Model based reference metrology for dimensional characterization of micro- and nanostructures*

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The requirements on the precision of dimensional metrology are especially stringent in the area of semiconductor manufacturing. This holds in particular for the measurement and control of the linewidths of the smallest structures on masks and silicon wafers and their corresponding reference metrology. In this paper we will describe the physical models and the reference instrumentation which were developed for photomask linewidth metrology at the PTB. It will be shown, how the results of the different methods can be used for comparative analyses. Application of these methods will be demonstrated exemplarily on the basis of newly developed photomask linewidth standards.

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Linewidth or critical dimension (CD) metrology is crucially important for production control in semiconductor and mask manufacturing. Stringent requirements on the stability of process control need highly stable CD metrology instrumentation and measurement processes with sub-nm reproducibility. These requirements are specified for current as well as future technology nodes in the so-called International Technology Roadmap for Semiconductors, (ITRS) [1]. In many cases different types of CD metrology instrumentation are in use in industry today and a meaningful comparison of their measurement results requires development and application of appropriate models for the different methods, especially if structural details are changing due to process variations. The PTB has developed different types of linewidth metrology instrumentation and corresponding physical models for image signal analysis and interpretation. These methods will be described here and their application to a photomask linewidth standard will be shown [2].

The different linewidth metrology methods will shortly be described with respect to the applied signal modelling approaches and the different experimental realizations. In our approaches we assume that the photomask features to be measured can usually well be approximated by trapezoidal shapes and by the material parameters for the absorbing or phase shifting material and additional anti-reflective layers, see Fig.1. However, this simplified trapezoidal model can be modified to also take into account more complex feature geometries.[3, 4].

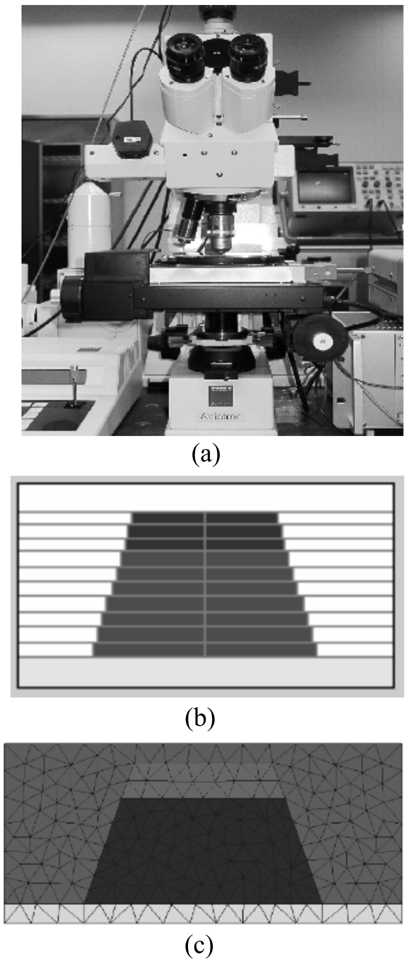

Fig.1 (a) UV transmission microscope setup used for CD metrology;(b) trapezoidal feature geometries modelled in RCWA (program package Microsim) and (c) FEM based simulations (program package DiPoG).

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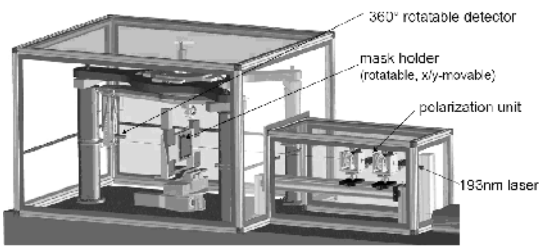
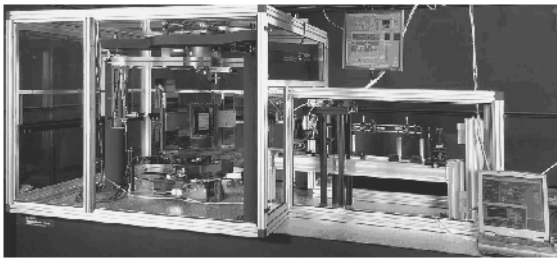
The PTB uses an object scanning method for CD measurements. The line feature of interest is translated in the object plane, its image is shifted accordingly in the image plane relative to a fixed slit aperture and the transmitted light intensity is detected. By this procedure, the length scale of the recorded intensity profile is directly traceable to the length definition. For linewidth analysis of the recorded intensity line profiles, two different approaches are used: The so-called rigorous coupled-wave analysis (RCWA) method and a finite element method [5]. Both approaches offer solutions to Maxwell equations for the respective measurement configuration.

All optical models require precise input data for the optical parameters, namely refractive index n and absorption coefficient k, at the respective wavelengths for all relevant materials of the measurement object (substrate and thin film stack). If these are known or can be determined with independent methods, measurement uncertainties for linewidth of $U_{95\%}$ = 20 nm can be achieved. It should also be mentioned that on isolated features, a method developed at PTB called alternating grazing incidence darkfield microscopy (AGID) allows to measure linearly down to feature sizes of 100 nm[6] .

So-called scatterometry techniques, which analyze the far-field diffraction patterns of illuminated periodic structures within areas between 10 μm and 1 mm square are already widely in use for process control in semiconductor manufacturing, because of their high sensitivity to process variations and their comparatively simple hardware configuration. These non-imaging methods provide valuable information about the dimensional properties within the illuminated area if supported by appropriate signal modelling approaches. For the modelling of the scatterometric measurements the same rigorous diffraction models are used as for the microscopic imaging description. At PTB scatterometry methods and simulation models are investigated and applied in different wavelength regimes from the visible spectrum down to the EUV range [7-9], see Fig.2 for the newly developed DUV scatterometer.



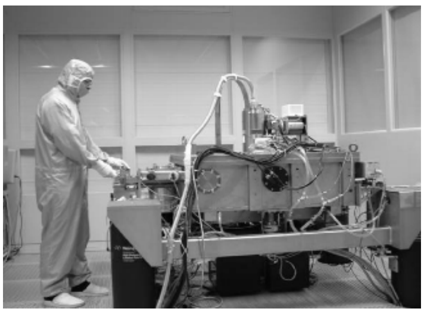
(a)



(b)

Fig.2 Sketch of the new PTB DUV ellipsometric scatterometer (a) and its realization (b).

For traceable calibration of linewidths on masks and wafers by scanning electron beam methods, the PTB primarily uses the electron optical metrology system (EOMS) [10]. The analysis of measured SEM line profiles is based on Monte Carlo simulation method, which model the elastic and inelastic scattering events of the primary electrons as well as the generated backscattered and secondary electrons. These simulations allow to describe the signal variation close to feature edges and thus to determine characteristic dimensional feature parameters. For example, to deduce the linewidth at the top of a trapezoidal line feature an exponential edge operator was proposed and successfully applied, which offers measurement uncertainties of $U_{95\%}$ = 15 nm for top CD [11], see Fig.3. An extension to a generalized SEM edge operator for trapezoidal line features was proposed recently [12], which allows to determine the top and the bottom CD, too.



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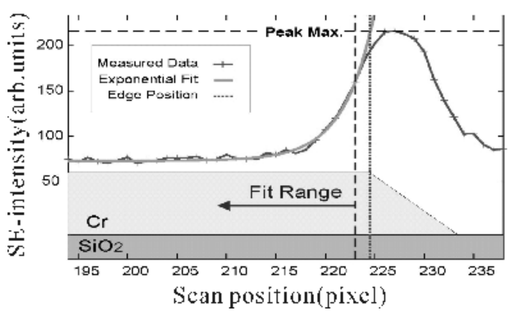
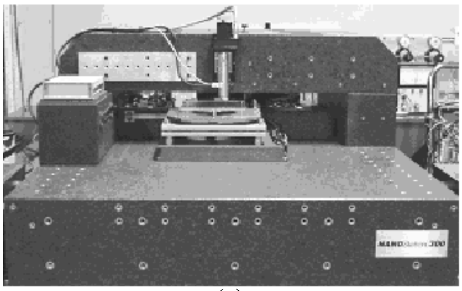


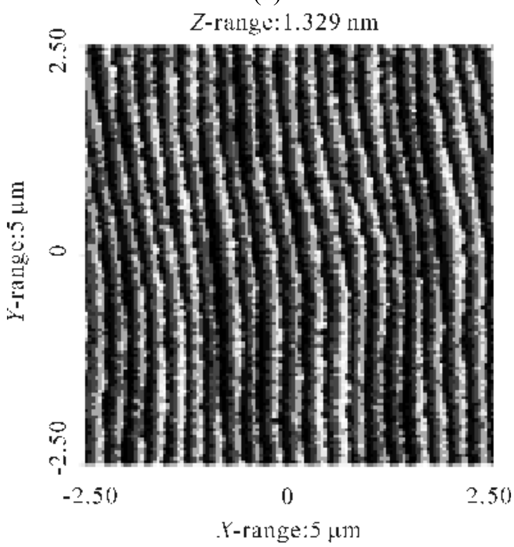
(b)

Fig.3 Electron optical metrology system of the PTB (a) and principle of the exponential fit edge operator for determination of top feature linewidth and edge position (b).

So far AFM or scanning force microscopy is used at PTB in mask metrology primarily for determination of feature height and sidewall angle or in general line profile shape metrology as an additional measurement method, which provides valuable input data for the signal modelling approaches of the other (faster) CD methods. For this task different types of AFM are in use. Fig.4 for example shows a newly developed system for AFM measurements on larger substrates of up to 300 mm size. This system uses an air bearing stage and optical microscope position detection for positioning of the sample to within 1 μm below the AFM scanner. For the AFM measurements, the air bearing is switched off to increase the stability for high resolution AFM metrology.



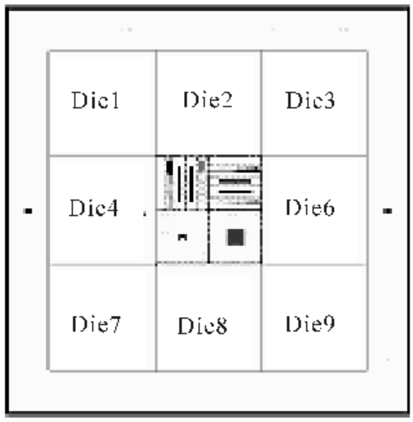
(a)



(b)

Fig.4 The PTB AFM for measurements on larger substrates (a) and a typical measurement scan by this system on a 5x5 μm polished silicon sample, cut to reveal atomic lattice steps (b). The step heights of 0. 2 nm are clearly resolved and illustrate the stability of this large object AFM.

In cooperation with some partners from mask industry in Germany, the PTB has developed a new photomask linewidth standard, whose suitability for mask metrology in industry was shown in a round robin measurement between the partners [2]. Fig.5 shows the basic layout of the 6025 format mask standard, which shows line and dot features in isolated as well as dense environments down to 100 nm.



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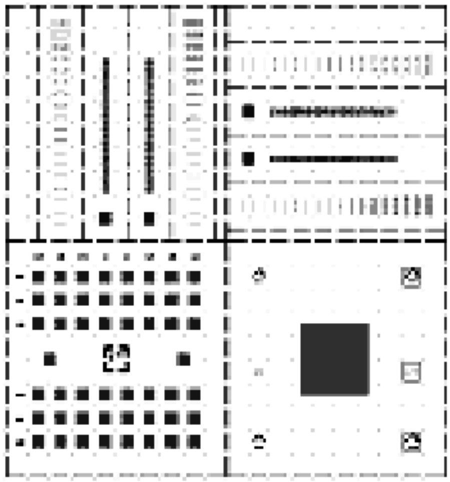

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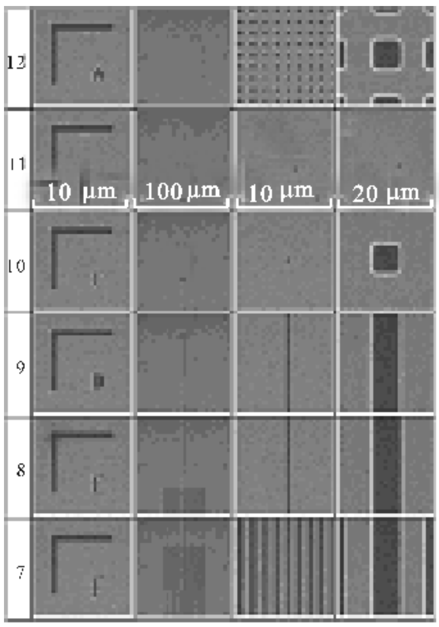

(c)

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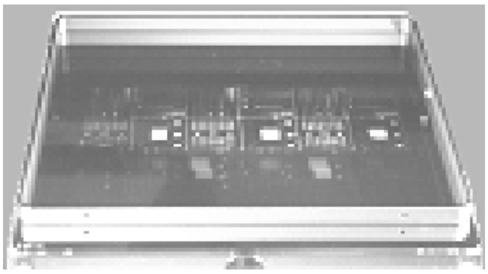
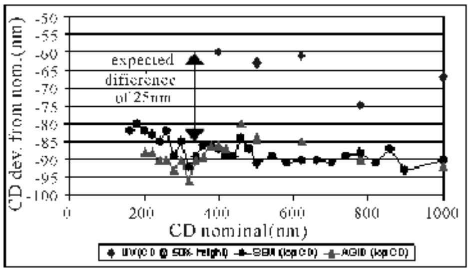


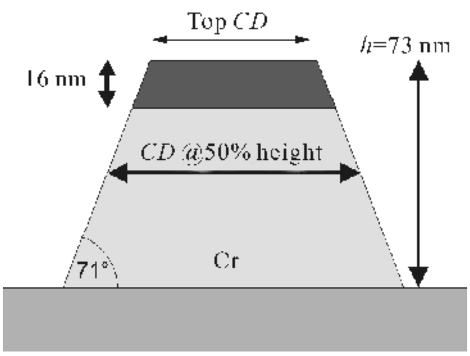
(d)

Fig.5 Overview of layout, measurement features and a photo of the 6025 format CD mask standard.

Fig.6 shows the PTB measurement results on a round robin CD mask standard and the results on line height and sidewall angle provided by AFM microscopy. On the basis of AFM data one would expect a difference of 25 nm between CD in the middle of the feature and CD at its top, the measured mean difference between SEM and UV transmission microscopy was 24 nm, thus supporting the models used. In addition the AGID method [6] was applied to deduce the top CD values and its results were in very good coincidence with the SEM results for top CD, see Fig.6.



(a)



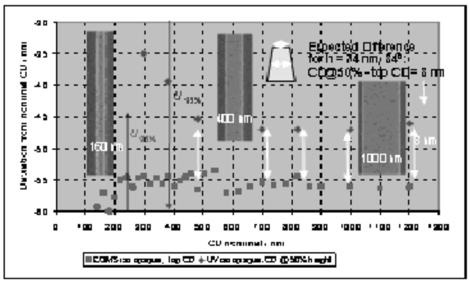
n_{ARC}=2.117+i・0.997 n_{Cr}=2.126+i・2.887

(b)

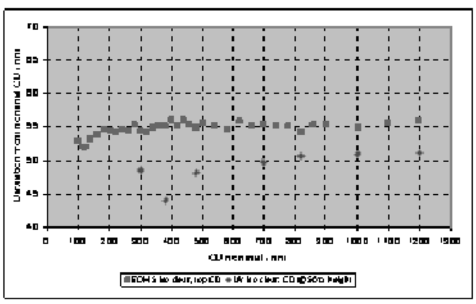
Fig.6 PTB results for single opaque line structures for different measurement techniques (a) on the CD photomask standard with chrome/quartz trapezoidal features with antireflective coating (b), which was used in the round robin linewidth comparison [2].

In addition to the measurement on the round robin standard shown before, some more masks from different production processes have been manufactured and characterized since then. All of these masks showed the same standard layout as illustrated in Fig.5. The advantage of the use of a well adopted standard layout is the efficient use of measurement jobs, which have only to be set up once. Recently, the smallest features on the CD mask standard have been reduced down to 50 nm nominal linewidth values, because for the currently used 65 nm production process, so-called assist features like scatter bars have tobe manufactured and controlled on the masks, which already are in the sub-100 nm range.

Fig.7 shows some PTB measurement results on such a mask standard in use for the 65 nm technology node. Also in this case, one can see a very good agreement between the expected difference of CD data at the top of the features and at 50% of their height, as deduced from AFM measurements and the measured CD data from SEM and UV transmission microscopy. For the isolated line features the expected difference amounts to 8 nm, which was also found experimentally, at least for the CD values down to 500 nm. The remaining larger differences between SEM and UV results for smaller structures below 400 nm may be due to the decreasing line edge roughness properties of the features, a slightly changing edge angle with CD values or remaining



(a)



(b)

Fig.7 *CD* calibration results by SEM (EOMS, top *CD*) and UV transmission microscopy (*CD* at 50% height) for a *CD* standard which was developed for production of 65 nm technology node masks. Results for opaque line structures (a) and for clear structures (b).

challenges in modelling the response of bright field UV microscopy for very small features in comparison to the already quite satisfying dark field microscopy results (AGID, see Fig.6). The results on dense line features are not shown here but do support the imaging modelling approaches.

We presented the different metrology methods and simulation approaches applied at PTB for linewidth metrology tasks. Each method has its specific advantages. It can be stated that a meaningful combination of the different methods has to be applied to determine all relevant mask feature parameters with the required precision. Our activities in high resolution microscopy methods, both with respect to instrumentation and modelling, will be continued and in particular the results from the optical non-imaging measurement set-up, the new DUV scatterometer, will provide valuable additional information on dense line arrays.

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