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Approaches for the RCWA-based non-destructive characterization of subwavelength-structured gratings

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Abstract. Nano-structuring enables us to add additional degrees of freedom to the design of optical elements. Especially the possibility of controlling the polarization is of great interest in the field of nano-structured optics. For being able to exploit the whole range of form-birefringent phase shifts, the aspect ratios of the resulting element are typically much higher than the aspect ratios of conventional diffractive optical elements (DOEs), which does not only pose a challenge on fabrication but also on characterization. We evaluate several well-established approaches for the nondestructive characterization, including Müller-Matrix-Ellipsometry, measurement of the diffraction efficiencies, scattering measurements and calibration with rigorous coupled-wave modelling. The goal is to understand the challenges with all these techniques and combine them to a reliable method for structural reconnaisance of high aspect ratio nanostructures.

1 Introduction

Linear subwavelength gratings, so called "zero-order gratings" show a form birefringence which can be tuned through choice of material and geometric shape. This can be utilized e.g. for the design of anti-reflective layers [1] as well as quarter- or half-waveplates [2–4]. The combination of binary form-birefringent subwavelength gratings and diffractive structures can be exploited for designing polarization-dependent optical elements such as compact polarizing beam splitters [5–7]. To achieve a high difference in phase shift for the different linear polarization states, it is necessary to produce gratings with an extraordinarily high aspect ratio. This poses stress on the fabrication, but also on the characterization of the fabricated grating. Conventional optical measurement techniques such as laser scanning microscopy or white light interferometry are not suitable to measure the depth and exact cross section of subwavelength structures with high aspect ratios. And for scanning electron microscopy (SEM)-imaging, one needs a defined and precisely cut cross-section (e.g. generated through focussed ion beam (FIB) cutting) for directly measuring the geometry (an SEM image of subwavelength structures taken at an opaque angle is shown in Figure 1).

We can circumvent FIB and SEM imaging by measuring the optical properties of the element and compare the results to the simulation results of rigorous coupled-wave analysis models (RCWA). The optical properties include the effects on polarization (Müller-Matrix-Ellipsometry) and the broadband measuring of transmission efficiencies under various angles. Those measurements contain a lot of information about the geometrical properties and fabrication errors, which can be utilized to non-destructively characterize subwavelength gratings.

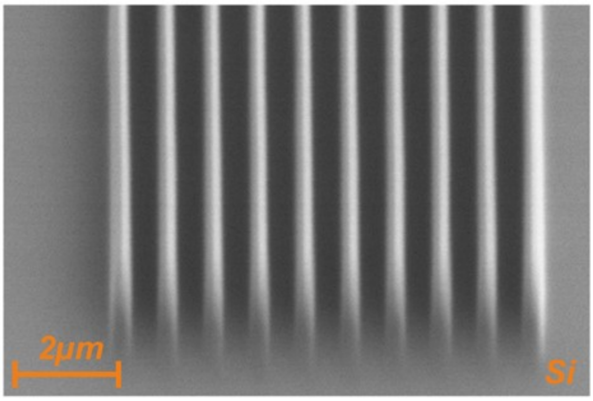

Figure 1. SEM image of subwavelength structures, the full grating layout is shown in Figure 3. Image: Patrick Feßer

2 Grating types

We demonstrate RCWA simulations on three types of binary gratings. Firstly, conventional diffraction gratings with a period of 9 µm with varying etch depths and aspect ratios both in Fused Silica and the Schott glass AF 32 Eco. Secondly, we investigate a linear grating solely consisting of subwavelength structures with the period of 200 nm and positive flank angles of 6°. It is a Silicon Master for Nanoimprint-Lithography (NIL), Eulitha P200L 90d, whose cross-section is shown in Figure 2. Lastly, we in-

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vestigate the properties of combined diffractive and subwavelength structures on the example of the aforementioned polarizing beamsplitter shown in Figure 3.

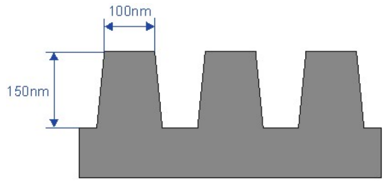

Figure 2. Cross section of Eulitha subwavelength grating (p = 200 nm) in Silicon with positive flank angles of 6°.

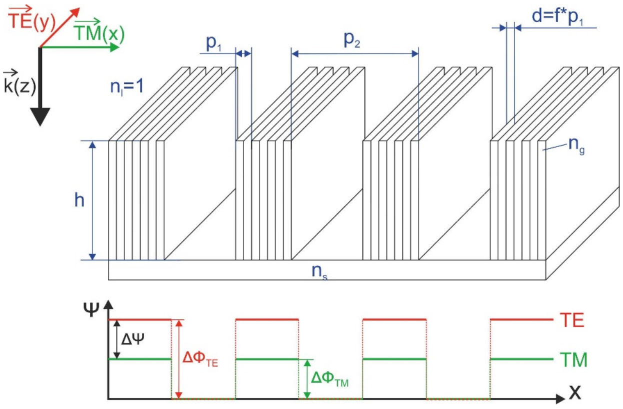

Figure 3. Cross section of subwavelength-structured diffraction grating ($p_1 = 500\,\text{nm}, p_2 = 10\,\mu\text{m}, h = 700\,\text{nm}$) in Silicon [7] Below, the relative phase shifts between TE- and TM-polarization are shown.

3 Measurements

The measurements are carried out with three different measurement systems. Mainly we use the Sentech spectroscopic ellipsometer SENresearch 4.0, which offers a spectral range from 190 nm to 2500 nm. We use it for determining the Müller-Matrix as well as transmission curves. We also have our own diffraction efficiency measurement setup including a tunable laser source utilized within the visible range and a scattered light measurement setup wit a fixed wavelength of 532 nm at our disposal (Albatross TT). Not all of the above measuring systems are suitable for each grating type due to the transmittivity of the materials and the possibility to control the polarization. We present an overview which system is most fitting for which grating.

4 Simulation

For modelling with RCWA we use the MC Grating software and for the Müller-Matrix-Ellipsometry the WVASE software of the J.A. Woollam company. For comprehensive simulation of the situation we investigate the effect of the following parameters: etching depth, flank angle, multi layer elements (due to oxidation of the Silicon material), the effects of different etching depths due to varying etch rate on variable size areas, several incidence angles, rounded edges and a broad wavelength range of the light source.

5 Discussion

The measurement techniques we are using are well-known, but the combination of transmission, reflection and polarization measurements leads to new possibilities for characterizing high aspect ratio structures. The RCWA-modelling of gratings enables us to execute extensive parameter studies. This way one can identify the parameter sets (e.g. fabrication errors) which have the main influence on the performance of the optical element. Those are, in descending order, reflectivity (material), etching depth and flank angle. The parameter studies work well for each variable individually but a remaining challenge is the combination of various variables. All the RCWA studies require a sufficient prior knowledge about the geometry of the grating. Nevertheless, we learn both about the charateristics of nanostructures and about the processing deviations, which occurred. Being able to quantize the effect of each parameter is potentially of great importance to utilize those effects for the design of other subwavelength-structured optical elements and optimize the fabrication process.

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