

# Sub-Wavelength Features in Spectroscopic Mueller Matrix Ellipsometry

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We designed, fabricated and characterized a set of individual resist nanostructures on a silicon wafer. The structures possess distinct geometrical features in the range from several nanometers to a few micrometers and will be used in future measurements to investigate in the link between geometrical features and off-diagonal Mueller matrix elements.

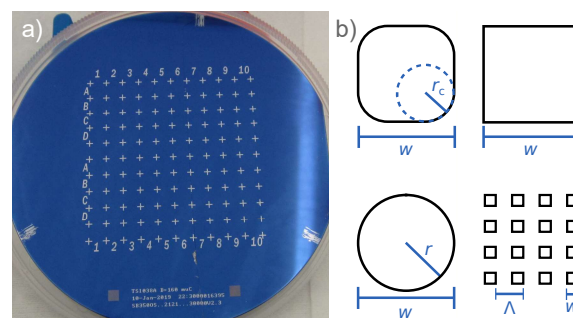
## 1 Introduction

Spectroscopic Mueller matrix ellipsometry (MME) is an indirect optical technique that gives access to information about all polarizing properties of the sample under investigation. Furthermore, MME serves as a useful tool for the measurement of structural features down to the nanoscale, for example in layer thickness and nanostructure characterization as well as critical dimension metrology [1]. Simulations of Mueller matrix images for individual geometric silicon structures have shown large influences of sub-wavelength features. Especially in off-diagonal matrix elements, significant distinctions between different shapes can be observed [2]. Our investigations focus on using these indications on nanoscale features optionally together with specially designed supporting nanostructures in an MME setup to enhance the sensitivity for polarisation encoded topological information. As a first step, this contribution covers the design and characterization of structures that will serve as references in future MME experiments.

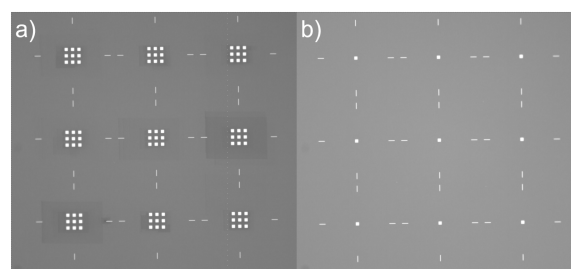
## 2 Reference Structure Design

To investigate in the link between geometrical features and Mueller matrix elements, we produced a series of individual nanostructures which we are going to use in future measurements. They are based on squares and circles as well as squares with rounded corners as a transition between both. The structures consist of 100 nm deep holes in PMMA resist on a 100 mm silicon wafer and were fabricated by electron beam lithography. Fig. 1 shows the test sample that has been fabricated as well as outlines of the structures. The circle and square structures range in size  $w$  between 50 nm and 2  $\mu\text{m}$ . The square structures presenting corner rounding are 5  $\mu\text{m}$  in size with corner radii  $r_c$  between 100 nm and 2  $\mu\text{m}$ . In addition to these individual structures, small

arrays with up to four by four elements were realized. They consist of 1  $\mu\text{m}$  sized square structures with a period  $\Lambda$  of 10 or 20  $\mu\text{m}$ . To easier localize them, all of these structures are arranged in a grid of ten by ten sections which are numbered by numerals for columns and characters for rows. Each section has a size of 5  $\mu\text{m} \times 5 \mu\text{m}$  to prevent interactions between different structures. The plus shaped markings that can be observed in Fig. 1 help to visually separate the sections. Inside each section, one individual structure or small array is supposed to be placed. However, for the test sample, the sections contain nine fields enclosed by microscope markers as can be seen in Fig. 2. The fields in the lower sections of the sample contain one structure each, whereas the



**Fig. 1** Reference Sample. a) Image of the first test sample. b) Outlines of the different nanostructures.

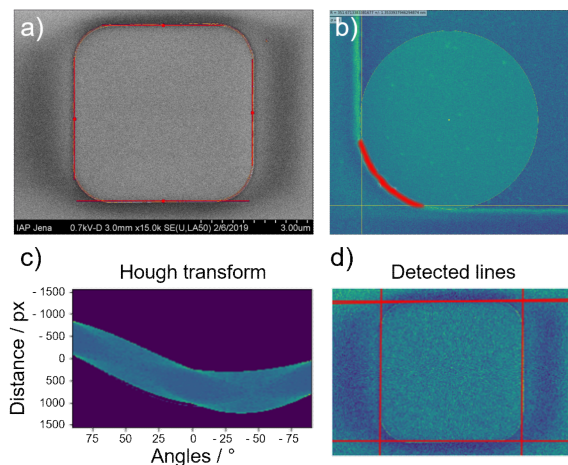


**Fig. 2** Microscope images of section A1 of the test sample. a) Upper half, b) lower half of the sample.

fields in the upper sections contain nine structures again which were produced using different doses during the lithography process. The dose is specified by the product of a base dose and a dose factor. In this case, a base dose of  $160 \mu\text{C}/\text{cm}^2$  was used. By evaluating the shape of the structures depending on the dose factor, the fabrication of future samples will be optimized.

### 3 SEM Characterization

In order to optimize the fabrication process of the reference structures, scanning electron microscope (SEM) images of each structure have been made. They were evaluated concerning the structure size as well as the corner radius of the rounded squares. This way, the ideal dose factor for the electron beam lithography process was determined to ensure that the structures have the desired shape. For the automated evaluation of the more than 6000 SEM images, an edge detection algorithm was used to determine the edges of the structures first. The detected edges of the circle structures were then fitted to a circle to determine their radius. To evaluate the size of the square structures, a Hough line transform was performed to determine straight edges in the image which were used to measure the width and height of the squares [3]. This ensured a correct determination of the sizes even for rounded or deformed structures. An example can be seen in Fig. 3. As small square structures degenerated into circles due to the fabrication process, they were evaluated the same way as the circle structures. The radii of the rounded corners were examined by computing the deviation from the second derivation of each edge points position first to find the start of the corner. Afterwards, edge points of the corner were fitted to a circle to determine the corner radius. Radii larger than 500 nm were hard to detect this way



**Fig. 3** Evaluation of the SEM images. Red color indicates relevant edges for the evaluation. a) Edge detection of a rounded square structure. b) Radius of a rounded corner. c) Hough line transform of a). d) Detected lines from c).

because the corner was partially larger than the image. Therefore, images affected by this were cut in half and each detected edge point was fitted to a circle. In general, the sizes and radii increased with increasing dose and best results were achieved with doses close to the base dose. Both square and circle structures had sizes close to the design even for small doses. Square structures had visible corner rounding and structures smaller than 200 nm degenerated into circles for each dose used. For the rounded square structures, corner radii corresponded well to the design for small dose factors, but varied widely for larger doses. In general, larger radii were more accurate to produce.

### 4 Conclusion and Outlook

We fabricated and characterized a first test sample for the use as reference structures in future MME measurements for advanced nanoform metrology. The structures consist of basic geometric shapes that were produced by electron beam lithography using varying doses. In general, structures met the design best for doses close to the base dose. Based on the results, optimised samples will be fabricated. For a correct evaluation of MME measurements, the comparison with numerical simulations is required. Therefore, we already perform simulations of the Mueller matrices of the structures using finite element method (FEM). Additionally, we investigate in the use of nanostructures in MME and imaging MME setups to further enhance the sensitivity for sub-wavelength features. First FEM simulations concerning these concepts have already been performed. For more details, see [4].

### 5 Acknowledgments

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