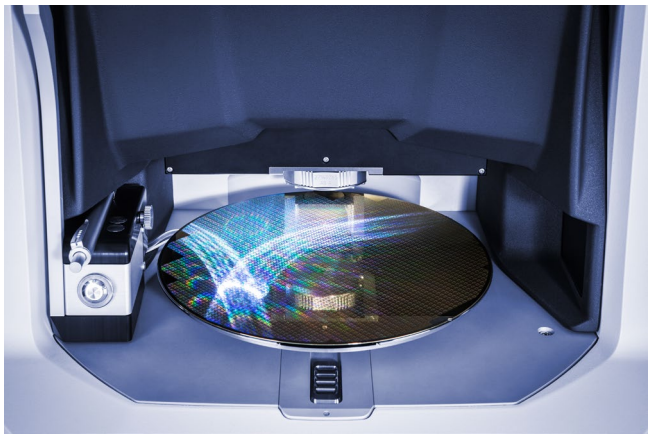
# How to Evaluate Roughness Distribution of Wafers by Means of Atomic Force Microscopy

**Relevant for: Semiconductor, Microelectronics, Nano materials, surface roughness, Atomic force microscopy**

Surface roughness is one of the most important quality parameters for wafer materials in industry and science. Atomic force microscopy is a perfect method to evaluate surface roughness with high precision. An optimized measurement workflow for wafer handling, batch measurement and data evaluation enables analysis on nano-scale with high efficiency.



## 1 Introduction

Wafers are the most important raw material in the semiconductor industry. The yearly demand for wafers has continuously increased over the last 10 years from 70 million units in 2010 to more than 100 million yearly units of for the period of 2017 - 2019 [1]. The microstructures that ultimately create the functional components like logic devices, memory chips, LEDs or sensors are produced by a complex sequence of coating, etching and cleaning steps which are repeated until the desired 3D structure is finished [2].

The initial surface quality and cleanliness of the wafer is of highest importance during the whole process of micro structuring. The specification of wafers involves parameters for flatness, thickness variation, acceptable number of particles and surface roughness. During the micro structuring a broad variety of parameters is controlled in order to maintain high quality and yield. Typical example are dimensional control after individual process steps, critical dimension analysis, line width- and line edge roughness, defect detection and defect control for lithographic masks and quality control of surface roughness after metallization, cleaning or chemo-mechanical polishing.

Therefore producers of wafers and the subsequent semiconductor industry, but also supplier of equipment like cutting or dicing facilities, instruments for cleaning or polishing or producer of photo-lithography masks require an efficient and reliable method for surface evaluation.

Atomic force microscopy is the most accurate, non-destructive method for measuring the surface topography on nanometer scale. It creates a 3-dimenional model of the surface which is the base of surface analysis including surface roughness, detection of particles or artifacts and measurement of critical dimensions.

The surface roughness of a wafer is a very important parameter. First it defines the quality of the wafer surface in the initial state, but as mentioned, it is also used to evaluate subsequent processing steps (coating, etching, cleaning etc.), as those processes modify the surface and influence the surface roughness. Quality control, incoming or outgoing inspection or statistical process control requires wafer analysis on a statistically significant number of points. For these tasks an efficient measurement process is needed, starting from save and easy loading of the sample, to definition of the point(s) you want to scan, automatic measurement and data acquisition and the analysis of the gained information.

Atomic force microscope “Tosca 400” by Anton Paar and the optionally available *wafer stage for Tosca 400* was designed to support all industries involved in the production or processing of wafer materials. Here we report on a typical measurement task - the analysis of surface roughness distribution of an industrial wafer sample. This includes the evaluation of 9 different locations of the surface and shows the complete measurement workflow from sample loading to data analysis.

## 2 Measurement workflow

### 2.1 Sample Handling

Before performing an AFM measurement, positioning of the wafer on the wafer stage is needed. A stable position of the wafer is very important during the very precise measurement in order to ensure high data quality. *Wafer stage for Tosca 400* offers three dedicated positions for wafers with diameter of 4, 6 and 8 inch (100, 150, 200 mm). For measurement of fragments or wafers with a diameter of 3 inch or less there is a dedicated fragment position (Fig. 1).

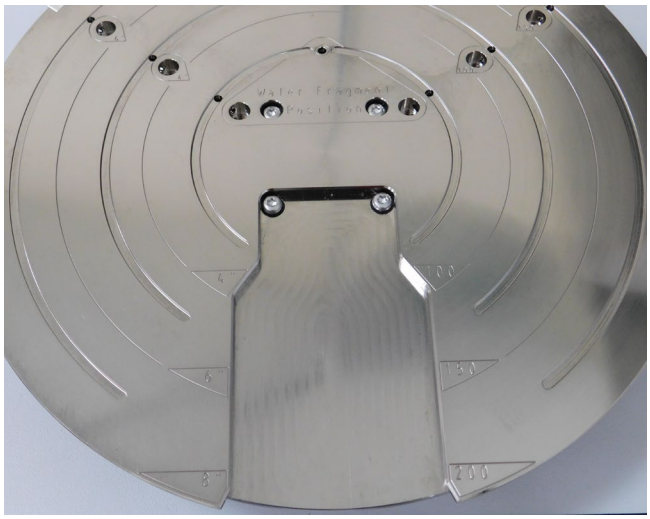


Figure 1: Wafer stage with dedicated positions for different diameters and fragments. The cut-out can accommodate standard vacuum tweezers for wafer handling (see Fig. 2)

The wafer position for each diameter is ensured by precisely designed stoppers. The stoppers also allow an automatic centering of the wafer. They can easily be placed and relocated by the magnetic pen.

To manipulate wafers, specially designed vacuum tweezers are typically used in the semiconductor industry. *Wafer stage for Tosca 400* is designed for use with common vacuum tweezers for wafer handling. This allows a safe and easy loading or unloading of the wafer into Tosca. After placing the wafer, the sample is fixed by vacuum which secures the location and ensures an optimized contact between wafer stage and sample.

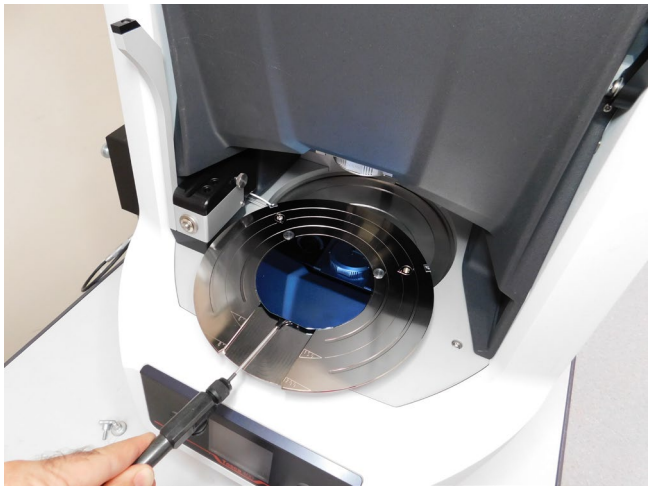


Figure 2 Sample handling by common vacuum tweezers in combination with mechanical stoppers allows safe and easy loading/unloading of wafer samples.

### 2.2 Wafer type selection and automatic wafer alignment

There are many types of wafer differing in diameter, doping and crystal orientation. Furthermore, the surface of interest can be on the wafers front or backside. These parameters are typically coded on the wafer mechanically by different location of the primary and the secondary flat of the wafer or a notch. After the sample has been loaded, the wafer type is chosen from a selection menu in the control software.

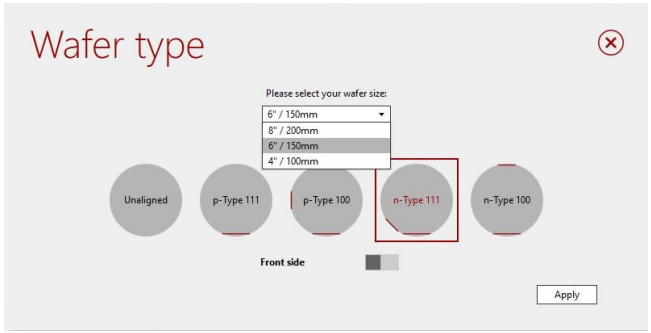



Figure 3 Selection of the wafer size, type and front/backside is done by only a few clicks.

Afterwards, the primary flat or the notch (for 200 mm, 8” wafers) of the wafer can be defined manually or by automatic detection. This is called “automatic wafer alignment”. Knowledge of the position of primary flat or the notch of the wafer allows establishing of a wafer based coordinate system. This makes it possible to navigate via absolute coordinates, to locate and also relocate specific spots on the wafer at any time or load existing coordinates from other analysis instruments to perform an AFM analysis with Tosca on the exact same position.

However, the wafer alignment is optional. If skipped, the navigation is done by relative coordinates based on the coordinate system of the wafer stage with the same high precision. In both cases, the user can decide between navigation in a Cartesian or a polar coordinate system.

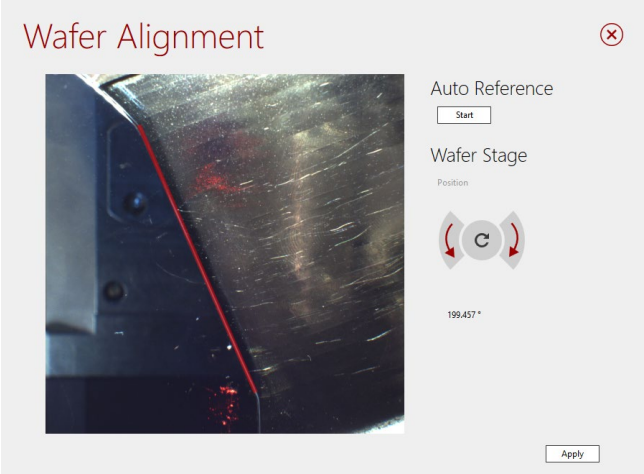



Figure 4: Graphical user interface with live image of automatic wafer alignment of a 4 inch wafer in Tosca Control. After detection of the primary flat, the system marks the position (red line). If needed, the user may correction or optimize the position of the flat manually.

## 2.3 Batch measurement

Representative statistics from AFM data when analyzing full wafers is essential in failure analysis and process optimization. The batch measurement function in the control software of Tosca 400 offers the definition of different measurement locations and to add, edit, reorder, and redefine existing measurements in an intuitive setup. After start of the batch measurement, Tosca performs the scans automatically in the defined sequence. Predefined batch files can be created and loaded for standardized measurements. Also the analysis of measurements can be performed automatically with the help of predefined templates in the software Tosca Analysis.

In the shown case, a batch measurement with a tapping mode scan of 500 x 500 nm at 9 different locations was defined to collect data for evaluating the surface roughness distribution of a 150 mm wafer (see Fig. 5)

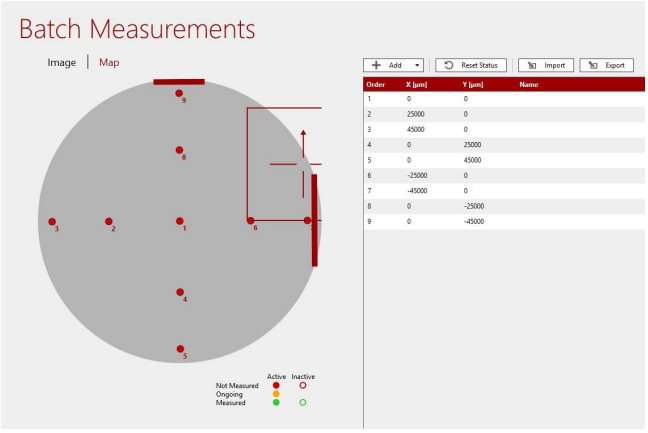



Figure 5 Graphical interface of batch definition, showing a schematic of the selected wafer type and measurement points by loading a predefined batch file for standardized measurements (QC pattern).

After starting the batch measurement, Tosca automatically navigates to each point, establishes contact to the surface (engagement), performs the defined scan and stores the acquired data.

## 2.4 Batch data processing by Tosca Analysis templates

The output of a batch measurement is typically one or two AFM datasets for each measurement point. Within one batch, all acquired data sets will be very similar, which suggests to make use of the functionality of Tosca Analysis templates.

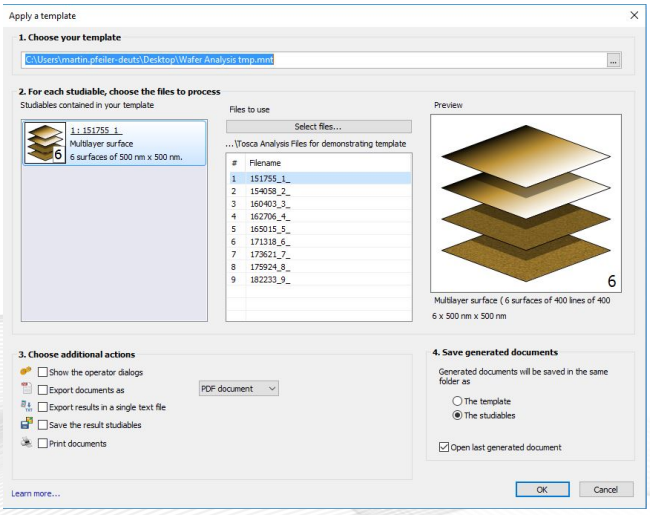



Figure 6 Tosca Analysis template enable efficient evaluation of similar datasets as typically gained by batch measurements

Here, the first dataset is evaluated manually, performing all necessary post-processing steps, analysis of interest and the desired display of the gained results. This first analysis file can then be used

as Tosca Analysis template for all other datasets of the batch to perform the identical analysis steps automatically with only a few clicks. This of course is not only possible for data sets from the same batch, but also for all following data sets that were measured with the same batch template.

## 3 Results

### 3.1 Topography, roughness and imaging

One example for the result of such a batch analysis by a Tosca Analysis template can be seen in Fig. 7.

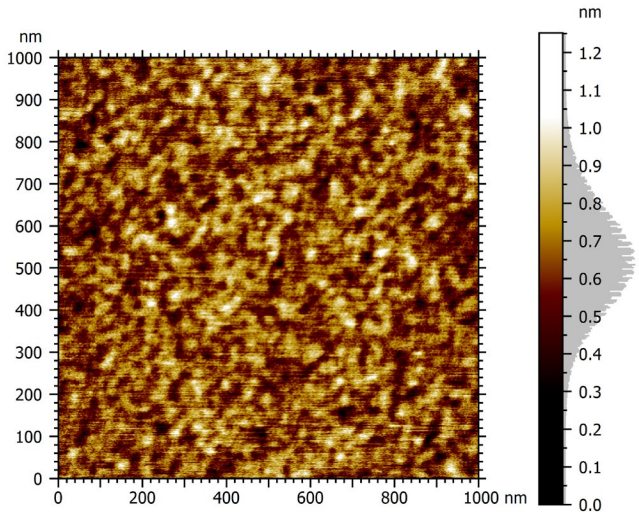



Figure 7 Topography of a polished silicon wafer determined by tapping mode. Unfiltered raw data. The calculated surface roughness is 136 pm (RMS roughness)

The image shows the unfiltered topographical raw data for the measured Silicon wafer. The calculated surface roughness is 136 pm (Sq, RMS surface roughness according to ISO 25178).

The Tosca Analysis software package offers many powerful features for postprocessing. This includes the possibility for correction of individual lines to remove artifacts from audible noise or mechanical shocks but also filter for smoothening and denoising or edge detection. Postprocessing and filtering of data to improve the clarity of the image and to support the conclusions is very common. However, one should always consider the possibility of data processing and filtering, when discussing AFM results based only on published images. Therefore, a fair comparison of AFM results (or AFM systems) is only possible by comparing raw data and not images. In general, the post processing of AFM data is considered acceptable, as long as the use of filters is clearly stated, the data is not falsified and the conclusion that are drawn from the image do not change. Figure 8 shows the same data as in figure 7 after the application of a “5x5 media denoising” filter.

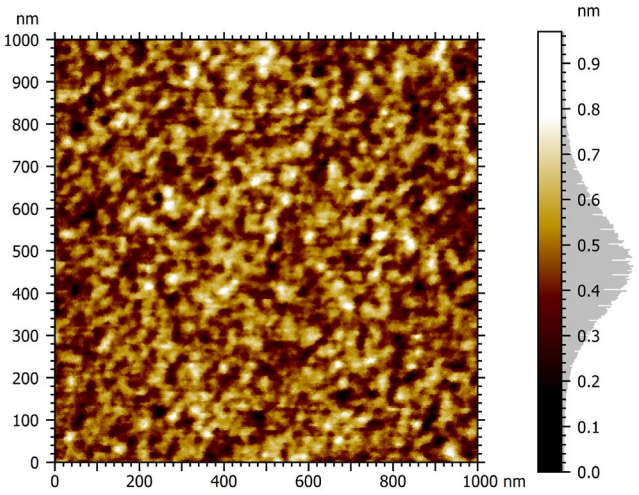



Figure 8 Topography of a polished silicon wafer as shown in Fig. 7 after application of a 5x5 median denoising filter.

### 3.2 Statistical evaluation

The obtained results can then be further processed in Tosca Analysis in a so-called statistical document. A statistical document allows to automatically summarize a high number of evaluated data sets. Tosca Analysis can search for individual, calculated parameters within the different data sets and summarize them in statistical populations.

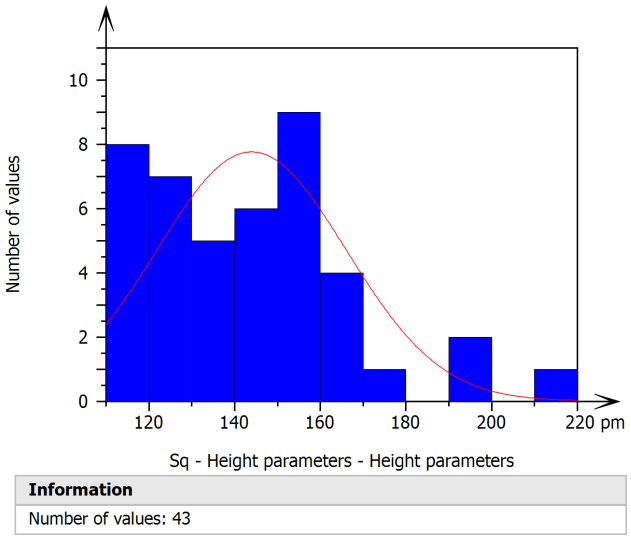
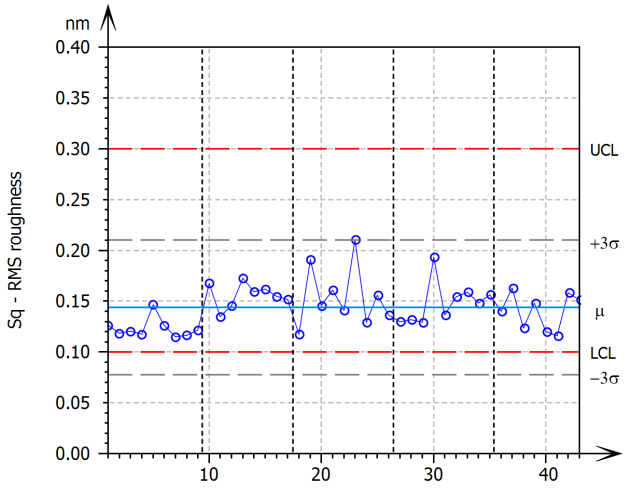



Figure 9 Histogram showing the statistical distribution of the roughness of a silicon wafer based on 43 individual scans.

The data can then be used to generate typical diagrams for statistical data display, such as

histograms, boxplots or control charts for statistical process control (see Fig 9 – 11).




| Information |
|---|
| Number of values: 43 |

| Parameters | Value | Unit |
|---|---|---|
| Variance | 0.000488 | nm² |
| Yield | 100 | % |
| Cpk | 0.663 | |

Figure 10 Control chart of wafer roughness by AFM showing the gained values for polished silicon wafer materials for 43 individual measurements.

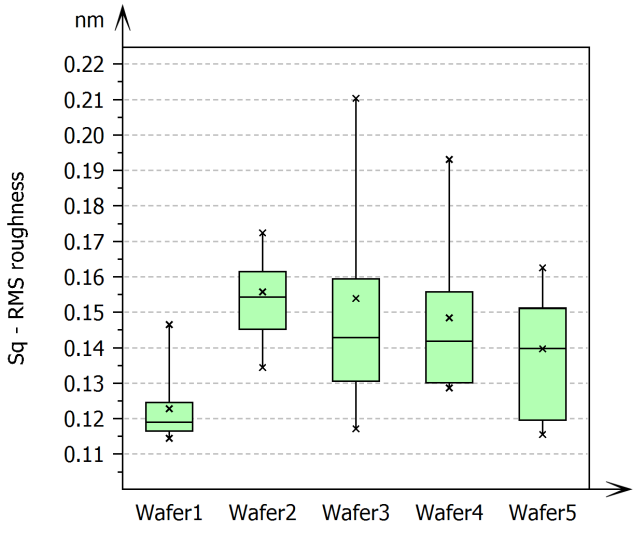



Figure 11 Boxplot diagram showing the surface roughness for five different silicon wafers. Each wafer was evaluated at 9 different positions (see also Fig 5)

## 4 Conclusion

Atomic force microscope Tosca 400 has been used to analyze the distribution of surface roughness of a polished silicon wafer. The *wafer stage for Tosca 400* enables easy and safe sample handling and positioning. In combination with the Tosca Control software it offers navigation by wafer coordinates to locate and relocate specific spots of interest. A batch measurement functionality automatically performs a predefined sequence of measurements. The batch settings can be exported and saved or re-imported to repeat the same batch for similar tasks in the future. The Tosca Analysis software package can be used to evaluate a high number of similar datasets simultaneously by the use of Tosca Analysis templates. Additionally, Tosca Analysis offers the possiblity to automatically process the calculated parameters into statistical diagrams which enables a fully automatic evaluation of a high number of AFM datasets, further increasing the overall efficiency of AFM measurements by Tosca AFM.

## 5 References

1. https://semiengineering.com/q1-2019-unit-drop-impacts-wafer-demand-for-2019/

2. Handbook of Silicon Based MEMS Materials and Technologies, 2015, Chapter 21, 444-469.

**Text and Measurement**
Dr. Martin Pfeiler-Deutschmann

**Contact Anton Paar GmbH**
Tel: +43 316 257-0
Support-nsp@anton-paar.com | www.anton-paar.com