

High Precision Dimensional Metrology of Periodic Nanostructures using Laser Scatterometry

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Abstract:

At PTB different laser scatterometers with partly novel and outstanding metrological capabilities have been developed and are available for high-resolution dimensional metrology of periodic nanostructures. Two different systems are described and their metrological potential discussed: a laser diffractometer for pitch calibration and a versatile goniometric scatterometer for multi-parameter characterisation of nanostructures.

Introduction

Many current and future technologies require a highly accurate and reproducible metrology of micro- and nanostructures. Especially the semiconductor industry greatly pushes the metrological requirements. Although sophisticated ultra-high resolution microscopic techniques like SEM and AFM are available, optical methods are of interest and are important because they are non-destructive, fast and have a good in-line capability.

Scatterometry is a promising candidate to solve future challenges in dimensional nanometrology. At PTB, recently two different laser scatterometers with partly novel and outstanding metrological capabilities have been developed, a diffractometer for pitch calibration and a versatile goniometric scatterometer. These systems are now available for high-resolution metrology and their features and capabilities are described in the following.

Diffractometer for pitch calibration

For the accurate measurement of the period (or mean pitch) of one- and two-dimensional gratings, an optical diffractometer has been developed at PTB which offers the possibility of period calibrations with an uncertainty down to a few pm [1]. The period of a grating is determined by means of diffraction of laser radiation using a Littrow configuration, see Fig.1. The sample is mounted on a precision turntable connected with a rotary encoder which is used to measure the angle of the incident laser beam relative to the sample. The detector, a CMOS linear image sensor, is mounted slightly below the incident laser beam (approximate Littrow configuration). Different lasers emitting at different wavelengths can be used: a

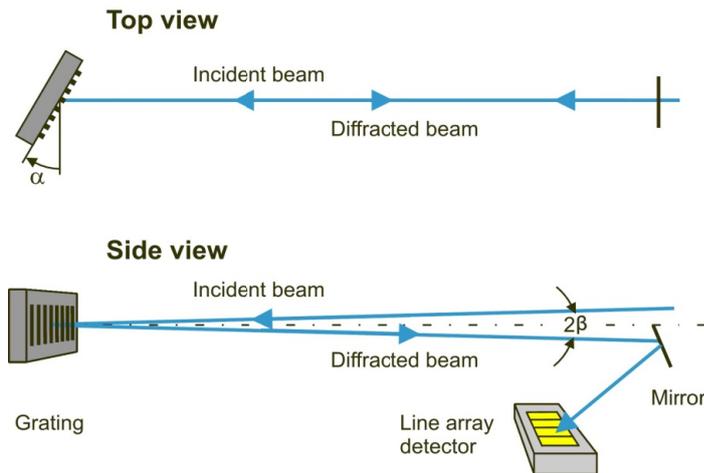


Fig. 1: Schematic view of the measurement principle using Littrow configuration

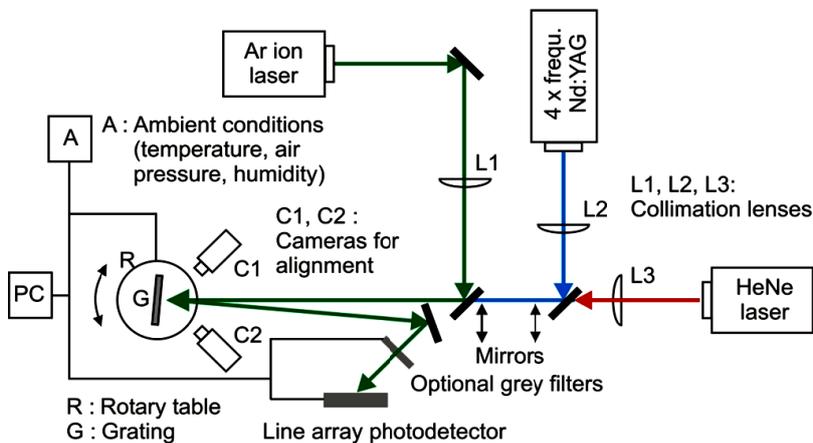


Fig. 2: Schematic diagram of the set-up of the optical diffractometer at PTB.

multiline HeNe laser, an Ar ion laser with various wavelengths and a UV laser emitting at 266 nm. Fig. 2 shows a schematic diagram of the complete set-up. According to the basic diffraction theory, a linear relationship between the sine of the diffraction angles and the diffraction order m is expected, i.e. $m \cdot (\lambda / p) = 2 \sin(\alpha_m) \cdot \cos(\beta)$. The factor $\cos(\beta)$ corrects for the slight deviation of the measurement geometry from the ideal Littrow geometry, see Fig. 1. The values $\sin(\alpha_m)$ are measured for various diffraction orders m , and a linear regression is calculated to determine the proportionality factor between wavelength and period. Fig. 3 shows a measurement of a nominal 1000 nm grating using the green HeNe laser line at $\lambda = 543$ nm.

In practice, the maximum angle of incidence is limited to about 70° in order to limit the size of the laser spot on the sample. Hence, the minimum mean pitch measurable with our instrument is approximately 140 nm using the 266 nm UV laser [2].

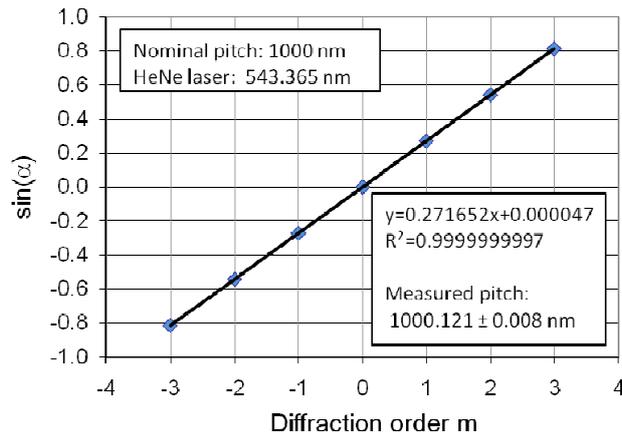


Fig. 3: Measurement of a 1000 nm grating pitch using the green HeNe laser line.

The uncertainty of the measured mean pitch depends on the uncertainty of the laser wavelength, the diffraction angles and as well on the quality of the sample. While the laser wavelength can easily be determined to the 10^{-6} level or less, the measurement of the diffraction angles is a major uncertainty component. Here, the determination of the centre position of the diffracted beam profiles is the critical point which is primarily affected by the quality of the laser beam profiles and unwanted coherent interference pattern [1,3,4]. Nevertheless, intercomparison measurements using well calibrated high-end optical diffractometers show that uncertainties in the 10 pm range are achievable [4,5]. Further reduction of the laser wavelength e.g. to 193 nm would make it possible to extend the measurement range down to about 100 nm.

Scatterometer for grating profile characterization

For the accurate dimensional characterization of further grating parameters, like the absorber linewidth (critical dimension, CD), side wall angle (SWA) or structure height, a goniometric scatterometer is used (see Fig. 4 and 5) [6]. It can be operated in a reflectometric, ellipsometric, and diffractometric measurement mode. As a radiation source a frequency multiplied Ti:Sa laser provides four wavelength ranges (fundamental: 772-840 nm, SHG: 386-420 nm, THG: 257-280 nm, FHG: 193-210 nm). To determine the periodic structures under test on a photolithography mask the scatterometer is usually operated in reflectometric mode with p-polarized illumination at a wavelength of 193 nm corresponding to the working wavelength in currently used in photolithography. The diffraction efficiencies in transmission and reflection are measured. These values are used as input parameters for a so-called Maxwell solver with integrated optimization routine. A Maxwell solver is able to solve the *direct* diffraction problem, which means that the scatterogram can be solved for a known

structure and a known illumination. With the help of the optimization routine also the *inverse* problem of diffraction can be solved [7]. Here the best fitting structure under test is calculated from measured diffraction efficiencies and with a known illumination. For this purpose we are using the software package DiPoG from WIAS [8].

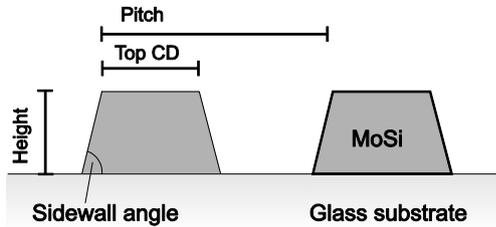


Fig. 4: Parameterized cross-section of a grating profile of an APS mask with MoSi lines.

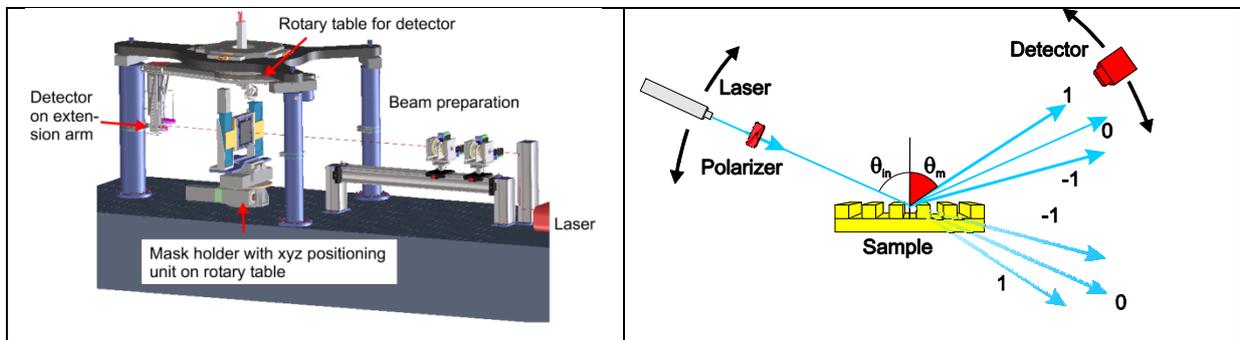


Fig. 5: Technical draft of the DUV scatterometer (left). Principle of a goniometric scatterometer (right). The diffraction efficiencies in reflection and transmission are measured.

To demonstrate the functionality of the scatterometer and the evaluation software, measurements achieved on an attenuated phase shift mask (APSM) are presented. The APSM is featured with nominally identical grating structures of MoSi-lines on a quartz substrate. Measurements have been performed at 12 fields and with seven different angles of incident varying from -45° to $+45^\circ$. As a first parameter, the grating period (mean pitch) was determined. With a mean value of (559.99 ± 0.74) nm (expanded uncertainty, $k=2$), the design value of 560 nm could be confirmed very well. The further geometrical parameters depend on the selected model. Four different models as shown in Fig. 6 have been tested.

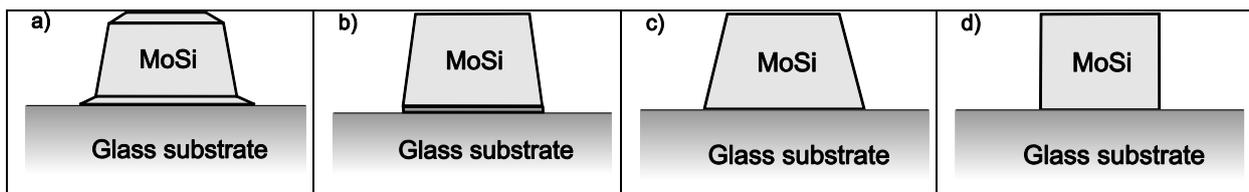


Fig. 6: Tested geometrical models: a) threefold stack of trapezoids, b) single trapezoid with quartz etching, c) single trapezoid, and d) single trapezoid with vertical edges.

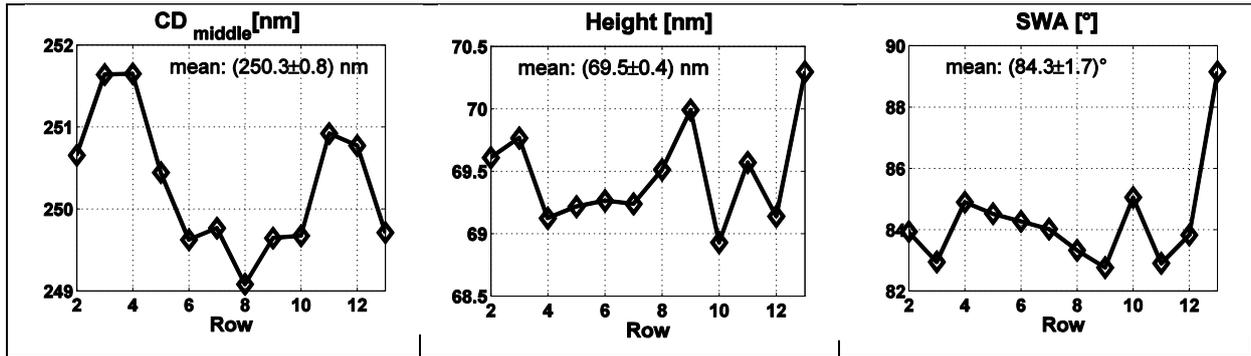


Fig. 7: Resulting CD at half of the height, the height and the sidewall angle for 12 nominally identical grating structures on the APSM.

They include a simplified simulation of corner rounding and footing as well as quartz etching effects (model a) and b)). However, no indication for this could be found. So, a geometrical model with a single trapezoid was sufficient (model c)). The best fitting geometrical parameters are shown in Fig. 7.

CD Measurements on this mask have also been performed by the ATMC with a scanning electron microscope (CD-SEM) and a spectroscopic scatterometer [9]. They used a simplified geometrical model with vertical edges. To achieve comparable data, the measurements obtained with the goniometric scatterometer have been recalculated with the limitation of a fixed SWA of 90° (model d) in Fig. 6). In Fig. 8 all results are depicted.

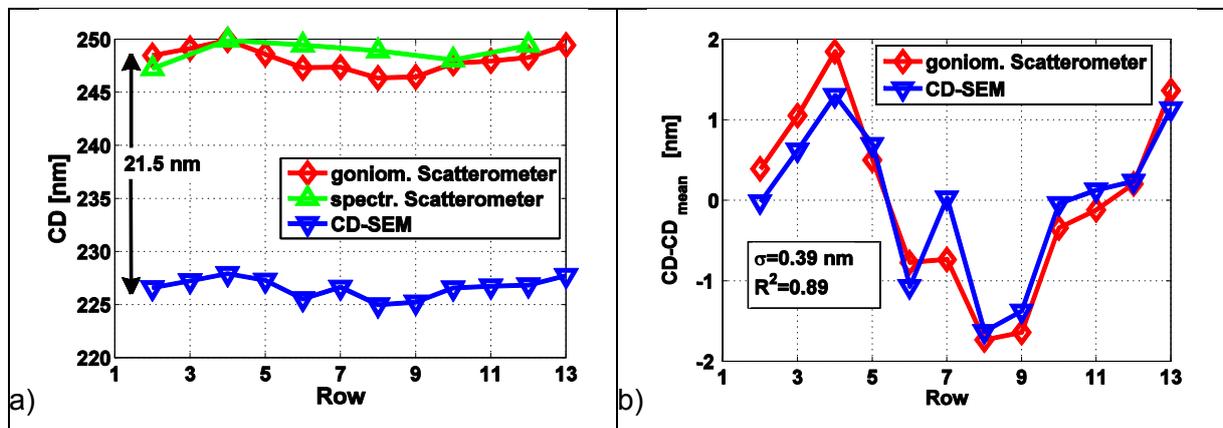


Fig. 8: a) Results for the CD values on 12 different fields, measured with a spectroscopic and the described goniometric scatterometer and a CD-SEM. Data evaluation was performed with the sidewall angles hold fix at 90° b) Trend of the CD values measured with the goniometric scatterometer and the CD-SEM after subtracting the mean values.

The mean CD values obtained in both scatterometric measurements are in very good accordance Fig. 8 a). They differ only by 0.8 nm. However, there is nearly no correlation between the results ($R^2=0.04$, $\sigma=1.4$ nm). The CD-SEM results differ from the results measured with the goniometric scatterometer by about 21.5 nm. In Fig. 8 b) the trend of the CD-SEM and PTB's scatterometrically achieved results are compared. Their conformity is very good: A coefficient of determination, R^2 , of 0.89 and a standard deviation of $\sigma=0.39$ nm could be reached. So the trend of the CD-SEM could be confirmed. However, the CD-SEM measurements are probably affected by a large systematic offset error. This most likely arises from the fact that the CD-SEM's calibration is only valid for chrome-on-glass mask and not for attenuated phase shift masks.

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