Comparative scatterometric CD measurements on a MoSi photo mask using different metrology tools

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ABSTRACT

The demands on CD metrology techniques in terms of both reproducibility and measurement uncertainty increase with decreasing critical dimensions (CD) on lithography masks. Additionally a full 3D characterization of the mask structures becomes more and more important to understand and control the printing behavior of state of the art photomasks. Furthermore, an extension of metrology characterization including material properties can provide the final puzzle pieces for a better correlation of mask metrology to wafer metrology. Here, optical metrology systems, especially at-wavelength systems, are very well suited to characterize structure features of a photomask regarding their printing behavior on a wafer. In particular scatterometry is able to provide a better understanding of the investigated structure and allows for modeling of secondary structure parameters as well as material composition.

AMTC has a commercial scatterometer from n&k Technology (n&k 5700-CDRT) in use. This system measures the spectral transmission and reflection, the 0th diffraction order. Beside thin film characterization this system is used for CD and edge profile characterization, also. The analysis of the data uses a look-up table approach in combination with a database, which has been generated and can be expanded, respectively, using a RCWA based software. At PTB we have realized a new DUV hybrid scatterometer which combines essential elements of a radiometer, an ellipsometer, and a diffractometer.

These two systems are different both in terms of the measurement modes, the data evaluation method and the Maxwell-solver used. Therefore we started to compare the performance of both systems to traditional metrology system for CD metrology and phase measurement. For this purpose we performed first comparative scatterometric measurements on a MoSi phase shifting mask.

Keywords: Scatterometry, Ellipsometry, Reflectometry, Diffractometry, CD, pitch, edge profile, polarisation, inverse diffraction problem, at-wavelength metrology

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Introduction

The recent introduction of scatterometry to photo mask metrology boosted a number of experiments to understand the opportunities and boundary conditions. The evaluation methods have been sophisticated and at the same time become more users friendly.[1-3] Essentially scatterometry is now an established analysis method that does not require the enormous specialist knowledge of the early days. Numerous publications have dealt with fundamental comparisons of the new method to the established ones in particular with CD-SEM, the current standard tool for photo mask critical dimension (CD) disposition.[4,5] Here, very good correlation has been established for numerous material systems for a wide range of CD values. These works nicely demonstrated the resemblance of the two different CD measurement methods. In this paper we will put our focus also to the dissimilarity of both methods and try to shed more light into the subject when and why the methods will provide different results.

The AMTC has a commercial scatterometer from n&k Technology (n&k 5700-CDRT) in use. This system measures the spectral transmission and reflection (i. e. the 0th diffraction order) and is used both for thin film characterisation and for CD and edge profile characterisation. The analysis of the data uses a look-up table approach in combination with a database based on a rigid coupled wave analysis (RCWA) software.[6,7]

At PTB we have realized a new DUV hybrid scatterometer which combines essential elements of a radiometer, an ellipsometer, and a diffractometer. Goniometric measurements are possible at wavelength between 840 nm and 193nm, giving also access to at-wavelength metrology of state of the art photolithography masks. The finite element based software package DIPOG is used for the evaluation of the scatterometric data. DIPOG has implemented several optimization algorithms which allow solving the inverse problem of diffraction within predefined parameter ranges.[8-10]

These two systems differ both in terms of the measurement modes, the data evaluation methods and the Maxwell-solvers used, thus establishing a perfect set up for comparing the methodologies, measurement hardware and analysis software. The first step is a systematic comparative CD and phase measurement study on scatterometry test figures on a state of the art embedded phase shift mask (MoSi) for 193nm technology. These data will be utilized to fine tune the scatterometer modelling and the understanding of additional parameters.

Experiment

The experimental data were obtained on a standard MoSi mask by means of a current generation CD-SEM and two Scatterometers. The data was collected on two 500×500 µm dense line fields repeating 13×13 times across the mask. One of the fields was a non-structured reference field and the other one was a structured dense line field with a pitch of 560 nm. The CD SEM measurements were taken on a state of the art CD SEM with a repeatability of less than 0.5 nm 3 sigma.

Comparision CD SEM – n&k scatterometry data

First, we discuss the matching of the n&k 5700-CDRT to traditional CD SEM results. One major parameter we looked at was the correlation of the difference of the CD SEM to n&k CD results versus the film thickness measurement of the n&k tool. This correlation was chosen because traditionally it shows quite well if some irregularities of the CD measurements are actually seen also in film thickness variations. In this case the film thickness and CD values are not completely decoupled, which is in general a good hint that secondary structure parameters like side wall angle need to be considered. Without this additional information it is very hard to decide on which improvement is required and therefore, we will not discuss the very easy method to use transmittance of a single wavelength for CD correlation. This method can be considered as zeroth order approximation of scatterometry completely without any modeling and represents a robust but powerful technique for CD monitoring. Unfortunately it is extremely complicated to build up on such little data.

We started with the simplest film model possible that is a single homogenous MoSi film and no variation of any parameter except CD (pitch 560 nm, side wall angle fixed at 90 degree). The film thickness is obtained by an additional measurement on the non-structured pads (about 1 mm apart) with also the simplest model possible containing only a single homogenous MoSi film and only local variation of the thickness is allowed. This 2-step model gives already very good results shown in figure 1. The figure shows thin plate spline (TPS) analysis of the CD-Data as well as the differences of the CD results and the film thickness.[11] The advantage of the TPS method is the averaging of nanoscale noise, resulting that changes on a length scale of some micrometers will be smoothed. This is essential for the CD-SEM data, since scatterometry is an averaging method that includes a large field in the measurements and is insensitive to small length scale changes.

As a first order approximation, the simple model with fixed n and k for MoSi achieved a 0.85 correlation with CD-SEM. All hills and valleys of the CD landscape are present in the data, with deviations smaller than 2.0 nm from average. The deviations seem to be closely connected to thickness variations shown in a rather large 0.5 correlation to MoSi thickness, which hints film thickness-CD coupling due to influences of so far neglected secondary structure parameters. Another interesting observation to note is that the difference plots show a clear corner effect with a radial signature. This might be connected to radial processes and again points into the direction that the process in question changes secondary structure parameters with a radial signature. The most prominent processes in question are the manufacturing process of the MoSi blank material and develop and etch processes during mask manufacturing.

The most crucial point is to find secondary structure parameters that can be investigated by other metrology tools independently of scatterometry. We decided that the best next parameter to measure with the needed accuracy besides CD is the phase shift of the MoSi material and measurements were performed on a Lasertec MPM193 system. This information was considered to be sufficient to take a deeper look at the derived MoSi thickness values and also the optical properties of the material

Before we proceed to the phase measurements we would like to note that the necessity to vary n and k for the MoSi film can be derived already from the scatterometer data. From simulation (see Fig. 2 a), for a given fixed n and k of MoSi and varying film thickness, the reflectance is bounded below a certain value due to the difference between the refractive index of the MoSi film and the refractive index of the quartz substrate.

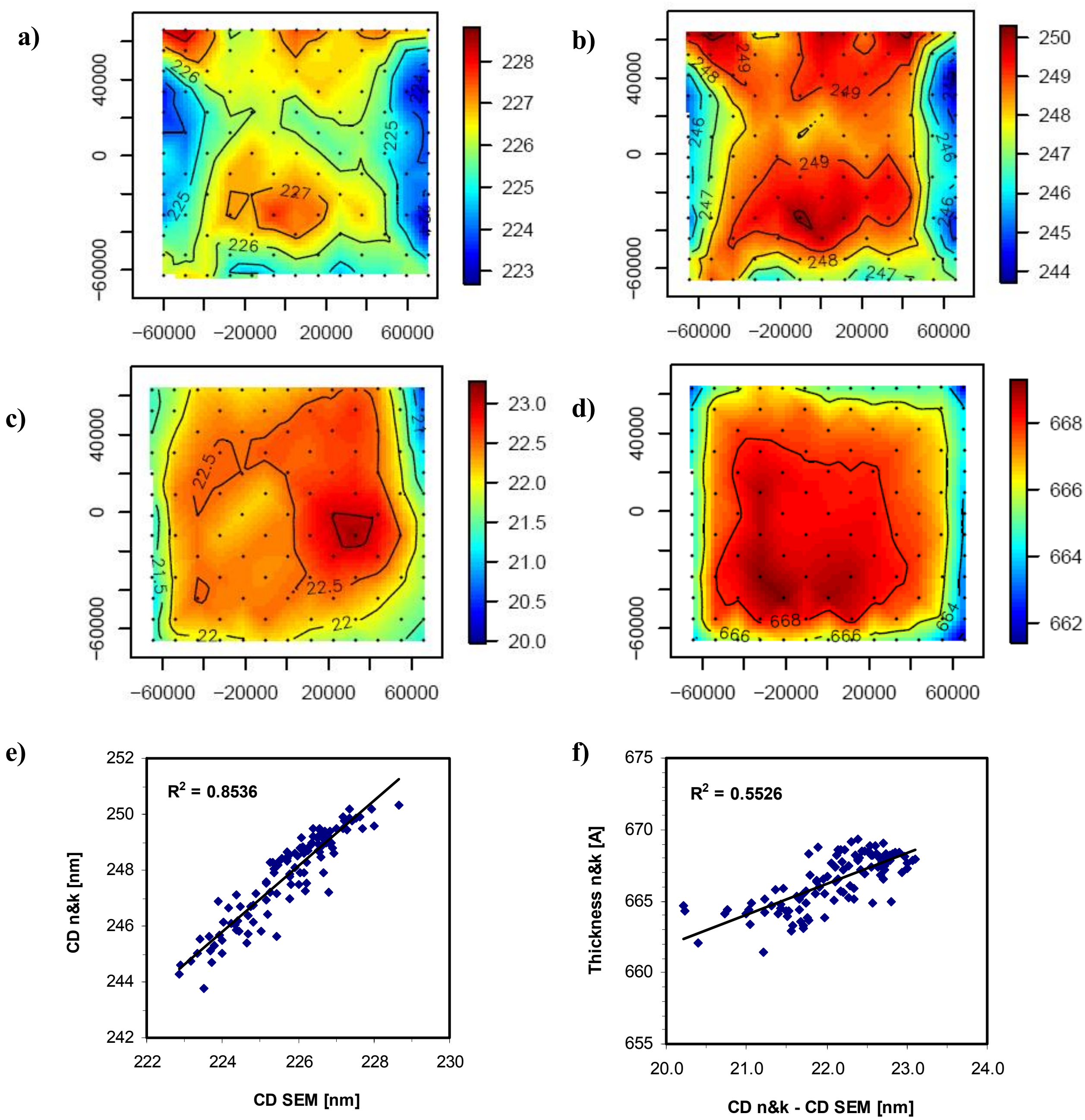

Figure 1: ***a)*** *CD SEM CD results [nm]* ***b)*** *n&k CD results [nm] the absolute difference is due to different calibrations* ***c)*** *difference n&k CD - CD SEM [nm]* ***d)*** *MoSi fim thickness as modeled by n&k [Å].* ***e)*** *Correlation plot of the difference n&k CD - CD SEM [nm].* ***f)*** *correlation of the difference n&k CD - CD SEM [nm] vs. MoSi film thickness[Å] in the simple model.*

For a series of different thicknesses, one can see a ceiling being formed in the simulations. However, for the measured reflectance map of the MoSi blank area, we see the reflectance breaking the "ceiling" (figure 2 b). Therefore, even from the scatterometry data alone it can be deduced that the refractive index of the MoSi film must vary across the mask.

a)

b)

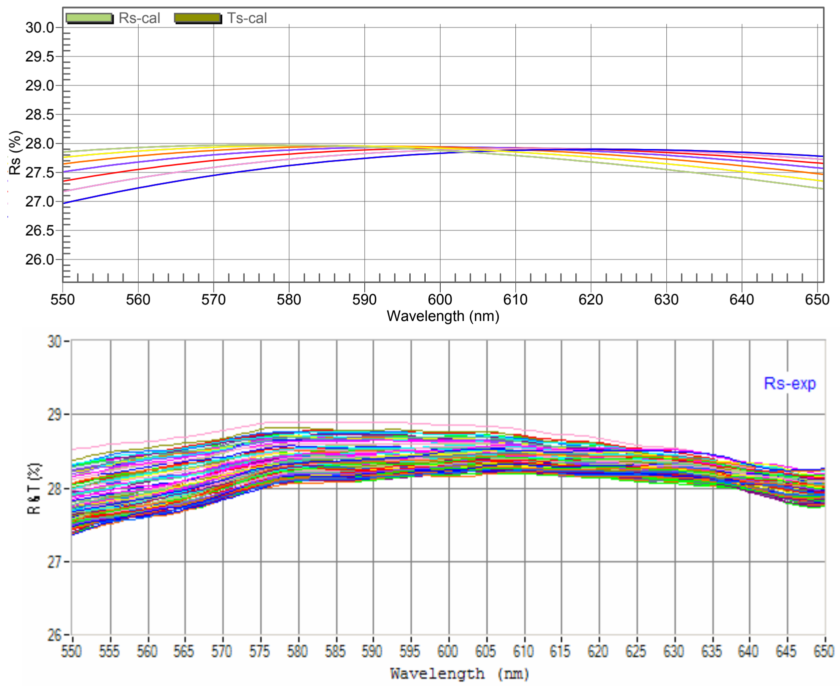

Figure 2: ***a)*** *Simulation of reflectance of blanket MoSi thickness from 64 to 69nm, for a given fixed n and k of MoSi.* ***b)*** *Measured reflectance map of MoSi non patterned area.*

Next we compared the measured phased shift range of about 3 degrees (figure 3 a) with a calculated phase shift range derived from the measured MoSi film thickness range. Here the film thickness range of ~ 8 Å implies only a phase shift range of about 2 degrees. Therefore, the improved model has to account for another structure parameter that describes the missing phase shift which represents about 50% of the total phase shift range. Here, the quartz etching has been considered to be the main contributor and an additional film for this effect has been included in the model. The results are given in figure 3 together with a plot of the calculated quartz etch depth distribution.

The calculated distribution does have a significant different distribution at the lower and upper side of the mask for the simple model (figure 3 a and b). These differences are nicely overcome by including quartz etching (figure 3 c) which has a prominent signature exactly at the lower side (figure 3 d).

Our results can be seen as an excellent indication that scatterometry captures alterations of secondary structure parameters that CD SEM can't. It would be an interesting task to investigate if the final n&k CD results match better with wafer prints because secondary structure parameters are better described.

The other interesting task will be to drive innovations on the CD SEM tools to allow detecting certain changes of structure parameters. With our latest finding of CD SEM tool interactions with photo mask surface changes[12] this adds up to new requirements for next generation tools. These new requirements should not be underestimated by tool manufacturers since it is possible that next generation mask deposition has to reflect the printing behavior of the mask much more closely than current tools achieve. Currently, techniques like scatterometry or areal image CD methods seem to be more suitable for this aspect than state of the art CD-SEM.

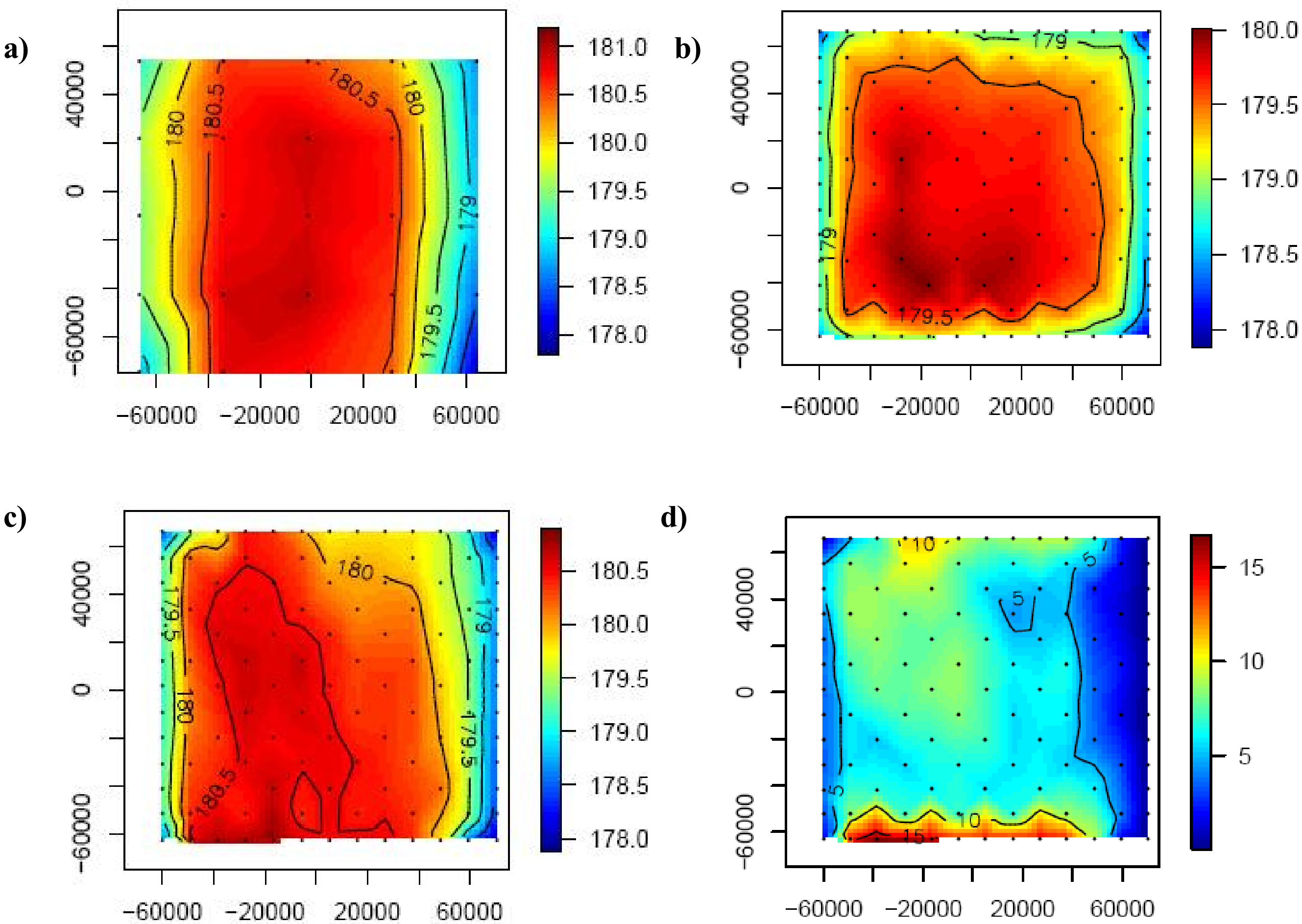

Figure 3: ***a)*** *Phase shift measurements by means of the MPM193 system [°]. Measurement locations differ slightly from CD measurement points.* ***b)*** *Phase shift calculated from n&k estimated Mosi thickness for simple model [°].* ***c)*** *Phase shift calculated from n&k estimated Mosi thickness and quartz etch depth [°].* ***d)*** *Calculated signature of quartz etch depth [Å].*

The following table summarizes the improvement in correlations due to different modeling scenarios. Even though the complexity is largest for the third model, the calculation time is still shorter than the measurement time and thus does not slow down the measurement. In general we observed that by increasing the complexity of model the correlation with CD-SEM to CD-n&k increases and the coupling of the remaining differences to the MoSi film thickness decreases.

Model	Correlation CD-SEM vs CD-n&k	Correlation of CD-SEM-CD n&k vs. MoSi film thickness
Fixed MoSi n and k, no quartz etch	0.85	0.55
Vary MoSi n and k, no quartz etch	0.85	0.39
Vary MoSi n and k, with quartz etch	0.88	0.18

Table 1: *Correlations of CD-SEM and MoSi thickness for 3 different modeling scenarios.*

Comparision PTB – n&k scatterometry data

In order to provide the a-priory information needed for the PTB simulation it is typically advantageous or even necessary to measure the complex refractive index of the sample materials independently. In principle, this can be done with both scatterometer measuring the reflection and/or transmission versus the angle of incidence in an non-structured area. For this comparison the complex refractive index has been measured using the n&k tool and these data have been used for evaluation of CD and layer thickness values.

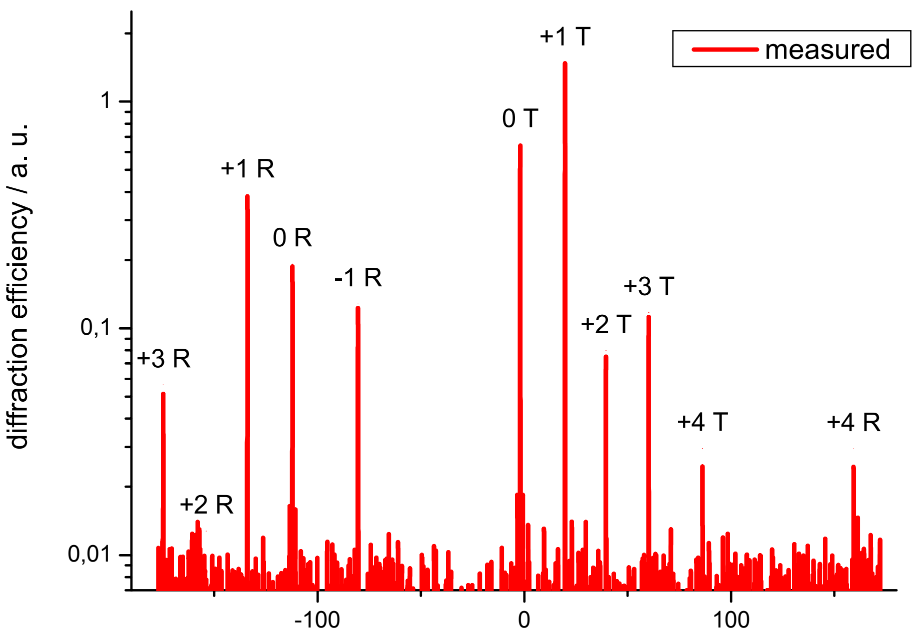

Figure 4*: Measurements of diffraction efficiencies in transmission (T) and reflection (R) for a MoSi phase shift mask; pitch of the grating structure was 560nm, the angle of incidence was 35°, and the illumination wavelength was 193nm.*

With the PTB scatterometer the MoSi phase shift mask has been measured applying classical scatterometry. Figure 4 depicts a typical measurement example of a scatterogram of transmitted and reflected diffraction orders. The system is not yet equipped with an automated measurement regime thus only singular points could be measured and analyzed. Here, we were able to measure CD's, edge angles and structure heights in two dies, that is die 7-7 (center die) and die 2-6 which is on the left side in the middle.

We measured in each die the scatterograms for four different angles of incidence: 20°, 35°, 50° and 65°. First results of a reconstruction based on the measured diffraction efficiencies are presented in table 2. In the PTB set up CD, flank angle and thickness have been varied. A variation of MoSi optical properties and the inclusion of quartz etch is omitted due to the current complexity of the calculation within DIPOG. The resulting quantities are given in table 2.

die 7-7	CD / nm	side wall angle / °	Mosi film thickness / Å
n&k (simple model)	248.9	90 1)	668.2 2)
PTB DUV-scatterometer	242.2	89	710
die 2-6			
n&k (simple model)	247.1	90 1)	667.5 2)
PTB DUV-scatterometer	239	89	710

Table 2: *Results of scatterometric CD, edge angle and height measurements with the PTB DUV-Scatterometer and comparison measurement results obtained with the n&k scatterometer, PTB height values include chrome edge. 1) no fit 2) measured on non patterned structure.*

The measured edge angles of 89° fits reasonable good the standard atomic force measurements that provide results in the 87-89° range. Thus, the assumption of a 90° edge angle is justified as well as the robustness of the PTB model for this parameter. The data so far reveals no change in side wall angle for the investigated two dies but more studies are required to disclose the overall behaviour. Interestingly, the PTB height values are much higher than the n&k values. Partly this can be attributed that a quartz etch has not been considered. Also here further work needs to be done to understand the differences in more detail and to build up a more complex evaluation scheme for the PTB system. Finally, a systematic offset of about 7 nm has been observed and the CD tendency is reproduced. It is important to note that the difference of the two Scatterometers is much smaller than their difference to the CD SEM values that are derived from top-CD PTB calibration.

Furthermore, the difference of 20 nm puts both scatterometer absolute values right in the middle of the PTB and NIST calibration, which differs by about 40 nm for MoSi. Again, further work is needed to fully understand this and experiments are under way for a deeper insight into the absolute calibration of CDs. For the purpose of this paper, it can be taken as a hint where a consolidated absolute CD result might be.

Finally, it is worth to note that besides the global offset of measurements, which can be easily calibrated, it is important to judge the sensitivity to small changes in CD and the repeatability to capture the subtle signatures. The 5700-CDRT is a very successful system in this regard due to the use of broadband measurements from 190 to 1000nm. It will be extremely interesting to learn what the repeatability and sensitivity is on the PTB scatterometer, since the tool is single wavelength tool but also compensated by multiple angles.

Conclusion

We have presented first results of a comparison of CD measurements of grating test structures on a MoSi phase shift mask obtained with three different tools: a CD SEM, a commercial scatterometer of n&k Technology and a new type of scatterometer recently developed and realised at the PTB. The results for basic parameters agree reasonably well and are promising for further studies.

Our main conclusion is that current commercially available scatterometry system matches with traditional CD SEMs very good for simple film structures like 193nm halftone material. The difference of up to 2 nm for single point comparison of a simple model can be reduced to about 1.5 nm with more sophisticated models. Furthermore, we were able to show that these remaining differences are driven by changes in secondary structure parameters. Here, additional phase measurements resulted in model improvements to include quartz etching and local variations of optical MoSi properties. Thus, we conclude that scatterometer and CD SEM can match with very high precision on the nanometer scale and even below.

Although it seems currently unthinkable that CD-SEM might not carry CD disposition in the nodes to come, this work provides some aspect that even the unthinkable is not too far off. Right now CD-SEMs are not able to detect changes in secondary structure parameters that other methods and in particular scatterometry can. In this work, varying optical properties and quartz etching were analyzed and both parameters change the local phase behavior. Phase changes on the photo masks are known to have little impact on the wafer CD thus no immediate action is required. However, it is not hard to think of parameters that will have direct impact on wafer CD. Here, changes in the side wall angle are considered to be the most promising one for future investigations.

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