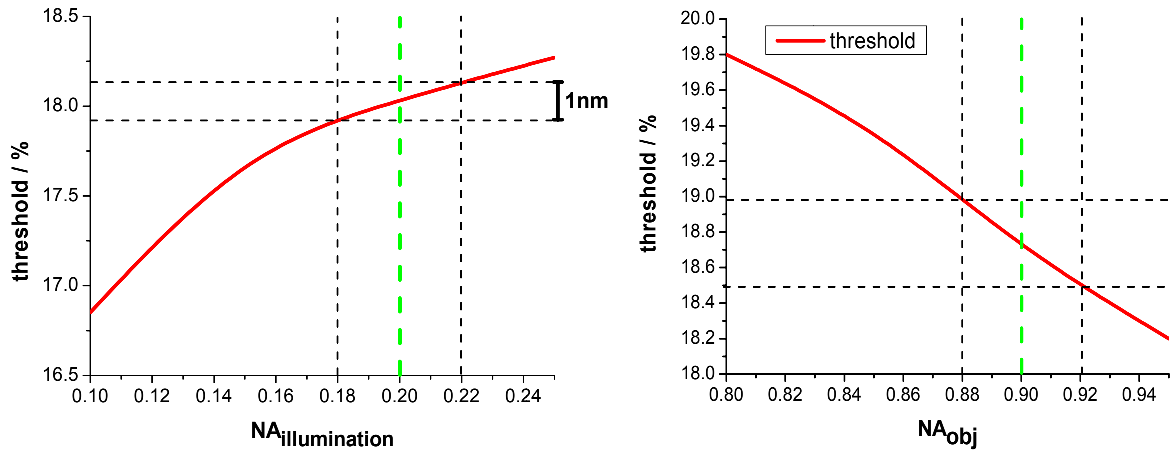



*Figure 6: Influence of the numerical aperture of the microscope illumination and objective on the threshold for a 1 µm wide line.*

diagram the uncertainty of 0.04 of the NA of the objective leads to an uncertainty of the threshold of about 0.5%. The uncertainty of the numerical aperture of the illumination plotted in the left diagram has a much lower influence.

### 2.3.2 Defocus

The question of how to focus is far away from being trivial. Practically different focus criteria lead to different distances between the objective and the object. The influence needs to be considered during the determination of the threshold. If focus sensors or even autofocus schemes are used the deviation from the real focus position needs to be determined experimentally and corrected for. Figure 7 shows the course of the simulated optical profiles within the region of the right edge for a different amount of defocus for a 10 µm wide line. We like to note here that the isofocal point at which all the profiles intersect is not at the real edge position. A width deviation of 300 nm will occur if a defocus of 3 µm has been reached. At 1 µm defocus still a deviation of about 100 nm remains. It is quite difficult to recognize such a small amount of defocus if a low NA objective is used.

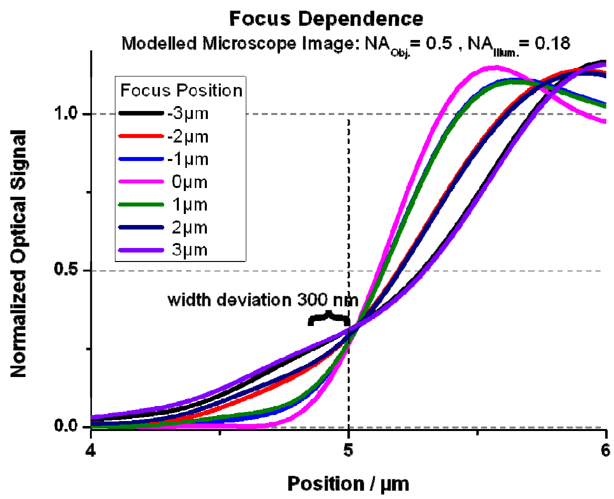



*Figure 7: Defocus influence on the course of the edge profile of a 10 µm wide line.*

The strong defocus dependence represents another argument for the use of a high NA objective for optical linewidth measurements. Therefore a height stage with a resolution of below 0.1 µm is required. Here the use of a piezoelectric focussing stage (PIFOC) for the objective or a piezo-driven sample stage offers a simple solution. In addition the focus drift needs to be reduced down to this level within the time frame of the measurements as well by constructive measures. The problem can likely be solved in many cases through the reduction of the power dissipation of the light source by either using an LED source or separating source from the microscope using a fibre based light source.

### 2.3.3 Edge angle

Because samples with structures of a predetermined edge angle cannot be produced this influence needs also be investigated by means of simulations. The results of these calculations are shown in figure 8. The right part shows the subject of the simulation. For a line, which has a constant width of

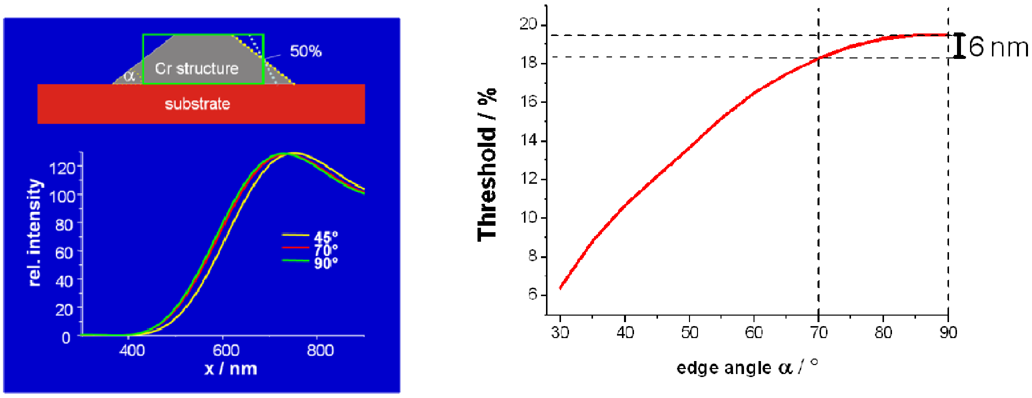
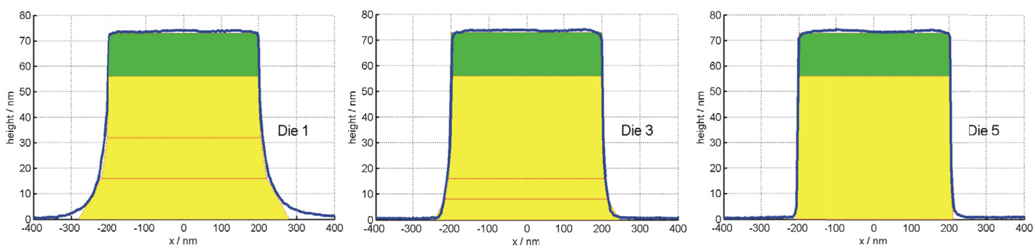



*Figure 8: Influence of the line structure's edge angle. Left: Principle of the simulation and resulting profiles of the right edge for different edge angles. Right: Change of the threshold. The simulations are performed for a 1 µm wide line (width constant at 50% of the height) and the linewidth calibration microscope described in detail below.*

1 µm at 50% of its geometrical height, the edge angle is varied from 30 to 90 degrees. The course of the resulting profiles of the right edge is shown in the left diagram. The right diagram shows the related change of the threshold. The threshold decreases dramatically towards small edge angles. Therefore the value needs to be known for accurate linewidth measurements. Above an angle of 70 degrees there is only a minor influence left. Therefore linewidth calibration standards should contain only structures with an edge angle larger than 70 degrees.

### 2.3.4 Footing

A similar severe influence has the footing of line structures if it is not considered in the simulation. Within the frame work of the ABBILD [12] project photo masks with a different amount of footing as shown in the top row of figure 9 were investigated.



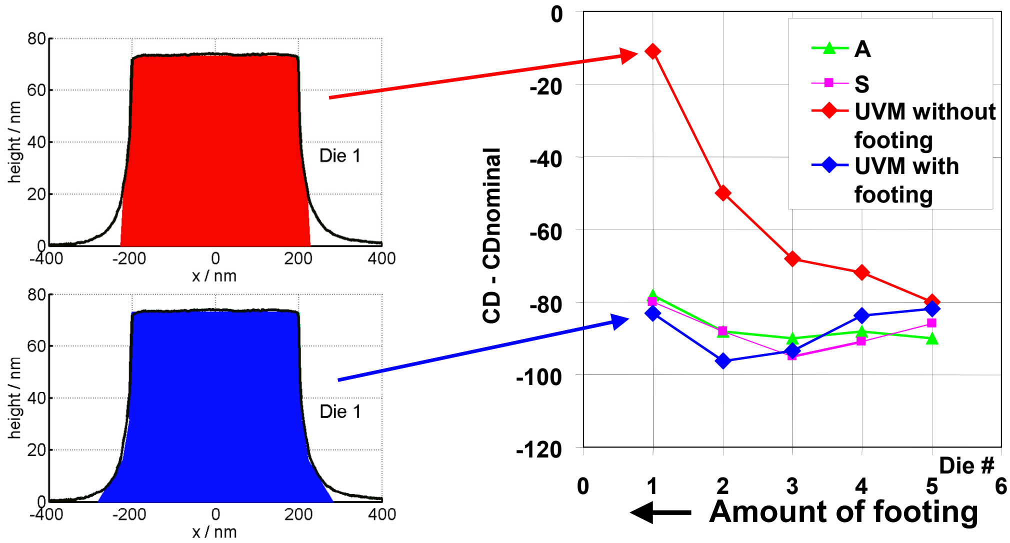



*Figure 9: Influence of footing. Top: graphical description of the phenomenon in the simulation of the microscopic optical image. The black curves (envelopes) show the line cross sections measured by an AFM. Bottom: Change of the line width as function of the nominal linewidth if the footing is considered in the simulation and not (red and blue curves). For a comparison the AFM (green curve, A) and SEM (magenta curve, S) CD measurements are shown as well.*

If the footing is not included in the simulation of the microscopic optical image as indicated by the red rectangle in the upper structure of the lower row and by the red curve in the diagram on the right in the lower row deviations in the linewidth of about 70 nm occur for a line of nominal width of 500 nm. This example also shows impressively that the properties of the sample structures need to be well known and to be included accurately into the simulation if the resulting deviation of the linewidth needs to be reduced down to a few 10 nm.

## 2.4 Optical Linewidth Calibrations at PTB

Despite all the difficulties described in the preceding subsection and as already mentioned in the introduction, the PTB performs optical linewidth calibrations of suitable, user supplied samples. First we will describe the current linewidth calibration facility. We also will present the related uncertainty budget, which concludes the discussion of the influence parameters. The uncertainty estimation has been validated by an internal comparison. These results are shown in the last subsection.

### 2.4.1 Linewidth Calibration Microscope

The microscope currently used for line width calibrations is shown in figure 10. It is based on a Zeiss Axiotron and operates in transmission mode at a wavelength of 365 nm. The optical schematic is shown on the right side of figure 10. It documents, that a Koehler illumination scheme has been implemented. The microscope uses a slit and a photomultiplier as image detector. For a measurement the sample is scanned underneath the microscope in such a way that the image of the line passes the region of the slit and the readings of the photoelectric signal and the position readings of the interferometer are acquired synchronously. Therefore the measurements are inherently traceable. A piezoelectric focus control was added in order to allow performing the measurements at the exact focus position.

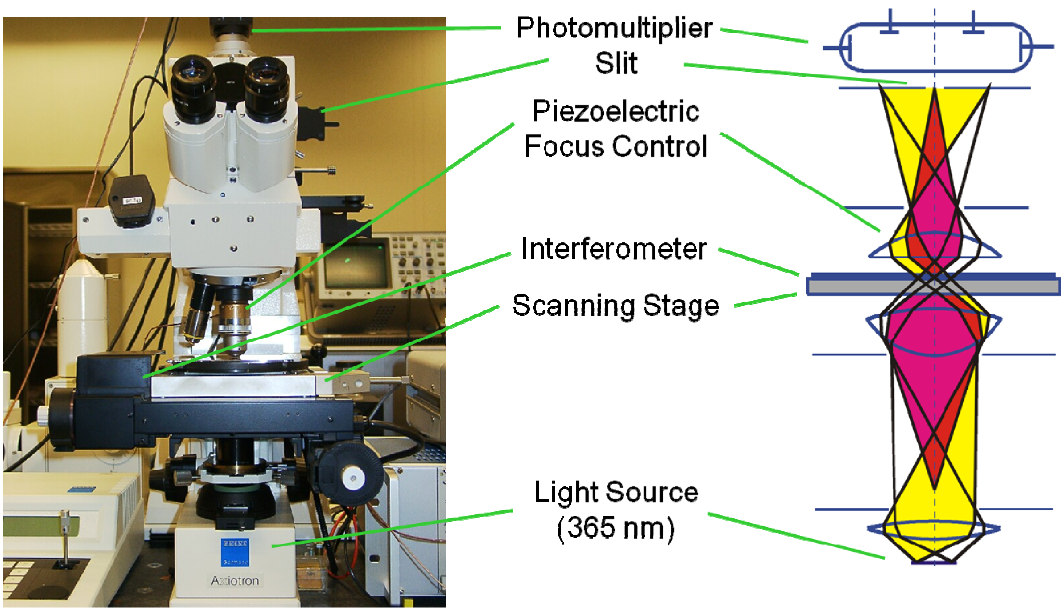



*Figure 10: Line width calibration microscope*

The uncertainty budget for line width measurement of a 1 µm wide chromium line on quartz of this setup is summarized in table 1. The budget is divided in three groups and the main contributors in each group encircled by a red line. The stray light leads to the major uncertainty contribution of the microscope.

Table 1: Linewidth uncertainty budget

| **Input Quantity** | **uncertainty / nm** | |
|---|---|---|
| Wavelength | 0.8 | |
| NA Illumination | 0.5 | |
| NA Objective | 2.2 | |
| Defocus | 1.2 | |
| Stray light | 4 | |
| Optical signal | 2.6 | |
| Position measurement | 2.3 | |
| Sampling aperture | 3 | Instrument (6.6 nm) |
| Cr k | 5 | |
| Cr n | 0.3 | |
| Cr thickness | 3 | |
| Edge profile | 4 | Object (7.1 nm) |
| Model | 4.5 | Model (4.5 nm) |
| **Quadr. sum U (k=2):** | **21** | |

The contribution optical signal denotes the influence of residual aberrations of the imaging optical system. The largest contribution of the three groups is caused by the object. Here it should be noted that the material properties of the thin chromium film differ considerably from the properties of chromium bulk material. In particular the absorption index is usually increased and exhibits the largest uncertainty followed by the structure irregularities leading to deviations of the edge profile including the influence of the uncertainty of the edge angle. For this uncertainty budget it has been assumed that the material parameters have already been characterized. It has to be stressed, that this budget is valid only for high quality structures as found e. g. on state of the art photomasks with structures of very low edge roughness, very steep edge angles (> 70°) and with negligible edge profile features like footing or corner rounding. For lower quality structures the contribution of the object to the uncertainty budget can increase dramatically. Additionally we like to add that the PTB has built a new linewidth calibration microscope, which operates at a wavelength of 193 nm. It was designed to achieve an expanded uncertainty of 10 nm and currently starts to operate [13].

2.4.2 Linewidth comparison

In order to verify the appropriateness of the whole measurement procedure and the correctness of the uncertainty model and the size of the different uncertainty contributions a linewidth comparison with the Electron Optical Metrology System (EOMS) [14] of the PTB has been performed.

We like to emphasize here that the image formation process of the Scanning Electron Microscope has to be simulated as well if accurate linewidth measurements are to be performed. The PTB developed a software package especially designed for this purpose [15, 16]. Here the material parameters like electron scattering cross sections and the geometrical dimensions of the structures have to be known as well. In this case AFM measurements were performed to determine the height and the edge angle. The material parameters were characterized during the production of the photo mask.

The results of the comparison are plotted in figure 11. The EOMS estimates, due to the algorithm

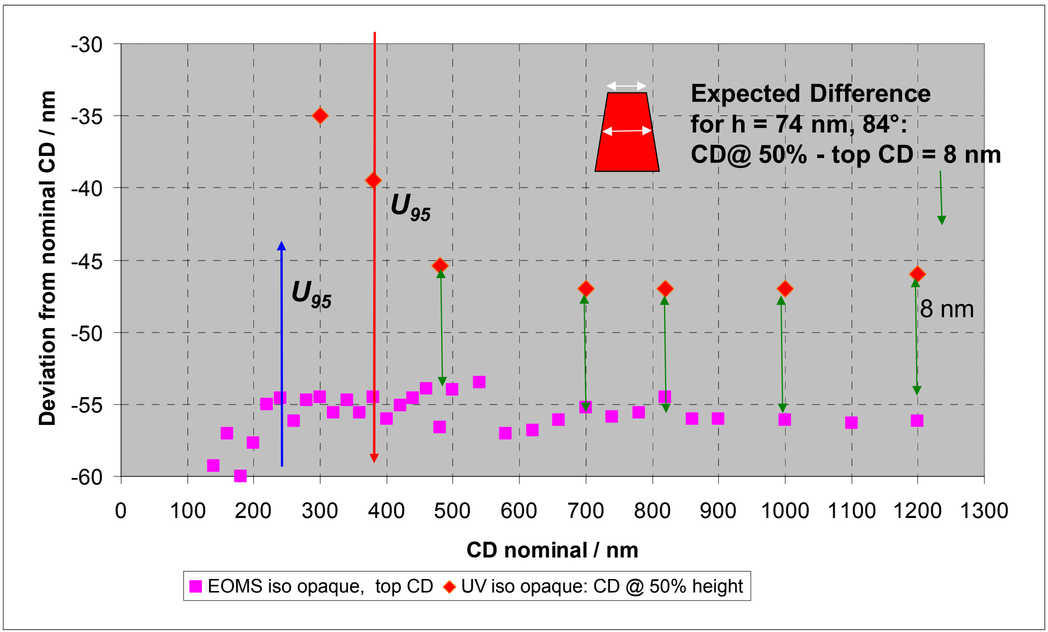



*Figure 11: Results of a linewidth comparison between the UV-Linewidth-Microscope and the EOMS of isolated opaque chromium lines of a photo mask.*

used, the linewidth at the top of the structure. The values of the optical microscope are determined at 50% of the geometrical height. If the edge angle obtained by the AFM measurements is considered and the resulting difference of 8 nm (indicated by the green arrows) is taken into account the EOMS and optical microscope values agree down to the nanometre level for linewidth values down to 0.5 µm. In addition the errors bars indicate that the agreement is complete for all width values measured.

2.4.3 Linewidth calibrations

A closer look at the setup of the linewidth calibration microscope in figure 10 reveals that there are limitations on size of the sample and the feature width. The nanopositioning sample stage has a supporting area of about 100 mm x 100 mm, which corresponds to the scanning range of the macro scanning stage. Thus structures on larger samples can be measured only with some restrictions and in the central part. The maximum thickness of the samples is limited by the maximum distance between the microscope objective and the scanning stage and should not exceed 10 mm. Further on, the sample support cannot handle samples with a weight above 600 g. The scanning stage has a range of 400 µm. But because the maximum and the minimum intensity need to be estimated experimentally to determine the threshold voltage a sufficiently large range on both sides next to the line needs to be scanned as well. Therefore the maximum linewidth range is limited to about 200 µm. In order to calibrate structures of larger width a second instrument with larger scan range, like the LMS 2020 [17] or the Nanometer Comparator [18, 19], has to be used in addition. In this case auxiliary linewidth structures of smaller widths, which can be measured by the linewidth microscope and which are produced together with the larger structures, so that it can be reasonably assumed that they have the same geometrical and material properties, are required. These auxiliary structures are used to calibrate the threshold value of the microscope of the large range instruments. Then the width of the large structure is calibrated. Therefore the total measurement uncertainty is the rms sum of the uncertainty of the three measurements required. As a consequence the achievable total uncertainty increases considerably. In any case the geometrical and optical properties (at a wavelength of 365 nm) of the structures and the substrate are required to determine the threshold values for the line width calibration performed by the linewidth calibration microscope.

# 3 A proposal for a solution of the bidirectional measurement problem

In the last subsection we demonstrated that optical linewidth measurements, which represent one example of bidirectional measurements, can be performed with measurement uncertainties down to about 20 nm. So it is straight forward to apply the same approach and procedures to the area of optical CMM metrology as well and solve the bidirectional measurement issue in this way. In this last section we formulate the requirements which we deduce from the data presented.

## 3.1 Threshold value

The first requisite is the use of the correct threshold value. This includes the use of an evaluation algorithm that yields the width at this threshold. The threshold can be determined in two ways. One is to simulate the optical image. The other one is to obtain the threshold value by a calibration as described in subsection 2.4.3. Because the threshold value depends on the geometrical and material properties of the object, this approach is of very limited use.

The simulation of the microscopic image on the other hand requires the geometrical and material properties as well as the properties of the microscope used to be provided as input parameters. In the case of calibration standards we suggest that the users obtain these from the vendors of the standard together with the standard. Many of these parameters are measured by the vendors for quality control purposes. The material parameters of the optical glass used as substrate for example are measured by the glass manufactures and are usually published on their webpage. In addition, it would be favourable if the simulation could be performed within the program of the optical CMM. This requires a software module to be developed at a reasonable price and to be integrated into the control and measurement software of the optical CMMs by the vendors.

Another solution would be to simulate the threshold values for many objects, materials and combination of materials and microscopes and publish the results. The PTB performed such simulations e. g. for chromium features on quartz mask. This material combination is very popular for metrology applications due to the high quality of the produced structures. But the dependence of the threshold values on the material parameters is likely much less complicated for structures machined from one material like hole milled in aluminium. Unfortunately several project proposals submitted nationally and internationally to start these simulations were rejected.

## 3.2 Instrumental requirements

In order to be able to perform bidirectional measurements with expanded uncertainties of about 100 nm the optical imaging system of the instrument to be used needs to meet the following requirements:

- Numerical aperture.
  The experience gained during the accreditation of industrial labs for bidirectional measurements suggests that practically a NA of larger than 0.5 is necessary.
- Magnification

In order to be able to perform an accurate calculation of the edge position the measured image profile must contain some points within the transition regime. This is particular important if a CCD camera is used to acquire the image. If, for example a 20x objective with an NA of 0.9 and a CCD camera with a pixel distance of 4.65 µm are used, then about one point is located in the transition regime (determined by 0.61 $\lambda$/NA=339 nm, $\lambda$ =500 nm).

- Koehler illumination
  A Koehler illumination is assumed in the simulation of the microscopic image. For each wavelength of the illumination a new simulation has to be performed. Therefore if the threshold used is based on such simulations a Koehler illumination using a light source with a narrow spectral width, like a green or red LED, is required.
- Focus Control
  Due to the large influence of the defocus a focus drive with sufficient resolution (of about 100 nm or better) and a sufficiently low focus drift of a similar magnitude are necessary
- Software
  The algorithm used to evaluate the data needs to determine the width at the threshold value. The program must either determine the threshold itself or require a user input of this value.

Finally we like to emphasize that complying with the requirements listed here does not guarantee to achieve uncertainties of bidirectional measurements in the order of 100 nm. In many cases the limited quality of the object will prevent that this often formulated goal can be reached.

# References

[1] Geometrical Product Specifications Acceptance and Reverification tests for CMMs (ISO 10360) part 7

[2] Mutual Recognition Agreement, see http://www.bipm.org/en/cipm-mra/ for more information

[3] Key comparison data base, see http://kcdb.bipm.org/appendixB/KCDB_ApB_search.asp

[4] Potzick J E, Nunn J W 1996 *International comparison of photomask linewidth standards: United States (NIST) and United Kingdom (NPL)* Proc. SPIE Annual Symposium on Microlithography, **2725-08**,p.124-129

[5] List of calibration and measurement capabilities at the BIPM webpage, for details see http://kcdb.bipm.org/AppendixC/default.asp

[6] Abbe, E 1873 Beiträge zur Theorie des Mikroskops und der mikroskopischen Wahrnehmung. *Arch. mikrosk. Anat. Entwichlungsmech*. **9** 413-468

[7] Totzeck M 2001 Numerical simulation of high-NA quantitative polarization microscopy and corresponding near-fields *Optik* **9** 399-406

[8] S. Burger, L. Zschiedrich, F. Schmidt, R. Köhle, T. Henkel, B. Küchler, C. Nölscher: *3D Simulations of Electromagnetic Fields in Nanostructures.* In: Modeling Aspects in Optical Metrology. H. Bosse, B. Bodermann, R. M. Silver (ed), Proc. SPIE Vol. 6617, 66170V (2007)

[9] S. Burger, R. Köhle, L. Zschiedrich, W. Gao, F. Schmidt, R. März, C. Nölscher: *Benchmark of FEM, Waveguide and FDTD Algorithms for Rigorous Mask Simulation* , Proc. SPIE Vol. 5992 (2005) 599216, (25th Annual BACUS Symposium on Photomask Technology, J. T. Weed, P. M. Martin, Eds.)

[10] Bodermann B, Ehret G 2005 *Comparison of different approaches for modelling microscope images on the basis of rigorous diffraction calculation* SPIE International Symposium Optical Metrology: Conference on Nano- and Micro-Metrology, Munich, Germany Proc. of SPIE **5858** 09-1 - 09-12

[11] Ehret, Gerd; Bodermann, Bernd; Bergmann, Detlef; Diener, Alexander; Häßler-Grohne, Wolfgang *Theoretical modelling and experimental verification of the influence of Cr edge profiles on microscopic-optical edge signals for COG masks 2006* 26th Annual BACUS Symposium on Photomask Technology, Monterey, USA, 18-22, September, 2006; Proc. SPIE **6349** (2006), 63494Y-1-63494Y-10

[12] BMBF-Project "Abbildungsmethodiken für nanoelektronische Bauelemente" (ABBILD)

[13] Ehret G Pilarski F Bergmann D Bodermann B 2009 A new high-aperture 193nm microscope for the traceable characterization of micro- and nanostructures *Meas. Sci. Technol* **20** 084010

[14] Häßler-Grohne W and H Bosse H 1998 An electron optical metrology system for pattern placement measurements *Meas. Sci. Technol.* **9** 1120

[15] Gnieser D Frase C G, Bosse H and Tutsch R 2008 MCSEM—a modular Monte Carlo simulation program for various applications in SEM metrology and SEM photogrammetry *Proc. 14th Eur. Microsc. Cong.* ***1*** 549–50

[16] Frase C. G. Haessler-Grohne W. Use of Monte Carlo models in the development and validation of CD operators. *Surface and Interface Analysi***s** 37(11):11, 942 – 950,2005

[17] Haessler Grohne W et al. Two dimensional photomask standard calibration Proc. SPIE 1604 (1991)

[18] Flügge J Köning R Bosse H 2003 *Recent activities at PTB nanometer comparator,* Proc. SPIE, Vol. 5190, in Proceedings of Recent Developments in Traceable Dimensional Measurements, San Diego, p. 391-399

[19] Köning R Flügge J and Bosse H 2007 *Achievement of sub nanometer reproducibility in line scale measurements with the nanometer comparator, in Proceedings of Advanced Lithography*, Proc. SPIE 6518, San Jose, 65183F