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Nanoform evaluation approach using Mueller matrix microscopy and machine learning concepts

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Abstract. We realized an imaging Mueller matrix microscope for nanostructure characterization. For investigations on nanoform characterization via Mueller matrix images, we measured and simulated Mueller matrix images of specially designed nanostructures. As an approach towards machine learning evaluation in imaging ellipsometry, we calculated Haar-like features of the images and observed a higher sensitivity to subwavelength features in off-diagonal matrix elements compared to microscopy.

1 Introduction

Innovative devices that rely on shaping matter at the nanoscale are currently key for many technological advances in various fields, from photonics, nanotechnology and -electronics to metamaterial fabrication and semiconductor industries. Complementary to the technological progress in fabricating nanoscale structures, there is a need for precise metrology solutions for their characterization. For the examination of layer stack thicknesses or optical properties, Mueller matrix ellipsometry has been proven a useful tool [1]. By analysing the polarization properties of the sample and solving the inverse problem using numerical simulations, feature parameters at the nanoscale can be retrieved. As a purely optical method, ellipsometry benefits from being fast, non-invasive, and flexible to use. One disadvantage of conventional ellipsometry however is that measurement results are integrated over the whole illuminated area. For this reason, structural features that are smaller than the illumination area cannot be examined precisely, and their results are affected by signals from the surrounding media. For the local examination of polarization effects of nanostructures, imaging Mueller matrix ellipsometry is a reasonable alternative. It combines the conventional ellipsometric measurement principle with an imaging system, leading to a Mueller matrix for each pixel in an image of the structure under investigation and thus to so-called Mueller matrix images. These images allow for the observation of local changes of the samples' polarization properties, even in ranges much smaller than the illumination spot.

2 Measurement setup

For our investigations, we constructed and characterized an imaging Mueller matrix ellipsometry setup [2], which

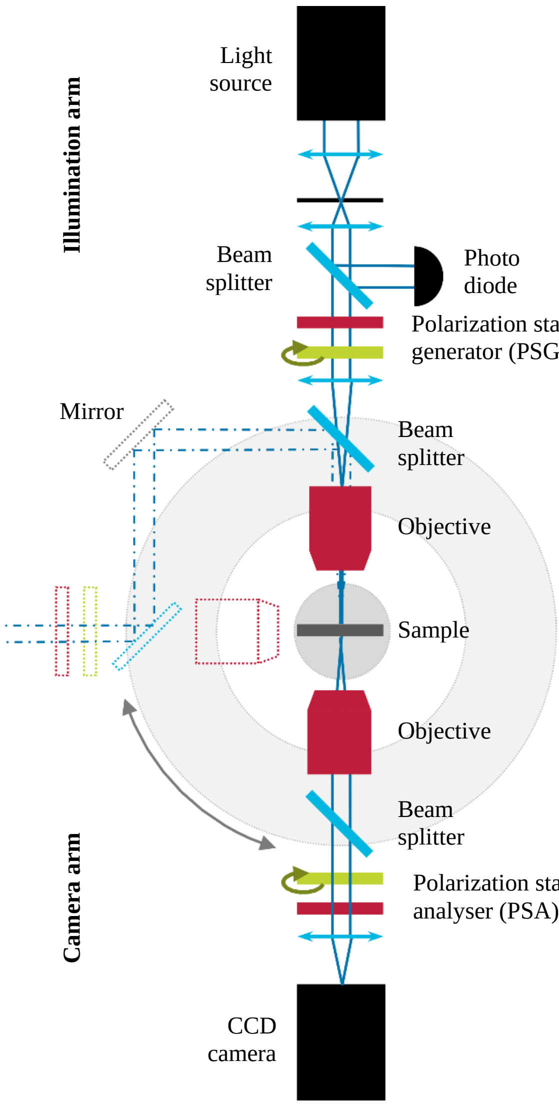

Fig. 1. Schematic representation of the Mueller matrix microscope setup.

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is depicted in Fig. 1. It consists of a fixed illumination arm and a pivotable camera arm in a conventional dual-rotating retarder configuration. The illumination arm prepares the light from an LED via a polarization state generator (PSG) system. An objective combined with a Koehler illumination system is used to guide the prepared light onto the sample which is mounted on top of several translation and rotation stages. The camera arm is attached to a rotation stage with a large aperture of 30 cm in diameter around the sample. An infinity corrected objective with a long working distance of 25.5 mm, a magnification of 50x and a numerical aperture of 0.42 combined with a tube lens creates a microscope image of the sample at a CCD camera at the end of the camera arm. A polarization state analyser (PSA) identical to the PSG but in reverse order is positioned between the objective and the tube lens. This way, the full Mueller matrix can be determined for each pixel in the obtained image. The configuration of the two arms allows for a fluent transition from reflection to transmission measurements for arbitrary angles of incidence. Reflection measurements can be performed for angles from 37.5° to 90°. Additionally, the setup can be operated in a direct incidence mode as a Mueller matrix microscope. In this mode, the camera arm is moved to a position in a 90° angle to the illumination arm. The light that reflects from the sample back into the first objective is then guided via beam splitters and mirrors to the PSA of the camera arm. This way, reflection measurements at perpendicular incidences can also be performed.

3 Samples and measurement results

To investigate the influence of small geometrical features on different elements of the Mueller matrix, we have produced nanoform reference structures with sizes and shapes varying in the range between 50 nm and 5 µm, including square and circular structures as well as square structures with varying corner radii. Mueller matrix images of these structures were measured and compared to AFM measurements and numerical simulations. An example for the images of a square structure with 400 nm corner radius is shown in Fig. 2. For both, simulated and measured Mueller matrix images, a deconstruction of the images showed significant influences of the corner radius on off-diagonal Mueller matrix elements, even for changes in the subwavelength regime [3].

4 Haar-like feature examinations

The evaluation of Mueller matrix images is usually performed either by analysing the average signal of selected regions of interest in the image, or by modelling the structure and solving the inverse problem. The former is easier applied and faster to use, but as with conventional ellipsometry, it delivers no information about lateral features exceeding those from microscopy. The latter can retrieve complete structural parameters but requires a complex model and laborious numerical simulations which make the evaluation process difficult and time-consuming. A possible compromise would be the use of

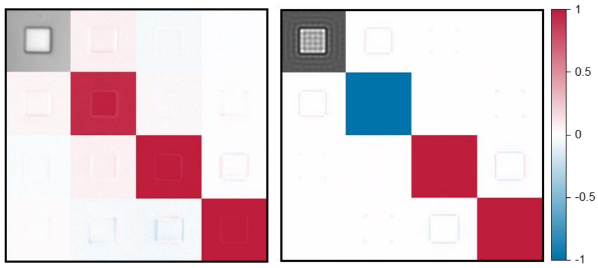

Fig. 2. Measurement (left) and simulation (right) of Mueller matrix images for a 5 µm sized square structure with 400 nm corner radius.

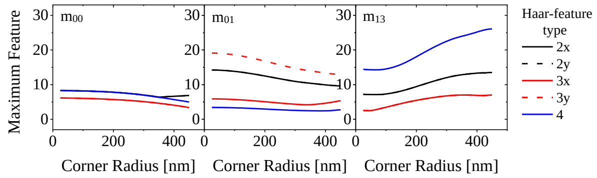

Fig. 3. Maximum Haar-like features extracted from simulated Mueller matrix images, depending on corner radius size.

machine learning, which was already successfully applied to the evaluation process in optical scatterometry [4]. Training a machine learning model for image evaluation initially also requires high computational costs, but once the training is finished, results are achieved fast and reliable. We approached this idea by calculating and evaluating Haar-like features [5] for the simulated Mueller matrix images of our nanoform structures. Haar-like features are certain patterns of intensity differences in images commonly used in object recognition techniques. An example for the features from simulated Muller matrix images is shown in Fig. 3. Especially in the images of off-diagonal matrix elements, a sensitivity of the Haar-like features to varying corner radii of the structures was observed that exceeded those from the microscope image alone. Thus, Haar-like features in Mueller matrix images present an information channel for nanostructure characterization, which hints towards a successful application of machine learning algorithms in Mueller matrix ellipsometry.

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