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Tapping AFM measurements artefacts in the acquisition of high-aspect-ratio rectangular nanostructures using dedicated sharp tips

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Abstract
In the application of diffractive optical elements (DOE), the aspect ratio of the surface features is continuously increasing on demand of a larger span of end applications. Measuring this kind of structures is, on the other hand, a non-trivial process, which requires dedicated metrological solution and approaches. When the structures cover a large span of the investigated surface, a compromise between measuring precision and field of investigation has to be met. In this research, a rectangular grating with a pitch of 700 nm, a trench size of 350 nm, a nominal height of 1100 nm, representing an aspect ratio of 3 is measured using an AFM (icon-Pt provided by company Bruker®). The grating structure covers an area of 2 mm x 2 mm and it is included in a specimen with global dimensions of 10 mm x 10 mm. The grating is manufactured on a pure silicon wafer using ion-beam lithography. The AFM is operated in tapping mode using dedicated sharp silicon tips. The research shows that even though the tip nominal geometry fits into the grating geometry, the tip convolution cannot be neglected in the reconstruction of the effective surface topography. Repetitive artefacts are sampled while measuring the grating topography and a deconvolution procedure is finally proposed.

AFM, High aspect ratio nanostructures, Measurements artefacts, Nanometrology

1. Introduction

The continuous development of surface functionalization by micro/nano structuring asks for metrological solutions for more and more demanding features to measure. In this research, Atomic Force Microscopy (AFM) is adopted for the measurements of an high-aspect-ratio rectangular grating (*r*=3). AFM usability for such structures is limited by several factors. The tip-shape and size can lead to frequent tip-related artefacts in AFM measurements [1-2]. Moreover, the tip convolution is always present in the topographies [3-4]. This implies the need to develop methods for the detection of the edges of the grating profile [5]. Another important aspect to be considered is the scanning velocity and the sampling rate. When measuring high slopes, it has been shown an improvement when using an adaptive scanning velocity and high sampling [6]. In this study, a discussion on the artefacts generated in AFM measurements are presented together with possible countermeasures.

2. Grating design structure

The investigated grating design structure is both measured and produced in a clean-room environment ISO 4. The grating is rectangular, with a duty cycle of 50 %. The investigated pitch is 750 nm with a trench size of 350 nm. The structure shows an aspect ratio, *i.e.* the ratio between the nominal height of the feature (1100 nm) and the nominal length of the feature (350 nm), of 3.1. The grating is fabricated in silicon using DUV lithography and it is the smallest on the cluster of gratings manufactured on the same silicon wafer [7]. The silicon wafer and the investigated grating are shown in Fig 1.

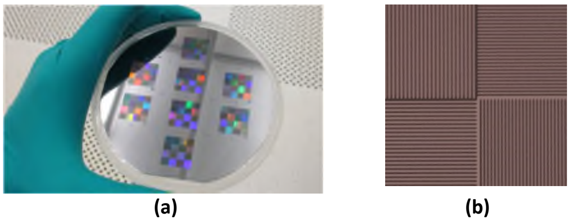
(a) (b)

Figure 1. Silicon wafer embedded with multiple diffraction gratings (a), the top view of the interaction of four rectangular gratings (b).

3. AFM measuring strategy

The employed microscope is the AFM icon®-Pt provided by company Bruker®. The control of the measurements is performed using the latest, at the time of measurement, software update NanoScope™ 9.4. The AFM is used in tapping mode**.** The acquisition is performed using the minimum scanning velocity (0.8 µm/s) corresponding to a sampling frequency of (0.1 Hz). The piezo is operated at 80 mV, which corresponds to cantilever free amplitude of 3.4 nm. The amplitude set-point is set to 2.1 nm, which provides an overall damping ratio of approximately 62 %. The AFM is equipped with a sharp cantilever (AR5T-NCHR), provided by Nanosensors™. The cantilever is designed to work in tapping mode, as it compensates the cantilever holder tilt by 13°. Moreover, the tip geometry is a cone shape with an incremental radius nominally up to 120 nm in the first 2.00 µm of tip height. The sample is initially oriented under the AFM microscope aligning the stage with respect to the grating longitudinal direction and scanning perpendicularly to that. The investigated area is the centre of the top right squared grating. The same area is measured after rotating by 90° the sample and by scanning perpendicularly to

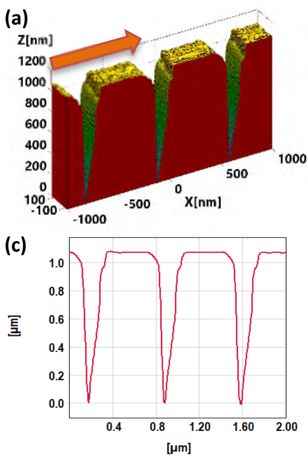

Figure 2. 3D view of the traced **(a)** and retraced **(b)** and respective average X profiles **(c)**, **(d)**, of the AFM acquisition sampled in the longitudinal scanning direction.

the cantilever longitudinal direction. The sampled images cover a field of view of 2.00 µm x 0.25 µm with a resolution of 512 x 64 pixels. To compensate the artefacts, tip deconvolution is performed using a blind characterization algorithm in SPIP™ software [8].

4. Results

The topographies are linearly levelled selecting only the top plateaus as levelling area. The results are presented in form of 3D view and average X profiles for both the traced and retraced scan in the horizontal (Figure 2) and vertical scanning direction after rotating the sample 90° (Figure 3). At last, the deconvoluted profiles of the orthogonally scanned topographies are plotted together with the other in Figure 4. Even though the measurements have been performed in the same inspection area, the topographies show significant differences. The reasons for the deviations are addressed to tip artefacts. First, all the profiles do not show an ideal rectangular grating geometry. Independently from traced or retraced profile, the measured slopes of the grating flanks are different, indicating a tip-surface interaction depending on the scanning direction. More closely, divot artefacts can be seen in the acquired topographies, due to the switch from attractive to repulsive tip force regime [9]. The divot artefacts are prone to happen when measuring with high aspect ratio tips, which are smaller than conventional tips. This makes the measurement more sensitive and in some cases unstable. It can also be seen in Figure 2c and 2d a double slope change in the left flank of the grating. Those are supposed to be generated by the higher repulsive force produced respectively by the grating wall and bottom. In the case, the scanning angle is orthogonal to the cantilever (Figure 3), the double slope effect is considerably smaller than in the previous case.

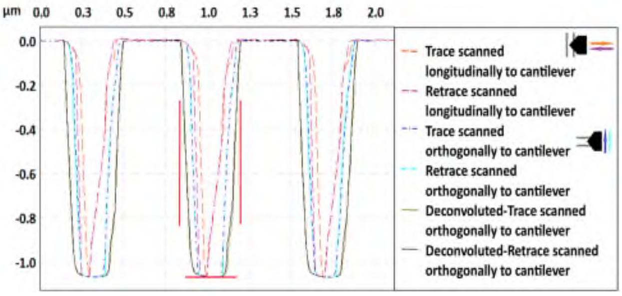

Figure 4 Deconvoluted X profile overlapped with the average scans from Fig. 3.

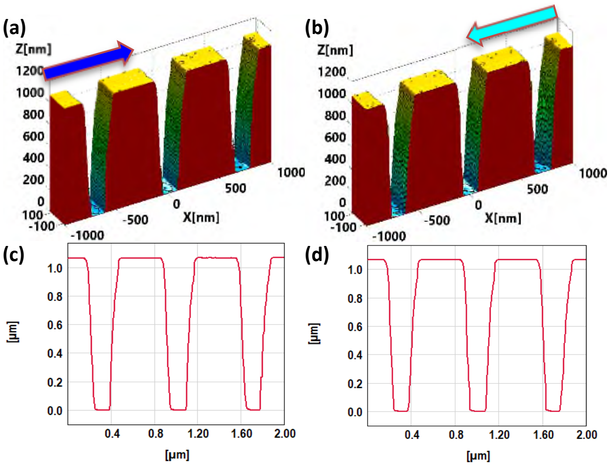

Figure 3. 3D view of the traced **(a)** and retraced **(b)** and respective average X profiles **(c)**, **(d)**, of the AFM acquisition sampled in the orthogonal scanning direction with the sample rotated 90°.

This proofs that the generated artefacts are tip dependent rather than being influenced by AFM parameter settings. Moreover, comparing Figure 2 and 3 it is possible to see that the measurement results more symmetric in the case of scanning in the orthogonal direction of the cantilever. This suggests that the tip “axe-shape” effect is avoided when scanning orthogonally to the cantilever. For this reason, a tip deconvolution of the tip is achieved only for the more symmetric, orthogonally scanned profiles. The deconvoluted profile gets closer to the nominal expected geometry but it is still not providing a traceable measurements for this case of structures. In numbers, for all the measurements a maximum step height of 1070 nm is reached. The bottom trench width is increased from 40 nm to 211 nm comparing the longitudinal scanning measurement with the deconvoluted orthogonally scanned one. The nominal dimensions should be 1100 nm for the step and 350 nm for the trench size.

5. Conclusion

Measurements of high aspect ratio (3+) sub-micrometric rectangular gratings can be achieved using AFM microscopes with some limitations. Even though scanning velocity is kept low, measurements are performed in tapping high resolution with dedicated sharp tips; the metrology task challenges the utilization of the microscope. An acceptable result can be achieved by performing tip deconvolution. However, the method is not traceable according to the standards.

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