Applied Surface Science xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Applied Surface Science

journal homepage: www.elsevier.com/locate/apsusc

Full Length Article

Traceable Mueller polarimetry and scatterometry for shape reconstruction of grating structures

Poul-Erik Hansen [a,*], Morten H. Madsen [a], Joonas Lehtolahti [b], Lars Nielsen [a]

[a] Danish Fundamental Metrology, Matematiktorvet 307, DK-2800 Kgs, Lyngby, Denmark
[b] Institute of Photonics, University of Eastern Finland, P.O. Box 111, FI-80101 Joensuu, Finland

ARTICLE INFO

Article history:
Received 8 July 2016
Received in revised form 10 February 2017
Accepted 12 February 2017
Available online xxx

Keywords:
Mueller polarimetry
Scatterometry
Ellipsometry
Grating
Nanostructures
Metrology

ABSTRACT

Dimensional measurements of multi-patterned transmission gratings with a mixture of long and small periods are great challenges for optical metrology today. It is a further challenge when the aspect ratio of the structures is high, that is, when the height of structures is larger than the pitch. Here we consider a double patterned transmission grating with pitches of 500 nm and 20 000 nm. For measuring the geometrical properties of double patterned transmission grating we use a combined spectroscopic Mueller polarimetry and scatterometry setup. For modelling the experimentally obtained data we rigorously compute the scattering signal by solving Maxwell's equations using the RCWA method on a supercell structure. We also present a new method for analyzing the Mueller polarimetry parameters that performs the analysis in the measured variables. This new inversion method for finding the best fit between measured and calculated values are tested on silicon gratings with periods from 300 to 600 nm. The method is shown to give results within the expanded uncertainty of reference AFM measurements. The application of the new inversion method and the supercell structure to the double patterned transmission grating gives best estimates of dimensional quantities that are in fair agreement with those derived from local AFM measurements

1. Introduction

Nondestructive dimensional measurements of buried structures and structures with dimensions less than 1 micrometer are a great challenge today. However, such structures are nowadays part of many industrial devices and applications including semiconductor and integrated circuits, micro-electro-mechanical systems, biomedical devices and optical devices [1,2,11]. Scatterometry is a well-known technology for studying surface relief periodic structures with simple geometrical profiles with very high accuracy [3,4,20] and is used for this within the semiconductor industry [19]. Many different scatterometry setups exist for characterization of surface relief structures: angular scatterometers, 2-theta scatterometers, spectroscopic scatterometers [9,24], coherent scatterometers [22,23] and imaging scatterometers [21]. A description of these techniques can be found in Refs. [16]. Investigation of line edge and line width roughness of simple scatterometry profile has also been performed [5–7]. Very little research has been on the study of complex devices using scatterometry since it is believed that unique solutions cannot be found. Double pitched grating structures is a particular important class of problems to study with scatterometry, because a long pitch grating around 20 μm is frequently observed in the grinding process of substrates that are used in the production of grating masters for nanoimprint and injection molding. If this long pitch grating is not completely removed before the substrate is further processed as a grating master, the result will be a double pitched grating structure, which in the case of nanoimprint or injection molding will be copied to a huge number of replica. Another important implication is the combination of refractive and diffractive based optical elements. The hybrid concept enables manufactures to produce lighter and more compact lenses for cameras and optical inspection systems [8]. Scatterometry needs to be able to solve more complex and less perfect structures before it can be used as an inline quality control within these technologies.

Scatterometry can be defined as the measurement and analysis of light diffracted by structures. The scattered or diffracted light is a fingerprint or 'signature' which reflects the details of the structure itself. For a periodic device, such as a series of lines and spaces in silicon, the scattered light consist of distinct diffraction orders at angular locations specified by the well-known grating equation. The fraction of the incident power diffracted into any

* Corresponding author.
E-mail addresses: peh@dfm.dk, roermoseparkvej50@gmail.com (P.-E. Hansen).

http://dx.doi.org/10.1016/j.apsusc.2017.02.091
0169-4332/© 2017 Published by Elsevier B.V.

orders is sensitive to the shape and dimensional parameters of the diffracting structure and may therefore be used to characterize the structure itself [16,20]. 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 dimensional parameters are obtained by varying the variables using a best-fit procedure between experimental data and calculated values [9]. Scatterometry has the additional advantage that it is a technique capable of investigating embedded structures in a material. However, as the dimension shrinks and the complexity of the structure increases, the measurement capability of scatterometry is challenged. This challenge may be overcome by turning the scatterometer into a Mueller Polarimeter [24,25]. A Mueller Polarimeter measures the polarization-depending response from a sample [14]. The sensitivity of this response is due to the measurement of both the magnitude and phase of the Fresnel response from the sample and as a rule of thumb the sensitivity increases with decreasing structure dimensions. Furthermore it is possible to use the same mathematical modelling as in scatterometry. In this paper we report on the progress of determining the dimensional parameters of buried, complex structures using a combined Mueller Polarimeter and scatterometer. The investigated samples are complex devices that possess polarization-sensitive and polarization-insensitive structures; in order to have the best sensitivity for both classes of structures, we use a combined setup.

Solving the inverse problem of Mueller Polarimetry and scatterometry is equal to determining the dimensional geometry of a structure from its diffraction pattern. Like many inverse problems, the inverse problem of Mueller Polarimetry and scatterometry is ill-posed [10] and its treatment requires a priori information. To regularize this problem we set up an equivalent low-dimensional optimization problem with a weighted least-squares function that is minimized using iterative algorithms [16]. The a priori information includes information about the geometrical profile of the investigated element and also knowledge of the variances of the measured data. The devices are modeled by a class of structures that can be parameterized by a small number of parameters describing the geometrical profile and the distribution of the material properties. The values of the parameters are assumed to lie in certain intervals according to the known quality of the manufacturing process. The weight factors in the least-squares function account for measurement uncertainties. Thus they represent the prior knowledge of the underlying statistical error model of the measurement process. The optimization is done using the newly developed methods that performs the fitting in the measurand variables instead of the ellipsometric parameters.

The present experimental, analytical and numerical study investigates how a combined Mueller polarimeter and scatterometer may be used to retrieve the geometrical dimensions of complex devices such as double patterned transmission grating with pitches of 500 nm and 20 000 nm and four standard silicon line gratings with pitches from 300 nm to 600 nm. We show that distinctive features in the measured spectra are correlated with the geometrical dimensions.

After presenting the experimental method and measurements in Section 2, Section 3 describes the analytical and numerical forward methods used for the analysis of the experimental data. Section 4 gives a brief description of the applied new inverse method used for finding the optimum solution for the silicon gratings and the double patterned transmission grating. The details for the new inversion method are described in the Appendix A. Finally, section 5 and 6 closes the paper with a discussion of the results and the conclusion.

2. Experimental setup

The double pitched grating structure has been fabricated by spatial selective etching of the structure into a fused silica substrate. A quick check of the fabrication process was made by observing the color change across the structures when observed in white light. The color change in Fig. 1 clearly demonstrate that a double pitched structure has been successful manufactured. The four silicon grating has been fabricated by Eulitha AG (Switzerland) and Fig. 1 shows an AFM picture of one of the gratings.

Fig. 1 shows a technical illustration of the system. It is a goniometric and spectroscopic scatterometric setup that can be applied in reflectometric, generalized ellipsometric and diffractometric measurement mode. As radiation sources we use a fiber coupled stabilized Xenon lamp (Ocean optics, HPX-2000-HP-DUV). The Xenon lamp covers the wavelength range from 300 to 800 nm. The

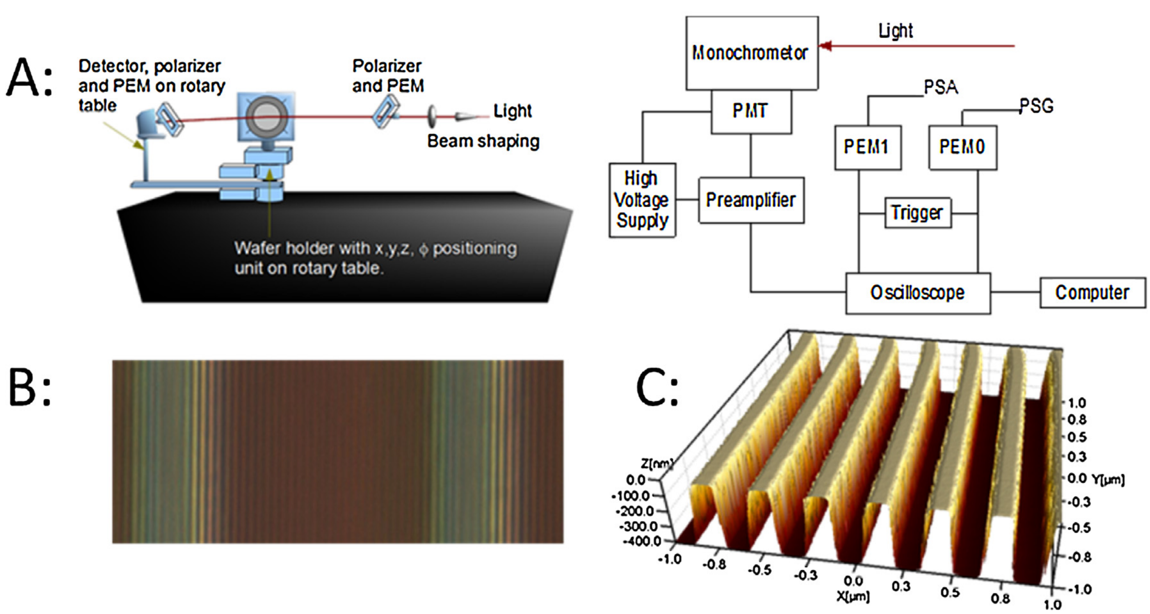

Fig. 1. A: Technical illustration of the Mueller polarimeter and scatterometry setup. B: Microscope image of double pitched grating. C: AFM picture of 300 nm pitched line grating.

Please cite this article in press as: P.-E. Hansen, et al., Traceable Mueller polarimetry and scatterometry for shape reconstruction of grating structures, Appl. Surf. Sci. (2017), http://dx.doi.org/10.1016/j.apsusc.2017.02.091