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Dimensional optical metrology of deep subwavelength grating structures

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Abstract
We present optical measurements of the size and geometry of grating structures with linewidths down to 25 nm on silicon wafers by means of goniometric scatterometry and spectroscopic Mueller ellipsometry. With respect to the applied inspection wavelengths the structure sizes are in the deep subwavelength regime.
We present both individual evaluations of the measured data as well as a combined analysis to reconstruct the cross-section profile. By this hybrid analysis method based on the Bayes approach parameter correlations can be reduced significantly compared to single measurement analyses, and lower measurement uncertainties are achieved.
Based on a covariance analysis we derive the statistical measurement uncertainty of the whole structure profile. This includes but is far beyond state-of-the-art uncertainty estimations for dedicated parameters such as structure width or height. For these parameters we typically estimate the resulting uncertainties to be between 1 to 5 nm.
Finally, by numerical simulations we have tested the limits of our approaches for the characterisation of even much smaller grating structures. As a result we have demonstrated the extendibility of our methods down to well below 10 nm and with it we have shown it's suitability even for current and future technology nodes in IC manufacturing technologies.

optical metrology, nanotechnologies, scatterometry, gratings, hybrid metrology

1. Introduction

Manufacturing for current and future nanotechnologies including nanoelectronics, nanoscale sensing devices and artificial materials require accurate, reliable and efficient dimensional metrology to characterise the size and shape of the nanostructures. Here scatterometric methods play a decisive role in particular for process monitoring and in-line metrology. For grating structures with periods below half of the optical wavelength sophisticated methods such as polarised reflectometry or Mueller matrix ellipsometry have to be applied to provide sufficient structure information and sensitivity. However, even for these approaches the question arise for possible sensitivity limits of optical scatterometry in the deep sub-wavelength regime with structure sizes ≤ $\lambda/10$ [1, 2]. Therefore we performed measurements with these two scatterometry methods on sub-subwavelength structures and tested by numerical simulations the theoretical limits for even much smaller grating structures.

2. Measurements

We measured different high quality silicon grating structures with grating periods down to 50 nm and linewidths down to nominal 25 nm. These samples have been produced via electron beam lithography and subsequent reactive ion etching by the Helmholtz-Zentrum Berlin (HZB).

2.1. DUV scatterometer

PTB's DUV scatterometer [3] has been used for goniometric polarised reflectometry on these samples. The measurements have been performed at a wavelength of 266 nm.

Four different measurement configurations differing in polarisation and sample orientation have been applied (fig. 1), while the spectroscopic ellipsometry measurement data has been recorded at different angles of incidence wavelength from 200 nm to 900 nm.

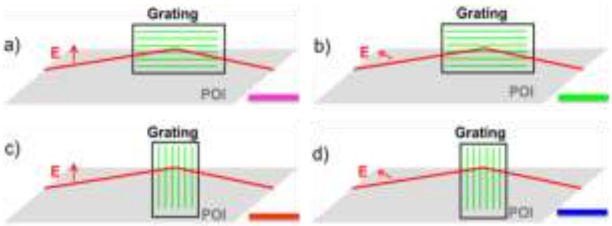

Figure 1. Four measurement configurations differing in polarisation (s- and p pol.) and sample orientation (TM, TE); POI: plane of incidence.

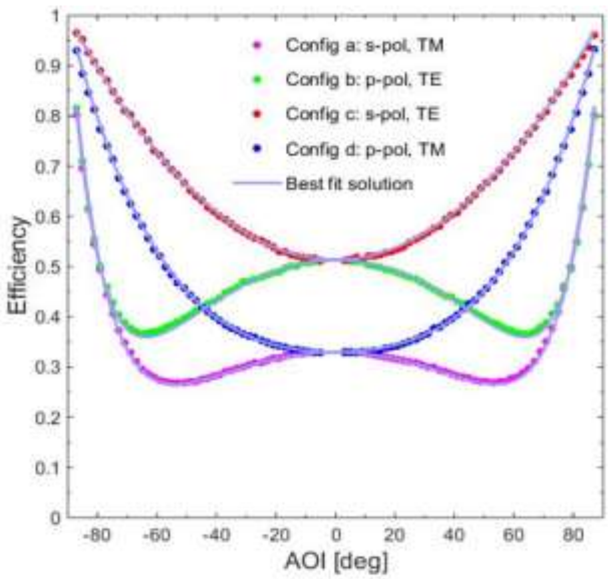

Figure 2. Measured diffraction efficiencies (dots) and best fitting simulated efficiencies for the structure with nom. linewidths of 25 nm.

2.2. Spectroscopic Mueller Matrix ellipsometer

Additionally conventional and Mueller matrix ellipsometric measurements on these samples have been performed by PTB's spectroscopic Mueller matrix ellipsometer (SENTECH SE 850 DUV), operating in the spectral range 190 nm – 2500 nm.

3. Modelling and data analysis

The measurements are simulated using the finite element method (FEM) based software package JCMSuite. It solves Maxwell's equations on an elementary cell of the grating.

For the description of the structure geometries a novel model based on rational Bézier curves is applied using seven geometry parameters. With this the flexibility of the model is increased, and unphysical results are excluded in contrast to other parametrisations commonly used.

To derive the structure geometry the inverse diffraction problem has to be solved. For this purpose we applied a combination the differential evolution method, a derivative-free algorithm commonly used for global optimisation and a Nelder Mead optimiser for fast local optimisation.

For the evaluation of the measured data we applied both an individual optimisation of the reflectometry and ellipsometry data, respectively, and in a combined data analysis of both data sets in a hybrid metrology based on a Bayes approach [4].

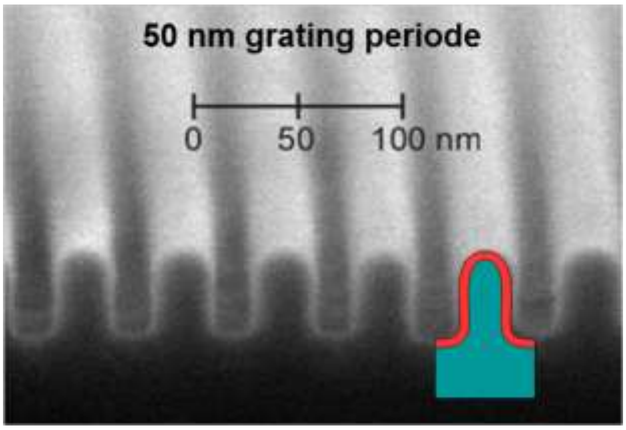

Figure 3. Reconstructed best fit cross section profile (green: Si, red: SiO_2) of the line with nom. widths of 25 nm compared with cross-section profile of identically manufactured grating measured with SEM.

4. Results

Figure 2 shows an example of polarised reflectometry measurements in comparison with the best fit optimisation result. In figure 3 the derived cross section profile is quantitatively compared with an SEM cross section profile measured at an identically manufactured sample. Both comparisons show excellent agreements.

Table 1 Measurement results obtained by reflectometry (DUV) for the smallest grating structure (nom. widths, height: 25 nm, 50 nm) compared with the result of hybrid data analysis of reflectometric and ellipsometric measurements and with results obtained by X-ray scatterometry (GISAXS).

Measurement results	Widths / nm	Height / nm
DUV scatterometry	25.9 (1.4)	50.0 (4.4)
Hybrid (Scatter. and MME)	26.4 (0.9)	48.9 (1.6)
GISAXS	25.1	48.2

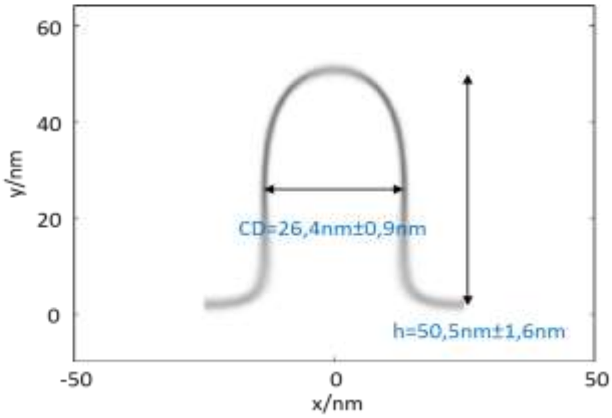

Figure 4. The standard deviation areas of the outer contour of the smallest test structures with nominal pitch, height and linewidths of 50, 50 and 25nm, respectively.

Table 1 shows the measured results for the important geometry parameters structure widths and height derived from the reflectometric measurements and compared with the results obtained from a hybrid data analysis of reflectometric and ellipsometric measurements and with results of X-ray scatterometry measurements [5]. Again an excellent agreement within the derived uncertainties is observed.

For these tiny structures the sensitivity of the described optical methods is still sufficient not only to derive the characteristic structure parameters widths and height reliably, but for the first time even the whole structure contour with stated uncertainties can be derived accurately (fig. 4). More details and results are given elsewhere [6].

5. Conclusion and outlook

We have shown that we can scatterometrically measure silicon structures with feature sizes down to a tenth of the inspection wavelength, which corresponds to a CD of about 25 nm. We performed both individual analysis of polarised reflectometry and spectroscopic ellipsometry measurements as well as combined data analysis. A Bézier curve-based geometry model was developed and used, which overcomes the inadequacies of simpler structure models. In combination with a co-variance analysis for the first time it was possible to derive the whole contour of the structure including reliable contour uncertainties.

Numerical studies predict the extendibility of these optical scatterometry measurements to even much smaller grating periods and structure sizes down to a few nm, i. e. down to the regime $\leq \lambda/100$ [7]! In a next step we are going to verify these predictions and the performance for this regime on corresponding nanogratings subject to the availability.

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