euspen's 15th International Conference &
Exhibition, Leuven, Belgium, June 2015
www.euspen.eu

Characterization of nano-textured samples in a production environment

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Abstract
Nano-textured surfaces have been characterized by optical diffraction techniques using an adapted commercial light microscope with two detectors, a CCD camera and a spectrometer. We demonstrate that the microscope has a resolution in the nanometre range and is suitable for use in an environment with many vibrations, such as a machine shop. The acquisition and analysing time for the topological parameters height, width and sidewall angle is only a few milliseconds.
It is demonstrated that by simple adaptions to an optical microscope we can measure nano-textured surfaces with an uncertainty of a few nanometers for the height and width of the structures. The microscope has been validated by measuring on certified transfer artefact and 1D gratings. The measurements are very robust, such that vibrations of the sample and/or the microscope do not affect the results. The sample can be translated during acquisition, as long as the beam spot is kept inside an area with homogenous structures, which makes the proposed microscope well suited for implementation in a production environment.

Scatterometry, Microscopy, Nanostructures, In-line characterization, Nanometrology

1. Introduction

Devices utilizing micro/nano-textured surfaces are entering the consumer market and thus large scale production facilities such as roll-to-roll and injection moulding technologies are fabricating these. With the new advanced structures, existing methods for characterisation are not suitable for industrial environments; for in-line characterisation instruments should be robust to vibrations and have a low acquisition time.

2. Scatterometry

In scatterometry the diffracted light from a textured surface, e.g. a periodic grating, in use as a fingerprint to reconstruct the geometrical properties; given that one can setup a proper model [1-3]. As shown in Fig. 1, the work flow for scatterometry measurements consist of three steps. (I) The spectrum of the specular reflection from a white LED light source is measured using a spectrometer fitted into an optical microscope. Typical acquisition time is a few milliseconds on a high reflecting surface. (II) From a priori information of the grating structure, scattering intensities are modelled using rigorous coupled wave approximation (RCWA) algorithms. All scattering intensities are stored in a database. The computation time can be up to a few hours on a normal desktop computer, but only has to be generated once. (III) The grating parameters, such as height, width, and sidewall angle can now be reconstructed using an inverse modelling approach. Each database value is compared to the experimental data using a χ^2 minimization,

$$\chi^2 = \sum_{i=1}^{N}\left[\frac{\eta - f_i(\alpha)}{\sigma_i}\right]^2 \qquad (1)$$

where σ_i are the uncertainties on the experimental data as described in Ref. [1], and $f_i(\alpha)$ are the modelled scattering intensities for the i'th element with the shape α, with dimensional parameters indicated in Fig. 2.

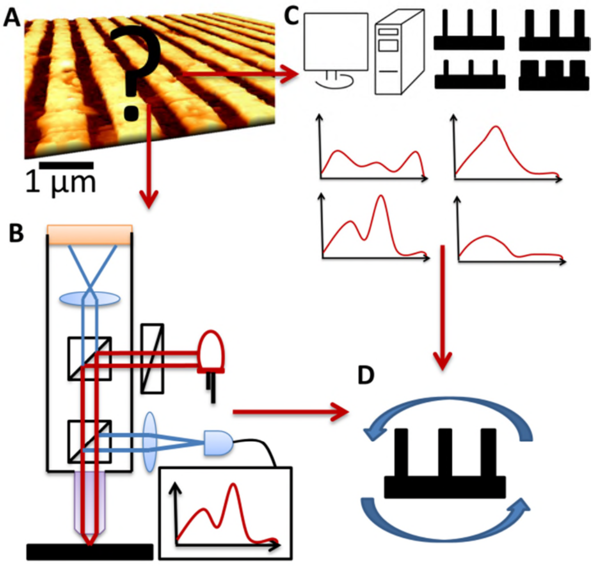

Figure 1. The principle of scatterometry. (A) A surface with unknown nanostructures. (B) Imaging of the surface using the scatterometer. (C) Computer simulations of the diffraction efficiencies. (D) The measured diffraction efficiencies are compared with the simulated data and the best match give the structure of the imaged object.

3. Reference measurements

A traceable atomic force microscope (AFM) is used for reference measurements of the sample. A topographic AFM image is shown in Fig. 2, and following the ISO 5436 procedure for step height calibration, the average height of the ridges is within the image found to h=320.2 nm, with an associated expanded uncertainty of U(h)=4.0 nm. The sidewall angle is found by tilting the sample around 20^{o} in the AFM as described in Ref. [4], and is found to ϑ=89.7^{o} with an expanded uncertainty of U(ϑ)=1.5^{o}. The filling factor, that is w/p, is found to 0.537 using scanning electron microscopy. The reference measurements are summarized in Table 1.

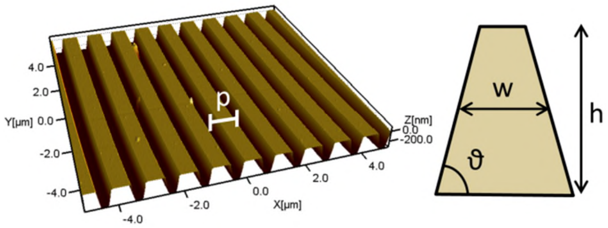

Figure 2. Topographic AFM image of the 1D grating with a pitch, p = 1000 nm and average height measured to 320 nm. The sketch to the right defines the other dimensional parameters that are included in the scatterometry analysis.

4. Experimental Data

Three spectra are needed for the calculation of the diffraction efficiencies; a reference, a dark, and the sample spectrum, as shown in the insert in Fig. 3A. The reference spectrum is obtained on a surface where the reflectivity is well-known, e.g. a silicon sample, and the dark spectrum is obtained with the sample removed. The diffraction efficiency for each wavelength is calculated from these three spectra and plotted in Fig. 3A.

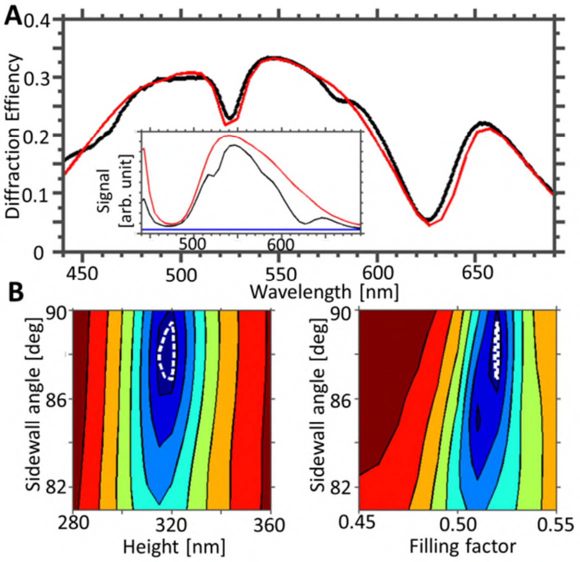

Figure 3. Scatterometry data. (A) Diffraction efficiency from scatterometry on a 1D grating with a 1000 nm pitch. Black points are experimental data and the red curve is the best fit found using an inverse modelling approach. The insert shows the raw data with the reference, sample, and dark signals from top to bottom. (B) 2D plots of the χ^2 values. Dark blue areas indicate a better agreement with simulated values. The white dashed lines indicate the 95% confidence interval of the fit.

The diffraction efficiency is compared to the pre-generated database using Eq. (1) and the best fit is plotted on top of the experimental data points in Fig. 3A. To estimate the confidence limit of the fit, the χ^2 values are plotted for two dimensional parameters at the time in Fig. 3B. The white dashed line indicates the 95% confidence limit of the fit found by calculating $\Delta\chi^2$ for each point [5]. It should be noted that confidence interval does not include the uncertainty from the material properties and experimental setup. Thus, the confidence interval will always be smaller or equal to the uncertainty of a measurement. Values found using scatterometry is summarized in Table 1.

Table 1 Summary of experimental values found using the scatterometer and reference measurements. The ± indicates the 95% confidence interval of the fit for the scatterometry data and the expanded uncertainty (k=2) for the reference measurements.

Parameter	**Method and Value**		
	Scatterometry	**AFM**	**SEM**
Height	(319 ± 2) nm	(320.2 ± 4) nm	
Filling factor	0.520 ± 0.001		0.537 ± 0.010
Angle	$(88 \pm 2)^{o}$	$(89.7 \pm 1.5)^{o}$	

As the technique measures the average light intensity over an area defined by the spot size, the sample can be moved during measurements, when one observes a uniform area. That makes the scatterometry technique suitable for measurements in an industrial environment. The microscope has been tested at a large scale production facility placed next to very heavy machines, and still measuring with a few nanometers uncertainty.

5. Summary

The scatterometry technique is suitable for characterization of micro/nano-textured surfaces in an environment with many vibrations, such as production facilities of roll-to-roll and injection moulding. We have demonstrated this by adapting a commercial microscope to include scatterometry measuring capability and measured on moving samples. Using an inverse-modelling approach we have achieved a confidence interval of the fit of a few nanometers for the height and width for a 1D periodic sample with a pitch of 1000 nm.

Acknowledgement

The present research was carried out within the project NEMI (org.uib.no/nemi/) supported by the European Commission (Grant no: 309672) and the project InFoScat (www.InFoScat.eu) supported by the Eurostars Programme.

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