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A virtual microscope for simulation of Nanostructures

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Abstract. Light-matter interplay is widely used for analyzing the topology of surfaces on small scales for use in areas such as nanotechnology, nanoelectronics, photonics, and advanced materials. Conventional optical microscope imaging methods are limited in resolution to a value comparable to the wavelength, the so-called Abbe limit, and cannot be used to measure nano-sized structures. Scatterometry is an optical method that can measure structures smaller than the wavelength. However, the relative uncertainties of the structure dimensions measured with scatterometry increase with decreasing structure size, and the industry is therefore looking for replacing simple intensity based scatterometry with a phase-sensitive measurement method such as coherent Mueller ellipsometry. In this work, we present a virtual microscope capable of simulating the coherent Mueller ellipsometry and scatterometry response from one-dimensional and two-dimensional periodic structures. Furthermore, we argue that coherent nonnormalized Mueller ellipsometry gives results with less uncertainties than standard normalized Mueller ellipsometry.

1 Introduction

Nanostructures have a wide array of applications in optics, diagnostics, food science, sensing, and process inspection monitoring. Some of these applications include enhancing waveguide coupling, improving linear encoders, making hyperspectral cameras and printing color images. Imaging technologies like Optical Microscopy (OM), Atomic Force Microscopy (AFM) and Scanning Electron Microscopy (SEM) are the dominating quality assessment technologies in low volume, high-cost nanoscale manufacturing, whereas scatterometry and Mueller ellipsometry are the preferred technologies for high volume manufacturing. However, the measurement accuracy for all of the above-mentioned technologies is decreasing with the ever-decreasing nanostructure sizes. OM cannot measure the shape of objects with lateral sizes less than one µm; AFM cannot accurately measure shape but can measure the nanostructure height if the separation width is longer than the tip width; lateral and vertical dimensions from SEM pictures are hard to obtain if the width of the borderline produced by the secondary electron becomes a significant part of the dimension to be measured. Scatterometry and Mueller ellipsometry can measure the shape of periodic nanostructures, however, the accuracy of the shape dimensions decreases with decreasing nanostructure sizes and increasing complexity. We proposed to use coherent Mueller ellipsometry for shape reconstruction of nanostructures.

Scatterometry and coherent scatterometry can be defined as the measurement and analysis of light diffracted by structures using fixed polarization settings. The scattered light is a signature which reflects the details of the structure itself. For a periodic device, the scattered light consists of distinct diffraction orders at angular locations specified by the grating equation. The fraction of the incident power diffracted into any order is sensitive to the shape and dimensional parameters of the structure and may therefore be used to characterize the structure itself. This is done using a mathematical model of the structure based on a priori information and a rigorous simulation of the light-structure interaction. The diffraction efficiency may be obtained by adding the diffraction orders as intensities (scatterometry) or as fields (coherent scatterometry). Mueller ellipsometry measures the polarization-dependent optical response from a sample.
Mueller ellipsometry may be further divided into two groups: Nonnormalized Mueller ellipsometers that measure all 16 Mueller matrix elements, and normalized Mueller ellipsometers in which the 16 Mueller matrix elements are normalized with the first Mueller matrix element m_{11}. For a microscope setup, Fig. 1, we may have multiple diffraction orders contributing to the field detected in one pixel. The sensitivity of coherent Mueller ellipsometry comes from the measurement of both the magnitude and phase of the Fresnel response from the sample.

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2 Virtual microscope

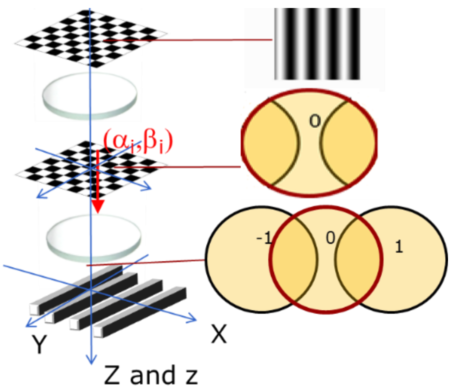

Fig. 1. Illustration of the basic principles of a microscope.

The working principle of a microscope may be explained in terms of how the scattered light from the surface is collected and processed by the microscope. The left column in Fig. 1 shows a schematic illustration of a grating (sample), lenses and planes (checkboard) in a microscope, while the right column shows the angular distribution of light before the first lens, the angular distribution after the first lens and the image after the second lens. The difference between the angular distribution before and after the first lens is due to the limited numerical aperture (NA) of the first lens, which sets the fundamental resolution limits for traditional optics. The virtual microscope works in the following way

1. The incident field is a normal incident wave with a normalized k-vector $(0,0,1)^T$ and the amplitude in the entrance pupil plane

2. The light beam coordinate system defined by the unit vectors for TE-amplitude, TM-amplitude and k-vector is used to describe the optical propagation

3. The response from the periodic structure is calculated as a Jones matrix using the RCWA method.

4. All the points that enter the same pixel in the exit pupil plane are added coherently if we consider coherent scatterometry or coherent Mueller ellipsometry and incoherently if we consider scatterometry.

5. The virtual microscope forms an image from the position depending angular distribution of light in the exit pupil plane. Each sample position gives one image point.

A silicon line grating with a pitch of 700 nm, height 190 nm, width 287 nm and sidewall angel of 90 degrees is investigated using incident light of 600 nm and an infinity corrected objective with a numerical aperture (NA) of 0.55.

3 Results and conclusion

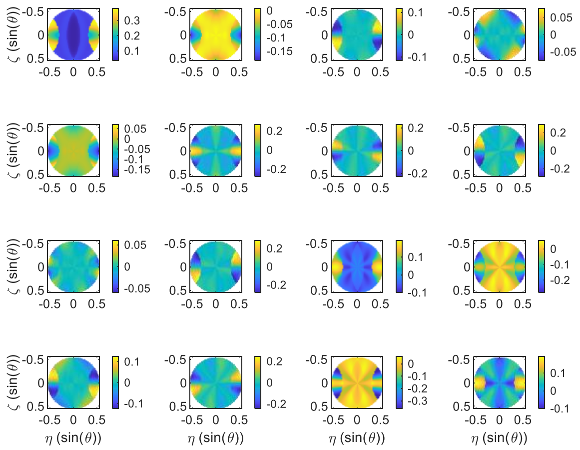

Fig. 2. Simulated nonnormalized coherent Mueller ellipsometry matrix elements m_{ij} i, j=1, … ,4. The m_{11} element is in the upper left corner and the m_{44} element is in the lower right corner. The η and ζ axis on the figure runs from -NA to NA.

Fig.2 shows the simulated nonnormalized coherent Mueller ellipsometry images in the exit pupil plane for the 16 Mueller matrix elements. The m_{11} element contains the coherent scatterometry signal and this element is frequently used to normalize all the Muller matrix elements. A recent study [1] shows that this is most unfortunately, since the normalization leads to higher correlation between the retrieved dimensional parameters than without the normalization. A microscope setup has the addition benefit that it only requires small metrology measurement areas on the wafer. We therefore suggest to use nonnormalized coherent Mueller ellipsometry for process inspection in high volume manufacturing.

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