euspen's 20th International Conference & Exhibition, Geneva, CH, June 2020

www.euspen.eu

Non-destructive roughness analysis of high aspect ratio rectangular grating sidewalls for nanostructured silicon wafer

Dario Loaldi[1], Danilo Quagliotti[1], Matteo Calaon[1], Ilja Czolkos[2], Alicia Johansson[2], Theodor Nielsen[2], Jørgen Garnæs[3] and Guido Tosello[1]

[1]Department of Mechanical Engineering, Technical University of Denmark, Kgs. Lyngby, Denmark
[2]NIL TECHNOLOGY ApS, Kgs. Lyngby, Denmark
[3]Danish Fundamental Metrology A/S, Hørsholm, Denmark

darloa@mek.dtu.dk

Abstract

The development of nanostructured sample components led to significant interest in metrological solutions and characterization methodologies for features laying on the nanoscale dimensional range. For the specific case of silicon lithography technologies, a well-known case geometry consists of rectangular gratings structures. Among the available equipment, the most commonly employed are Atomic Force Microscopy (AFM) and Scanning Electron Microscopy (SEM). For what concerns sidewalls, limited tools and methodologies are available, both for the evaluation of surface roughness and geometrical features. In this study, the use of AFM explores the measurements of surface roughness of rectangular grating sidewalls. The structures under analysis consist of a periodic structure manufactured by of Deep-Ultraviolet-Lithography (DUV) and subsequent dry etching on a silicon wafer, to generate a nominal pitch of 1400 nm (nominal trench size of 700 nm) and a nominal depth of 1130 nm. The resulting structure has a high aspect ratio (ratio between the nominal depth and trench width) of 1.6. The wafer is tilted beneath the microscope on an inclined stage (20°) to access the sidewalls of the grating. The adopted methodology enables the evaluation of surface roughness and geometry of the sidewalls in a non-destructive way. Different sampling lengths and locations are evaluated to investigate the cross-sections of the grating along multiple sidewalls. The results confirm that an isotropic sidewall surface with limited undercut formation along the depth is generated. Considering the variations within the standard deviation, the measured Ra roughness lies below 3 nm on a projected profile length of 650 nm, which corresponds to about 60 % of the total depth of the structure.

Nano Technology - Metrology - Atomic Force Microscopy (AFM) - Wafer

1. Introduction

Non-destructive measurements of nanostructure side walls is a challenging task for current metrological technologies. Atomic Force Microscopy (AFM) and Scanning Electron Microscopy (SEM) are versatile solutions, widely used for the quantitative and qualitative characterization of nano scale features respectively [1]. Considering a rectangular grating with a nominal pitch in a range of 100–1500 nm, AFM is well suited for the quantitative metrological investigation as long as the grating aspect ratio (peak-to-valley nominal distance over the trench grating size) is below 0.5.

The general assumption for the correct functioning of an AFM is that only the tip bottom radius interacts with the specimen for the detection of the specimen height for a given pixel locations. For non-contact or tapping AFM modes, the tip flanks should not be subjected to attraction/repulsion forces in order to avoid disturbances in the cantilever oscillation. However, when measuring gratings and features with a high aspect ratio (HAR), also the tip flank or tip holder might interact with the same specimen [2].

Even though an optimization of the measuring parameters including sampling rate, sampling distance, drive frequency, integral or proportional gain, and amplitude set-point can improve the dynamic behaviour of the cantilever and its interaction with the sample [3], there is a physical limitation when the tip cone angle is higher than the grating sidewalls slope. This final consideration led to the development of AFM tips for the specific purpose of HAR structures [4]. Such tips include carbon nanotubes, sharp tips and cone elliptical-shaped tips, where the radius tip is generally below 10-30 nm, a cone angle below 5°-10° and an overall length of 5-15 µm. The thickness reduction of HAR tips also reduces the stiffness of the cantilever, making the probing system (cantilever and tip) less rigid than a conventional one. The stiffness reduction can be an issue, as the tip is more subjected to off-axial forces and wear [5]. Even though the accessibility of most structures is possible using those probing systems, in some cases additional considerations are required to achieve an acceptable measurement.

In this study, an AFM system equipped with HAR tip is employed for the analysis of a Direct Ultra Violet (DUV) lithography, and dry etched silicon rectangular grating. Similarly to another research case [6-7], to characterize the sidewall of the structures, the specimen was tilted under the mounting stage to maintain a tip bottom to grating sidewall interaction during the measurement.

2. AFM measurement set-up

The AFM used for the analysis is a Park® NX 20 from Park Systems Corporation, Suwon, Korea, on which a high aspect ratio tip model ISC from company Team Nanotec GmbH, Villingen-Schwenningen, Germany, is mounted. The specimen is a silicon wafer master of 101.6 mm diameter on which different rectangular gratings are structured using deep-ultra-violet (DUV) lithography. The one under analysis has a nominal pitch of 1400 nm and nominal height 1130 nm. The grating is aligned under the microscope in such a way that the scanning direction is perpendicular to the grating orientation. The wafer is tilted under the microscope with an angle of 20° as shown in Figure 1a. A schematic representation of the untilted and tilted specimen is shown in Figure 1b and 1c respectively.

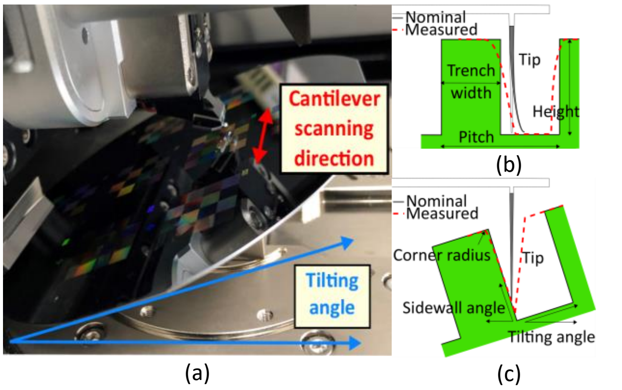

Figure 1. Set-up of the tilted wafer under the AFM microscope (a) and schematic measurement layout without (b) and with (c) tilting.

3. Measurements results

The results of the measurements are reported in Figure 2 and Figure 3. The topography in Figure 2a is the average from trace and retrace micrographs and it has a global dimension of 4.0 µm × 0.4 µm with a resolution of 8 × 4096 pixels. The section in Figure 2b is the average among 4 pixels from the centre on the X direction. The corner radius, as well as the cone angle (180° minus the tilting angle and the sidewall angle as labelled in Fig. 1c), are defined using the least square fitting method.

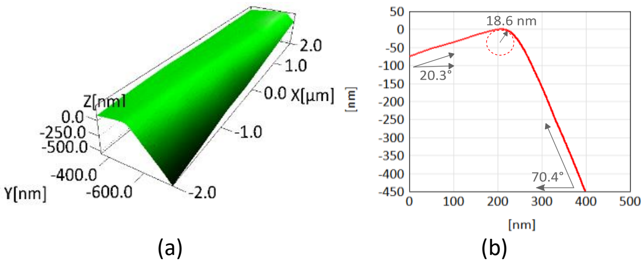

Figure 2. 3D (a) and Cross-Section view (b) of the tilted grating profile.

Figure 3a shows the levelled 3D view of the sidewall of the grating structure and in Figure 3b the Y-section is displayed. This section is longitudinal to the tilted sidewall. In this case, the image size is 8.0 µm × 0.4 µm with a resolution of 16 × 4096 pixels.

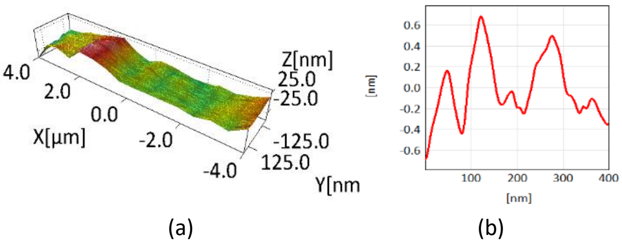

Figure 3. 3D (a) and Cross-Section view (b) of the tilted grating sidewall roughness.

Additional results in terms of corner radius, cone angle and profile roughness (Ra) along the sidewall, in the format of average ± standard deviation (relative standard deviation (COV) = standard deviation over average [%]) are sampled on four sections on three different consecutive gratings and reported in Table 1.

Table 1. Average ± standard deviation (COV/%) of four sections from three different consecutive grating sidewalls in terms of corner radius, cone angle and surface roughness (Ra).

Grating number	Corner Radius /nm	Cone angle /°	Sidewall Roughness (Ra) /nm
1	17.3 ± 1.7 (10 %)	90.7 ± 0.2 (0.3 %)	1.6 ± 0.9 (58 %)
2	17.2 ± 1.3 (7 %)	91.0 ± 0.3 (0.2 %)	1.3 ± 0.2 (14 %)
3	16.2 ± 2.6 (16 %)	90.8 ± 0.3 (0.3 %)	1.9 ± 0.4 (24 %)

4. Results discussions and implications

As depicted by the results in Table 1, the average shape of the grating, as result of the combination of DUV lithography and dry-etching, maintains a deviation within 1° from nominal (90°). The corners can be considered sharp, with a global average radius of 16.8 ± 1.9 nm. The profile roughness measured on the sidewalls has a global average of 1.6 ± 0.5 nm. This final result shows no significant trend along the sidewalls longitudinal direction, indicating that the etching process is isotropic.

From these results is it possible to draw the conclusion that there is a significant difference in the measurement of grating structures when compared to an untilted set-up [8]. The difference is shown in Figure 4a. In Figure 4b a reference untilted measurement is shown. The cone angle is higher by the least 2°, and the measured corner radius is more than 3 times larger.

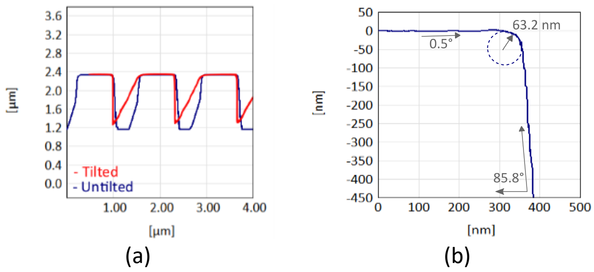

Figure 4. Cross-section profile comparison of the tilted and untilted grating (a) and reference measurement of the untiled specimen (b).

5. Conclusions

In comparison to a conventional set-up, tilting a wafer under the AFM allows a correct reconstruction of HAR rectangular gratings structures. The method also enables the correct evaluation of the sidewalls roughness of the manufactured nano features.

Acknowledgements

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 767589. PROSURF ("Surface Specifications and Process Chains for Functional Surfaces"). This project has received funding from the Danish Innovation Fund (https://innovationsfonden.dk/en), in the research project of MADE DIGITAL, Manufacturing Academy of Denmark (http://en.made.dk/), Work Package WP3 "Digital manufacturing processes". The work was supported by funds from the Danish Agency for Institutions and Educational Grants.

References

[1] Smith J R, Larson C and Campbell S A, 2011, *Trans. I.M.F.*, **89**, 18–27.
[2] Garnaes J et al. 2005, *Proc. SPIE 5878*, 587803.
[3] Zeng G, Dirscherl K and Garnæs J, 2018, *Nanomaterials*, **8**, 616.
[4] Tan S C, Zhao H and Thompson C V 2016 *J. Vac. Sci. Technol.* **34**, 051805.
[5] Strus M et al. 2005, *Nanotechnology*, **16**, 2482–2492.
[6] Svalgaard M et al. 2007 *IEEE Conf. on Lasers and Electro-Optics* , 2007; pp. 1–1.
[7] Garnaes J et al., 2006, *Applied Optics*, **45**, 3201-12.
[8] Loaldi D et al., 2018, Proc. euspen 2018 ICE Conf., Bilbao, Spain.