Surface roughness determination by AFM

Introduction

Surface roughness plays a significant role in many mechanical properties such as friction and adhesion, in surface reactivity, in the substrate quality of semi-conductors as well as the surface interaction with electromagnetic waves, in particularly ultraviolet (UV) light and X-ray. Accurate quantitative analysis of surface roughness is therefore essential to qualify the functionality and appearance of a surface. and is thus important to quantify accurately.

The most common roughness determination calculates the root mean square (RMS) height (S_q) compared to the average height $\bar{z}$ over an analyzed surface A and can be found in the ISO 25178 international standard for measurement of 3D surface texture.

$$S_q = \sqrt{\frac{1}{A}\int_{x1,y1}^{x2,y2}[z(x,y)-\bar{z}]^2\,dxdy} \qquad [1]$$

Numerically, this translates to a summation over all points on the surface:

$$S_q = \sqrt{\frac{1}{A}\sum_{k=0}^{M-1}\sum_{l=0}^{N-1}\left[z(x_k,y_l)-\bar{z}\right]^2\Delta x\Delta y} = \sqrt{\frac{1}{MN}\sum_{k=0}^{M-1}\sum_{l=0}^{N-1}\left[z(x_k,y_l)-\bar{z}\right]^2} \qquad [2]$$

As can be seen from eq. 1 and first part of eq. 2, the roughness is length scale dependent: It depends on the size of the analyzed area A and the lateral resolution Δx and Δy with which it is analyzed. The effective length scales depend on any image processing applied to the images. In AFM, it is common to subtract a reference plane from the height data or conduct a line-by-line flattening protocol to images to compensate for artifacts associated with a sample tilt or drift in z. Additional high-pass or low-pass filters can be applied. With a high pass filter the waviness of a sample is removed. This reduces the influence of features that are too close to the image size to be measured representatively. A low-pass filter can be applied to remove features that are too close to the digital resolution and that may create digitalization artefacts. To compare data, it is consequently important to collect and process the data with an identical set of measuring and processing parameters.

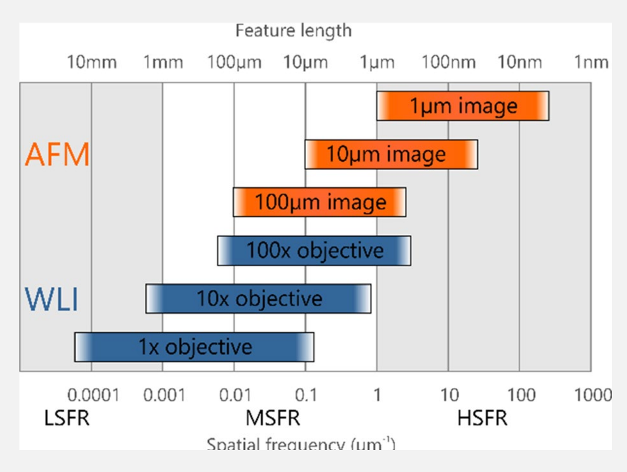

Figure 1: Spatial frequency bandwidth (SFB) accessible by WLI and AFM. Data digitization and image processing may affect the quantitative accuracy, particularly at ends of range. For AFM the image size is given in the graph and 512x512 pixels are assumed. With WLI 167µm field of view is assumed for the 100x objective magnification and numeral apertures of 0.9, 0.25 and 0.04 for a 100x, 10x and 1x objective, respectively.

Often the length scale is expressed by its inverse, the spatial frequency bandwidth (SFB) and is classified accordingly. Low spatial frequency roughness (LSFR) addresses lateral length scales above 1 mm, medium (MSFR) the length scale from 1 mm down to 1 µm, and high (HSFR) below 1 µm. In the MSFR and HSFR bandwidths the roughness of smooth surfaces goes down to values in the sub-nanometer range and is the domain for AFM measurements.

The MSFR and particularly the HSFR roughness is relevant for ultra-flat surfaces as used in EUV optical components for wafers and the semi-conductor industry. The creation of structures on wafers with dimensions of a few tens of nanometers requires a very low surface roughness. To create such small structures, synchrotron radiation or EUV with wavelengths <15nm are used in their production process. The optical components to illuminate wafers do not only need a well-defined shape to guarantee a clean wavefront, they also need a low HSFR to reduce undesired scattering fraction R of radiation, which depends on the ratio between surface roughness S_q and wavelength λ[1,2].

$$R = 1 - exp\left\{-\left(4\pi \cos\theta \cdot S_q/\lambda\right)^2\right\} \qquad [3]$$

with θ the angle of incidence. Roughness values in the 100pm range or less are required to bring down scattering sufficiently[3]

Two of the main available techniques to measure such roughness levels are white light interferometry (WLI) and atomic force microscopy (AFM). Figure 1 gives a rough indication of the SFBs that can be accessed by both techniques.

WLI and AFM are largely complementary with respect to the SFB, with an overlap in the center. The SFB of WLI is limited by the field of view and numerical aperture of the used objective. It mainly covers the MSFR bandwidth, extending into the LSFR with low magnification objectives and dipping into the HSFR bandwidth for a high magnification objective. WLI thus accesses length scales from the tens of millimeters down to a few hundred nanometers.

The SFM of an AFM is limited by the scan range of its scanner to the longer SFR side and the number of pixels or ultimately the tip radius of the AFM cantilever towards the higher SFR. Typically, AFM scanner ranges reach up to about 100µm. At the high spatial frequency end, it reaches down to features in the low nanometer range. With smaller scan sizes than 1 µm or more points sub-nanometer lateral resolution can be reached. AFM thus accesses the HSFR and the higher resolution part of the MSFR.

For optical surfaces, particularly those with thin coatings, the AFM has an additional advantage compared to WLI to analyze the surface roughness. The mechanical probing of the AFM makes it solely dependent on upper-surface features, whereas reflected light from underlying layers may interfere with the roughness measurement of the top surface by WLI.

In this application note we will discuss the main considerations for surface roughness analysis by AFM illustrated by some examples.

Dependence of roughness on system specifications

One of the parameters that can affect surface roughness as measured by AFM is the system noise. This is also referred to as AFM noise-floor and puts a limit on the minimum change in height that can be measured. The system noise contributes to any measurement. System noise levels of a few tens of picometers can be reached by careful AFM and stage design, using finite element simulation (FEM) for verification, use of acoustic enclosures, and use of passive or active vibration isolation.

The system noise S_{sys} can be determined directly from the variation in a height measurement on a surface without laterally moving the cantilever, obtaining a so called zero scan size image. In this way, surface features do not enter the measurement result. Although the system noise contributes to the measured topography, it is generally fair to assume that the system noise is independent from the real topography. Consequently, a more accurate value for the surface roughness can be obtained by correcting the measured values of the roughness $S_{q,m}$ with the system noise:

$$S_q = \sqrt{S_{q,m}^2 - S_{sys}^2}. \quad [4]$$

This contribution rapidly decreases if the system noise is smaller than the measured noise. To give an example: If a measured RMS roughness of 90pm is only 3x larger than a system noise of 30pm, the corrected roughness amounts to S_q = 85pm, about 6% smaller than the measured roughness. As will be shown later, this correction factor may still be larger than the repeatability error of the measurement and can be worthwhile to include in the analysis.

AFM design

A mentioned above, the AFM design plays a key role in the obtainable system noise. For small samples many commercial AFMs fulfill this requirement. For the semi-conductor and EUV optics industry, samples are often larger and heavier. The AFM needs translation axes to reach each position of the sample, either for random testing, or at specified positions where defects have been detected by other methods. An AFM with tip scanner is here generally required because the (heavy) sample can be kept stationary while the cantilever is raster scanned to record the surface topography. The Nanosurf Alphacen system is an AFM platform that

Figure 2: Alphacen tip scanning AFM, with a motorized stage providing full access to 300 x 300 mm^2 large samples with weights up to 40 kg. The system is placed in an acoustic enclosure and includes active vibration isolation to reduce the effect of environmental disturbances.

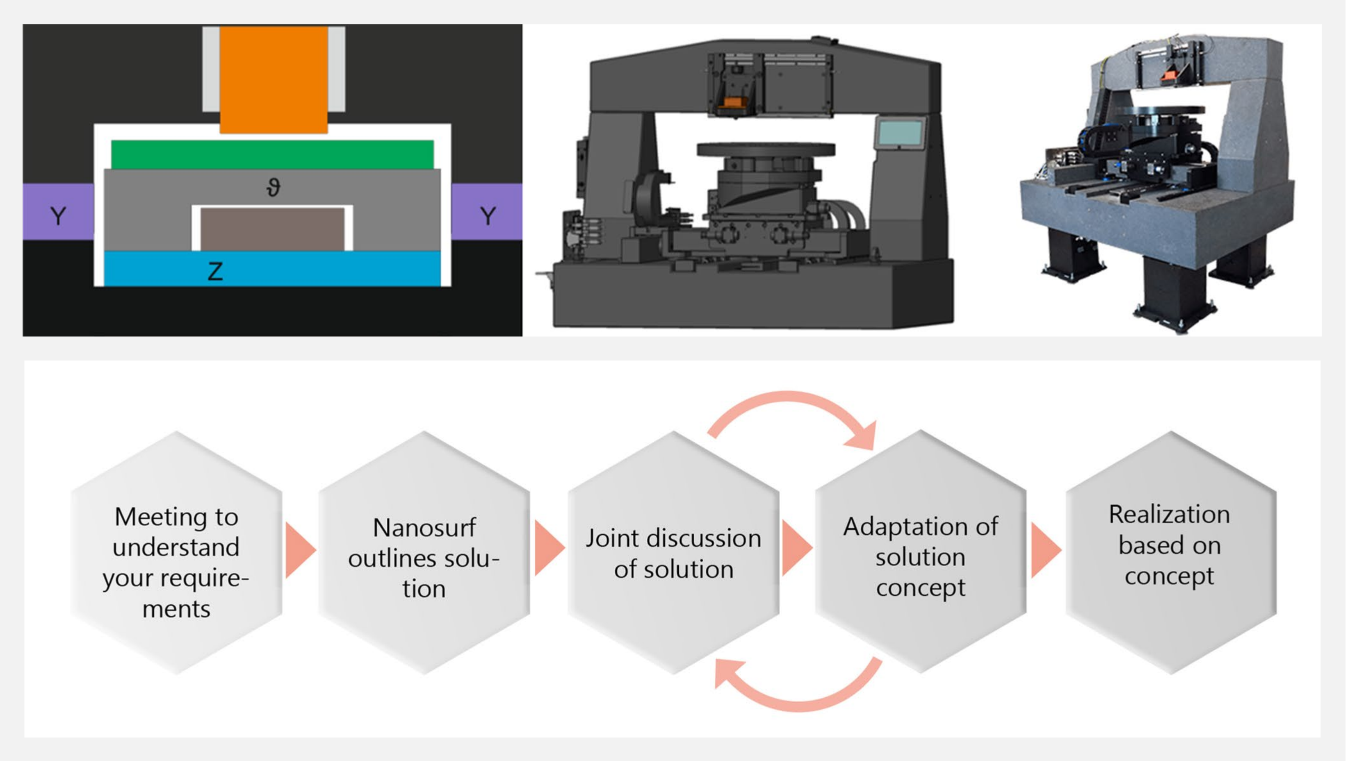

Figure 3: Design and realization process of tailor-made solutions for analysis of samples with geometries that cannot be handled by conventional AFM systems.

can handle samples between 200 and 300mm diameter side length and can be equipped with sample chucks for standard wafers (4“, 8” and 12” diameter). A stage concept with air bearings provides access to the complete sample. Due to the stage design in combination with the tip-scanning design of the AFM platform, sample weights up to 40 kg can be assessed for roughness below 100 pm.

Characterization of optical components for surface roughness, found in industries aligned to the semi-conductor space presents additional challenges. Optical components may have convex or concave surfaces, either spherical, ellipsoidal, paraboloidal, cylindrical, or toroidal. This necessitates tilting of sample or AFM scanhead. In addition, these samples may have special mounting requirements that do not damage the sample both on the side of the sample that is imaged and its opposite. In addition, the inherent system noise cannot exceed a few tens of picometers to characterize the sample roughness accurately. For EUV,samples must be measured in clean room facilities, requiring an AFM and stage that is clean-room compatible. To fulfill these requirements Nanosurf designs tailor-made solutions together with its customers to handle and measure the customer samples and fulfill all requirements according to the strict regulations within the industry . Modelling with FEM simulations is used extensively to verify the design.

Tip shape and imaging parameters

The AFM tip shape and sharpness is known to affect surface roughness measurement. A sharp tip that does not significantly convolute the morphology of the surface features is required for an accurate quantitative measurement. A blunt tip may not measure the features accurately and leads to a widening of protruding and/or shortening of deep features resulting in an incorrect measurement and will generally result in an underestimation of the roughness.

The two most common imaging modes are contact mode and dynamic mode. In contact mode the tip is in continuous contact with the surface during scanning. In dynamic mode, the cantilever is oscillated either close to its resonance frequency or well below this value (off resonance tapping, ORT): the tip intermittently taps the surface during the scanning process.

For roughness measurements in air dynamic imaging modes are most common. Contact mode would involve a more aggressive tip-sample interaction than dynamic mode and is more prone to blunting the tip. However, for some very rough samples, where tip radius is less critical, contact mode imaging has the advantage to follow the surface more reliably, as it can respond faster to the topography of the surface.

It is important to use gentle imaging parameters that prevent tip wear. Imaging mode and parameters such as setpoint and scan rate will affect the tip-sample interaction. In contact mode, the setpoint is the load with which the tip pushes on the sample. In dynamic mode the setpoint is a user-specified proportion of the free air amplitude. More aggressive imaging conditions such as higher load or larger amplitude reductions may accelerate the tip wear. Scan speed is a parameter that must be optimized once to find the shortest obtainable time to record an image while maintaining surface tracking and reducing tip wear. While tip wear is a common concern when measuring roughness, tip contamination resulting from imaging soft or sticky samples can also have a similar adverse effect on roughness calculations.

To obtain reliable roughness measurements by AFM, it is important develop a consistent workflow of imaging parameters, which includes besides the imaging parameters the sample preparation and cantilever definition. Furthermore, images must undergo identical post-processing routines.

Applications

Roughness of glass and fused silica at two spatial frequency bandwidths (SFB)

Figure 4 shows images recorded on polished glass and fused silica, both having sub-nanometer RMS roughness in the HSFR. Both samples were measured at two different SFBs with scan sizes of 15 x 15 µm^2 and 1.5 x1.5 µm^2 at 512 lines and 512 points per line. This covers features sizes between 59 nm and 15 µm (0.067 µm^{-1} < SFB < 17 µm^{-1}), or 6 nm and 1.5 µm (0.67 µm^{-1} < SFB < 170 µm^{-1}), respectively. To remove low frequency waviness, each scan line was corrected for by a parabolic background subtraction.

At 15 µm image the polished glass sample was slightly smoother than fused silica with a measured roughness of 82±3 pm (Figure 4A), compared to 103±3 pm (Figure 4B). The higher roughness on fused silica relates to features in the low micrometer length range that are not present on the polished glass sample. Measured at 1.5 µm both surfaces show similar fine granular structures that were not visible in the 15 µm image, putting their lateral dimensions between 6 nm and 60 nm. The roughness of the polished glass at 1.5 µm doubled compared to that measured at 15 µm image size (Figur 5C). For the fused silica the increase in roughness amounts to <10% (Figure 4D). The data illustrate the frequency dependence of roughness measurements and necessity to carefully define the required measurement parameters. The importance of the roughness at each SFB may be different for different applications.

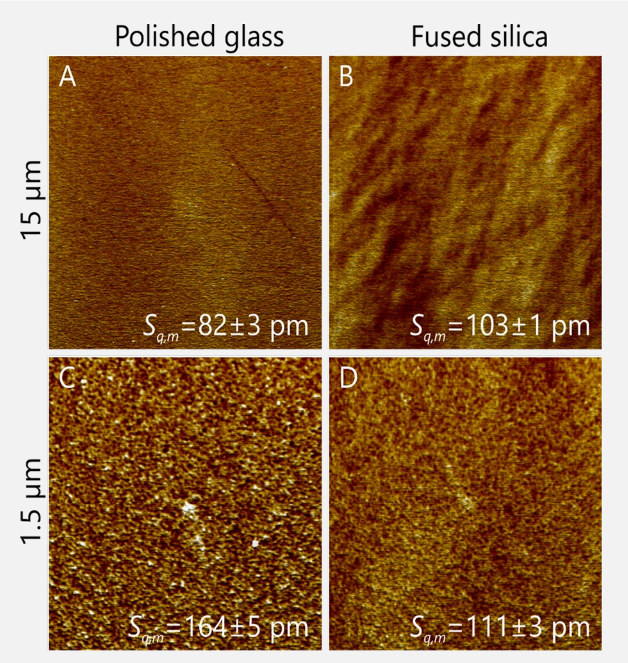

Figure 4: HSFR roughness on polished glass and fused silicon at two different images sizes. All images have been background-corrected line-by-line using a parabola function before the roughness analysis. Height range for all images: 1 nm.

Repeatability of roughness values

To illustrate the repeatability of roughness measurements, the samples from Figure 4 were repeatedly analysed 25 times each. Figure 4 shows the roughness at the two different scan sizes as well as the system noise for the polished glass and the fused silica sample. The measurement series were built up as 25 cycles of zero scan size measurement, 1.5 µm scan size and 15 µm scan size, thus enabling detection of correlations between variations in each of the scan sizes with the other scan sizes for example by tip wear. The standard deviation for each series of 25 measurements was 5 pm or less and around 1.5 pm for the system noise measurements. As can be seen in table 1, the correction obtained by eq. 3 of the measured RMS roughness for system noise is around 6% for the smoothest sample and less than 5% for the others. Except for the measurement with the highest roughness the correction is still larger than the obtained standard deviation of the 25 measurements, making it relevant to consider this correction for system noise.

Reproducibility with standard deviation of less than 1 pm has been obtained on proprietary samples.

	Image size	SFB	Polished glass	Fused silica
S_{Sys}	0	-	29.0±1.5 pm	31.1±1.3 pm
$S_{q,m}$ **S_q**	15 µm	0.067 µm^{-1} < SFB < 17 µm^{-1}	82±3 pm 77±3 pm	102.8±1.1 pm 98±2 pm
$S_{q,m}$ **S_q**	1.5 µm	0.67 µm^{-1} < SFB < 170 µm^{-1}	164±5 pm 161±5 pm	110±2 pm 106±3 pm

Table 1: Table caption Repeatability overview of roughness measurements on polished glass and fused silica. Values are the averages and standard deviations of the system noise S_{sys} and measured RMS surface roughness $S_{q,m}$ as shown in figure as well as the corrected value S_q using eq. 4.

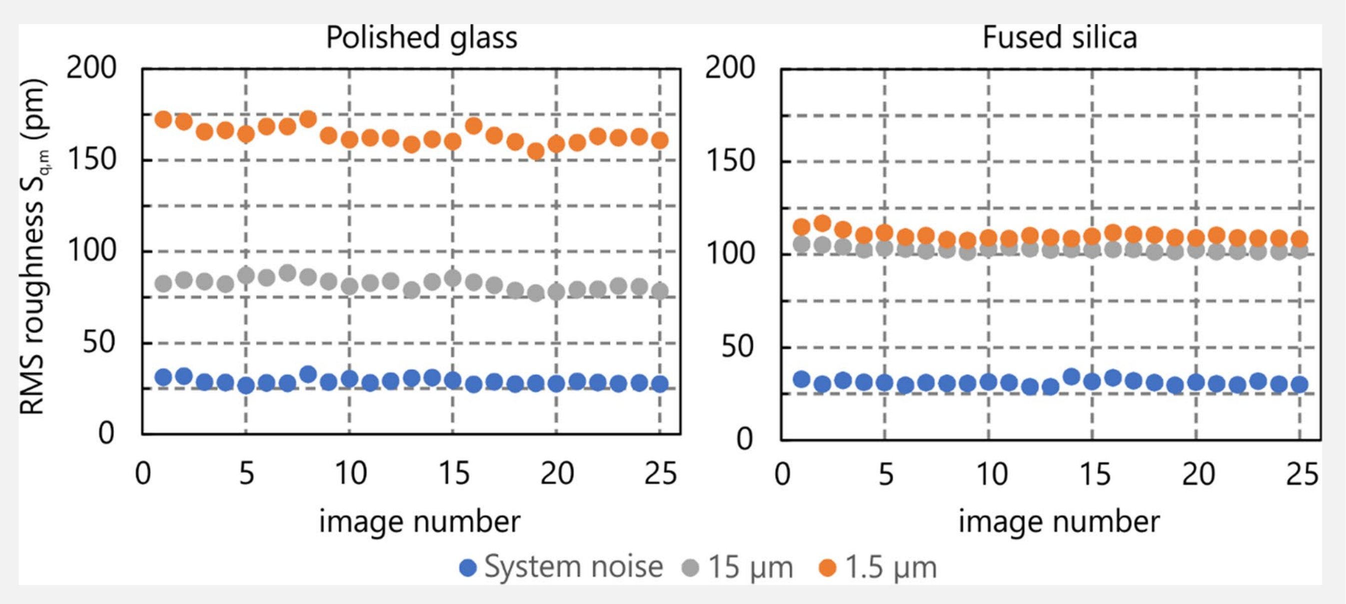

Figure 5: Repeatability of surface roughness measurements. 25 cycles were run, each containing height measurements with zero scan range (system noise), and scan ranges of 1.5 µm and 15 µm. Values are the measured RMS roughness values Sq,m after parabolic line-by-line background correction.

Roughness on concave samples

Tip-scanning AFMs enable greater flexibility to measure non-flat samples. In the example below a concave glass surface was measured, with radius of curvature 28 mm and diameter 30 mm. A stable and compact solution to access the complete sample is created with a single lateral translation axis and two rotation axes perpendicular to this translation axis. An example of a concave glass surface is shown in Figure 6. Due to its transparency and dielectric coatings this sample is not trivial to measure by WLI.

The image shows several topographical features, like pits and trenches. As a result, the height distribution is not Gaussian, making it more difficult to interpret the surface roughness. The measured roughness for the 20x20 µm^2 complete image amounts to $S_{q,m}$ = 199 pm, but is significantly influenced by the deep lying features. The measured roughness of a sub-area free of such topographic irregularities becomes $S_{q,m}$ < 150 pm. The comparison of the roughness between the complete image and sub-image must be taken with care since the SFB is obviously different for the two measurements.

Irregular distinct features like pits, trenches or protrusions make surface roughness analysis more complex. To be included reliably in the analysis, the resolution should be sufficient to detect the features. In addition, the analyzed surface needs to include sufficient features to reach a level where their amount becomes

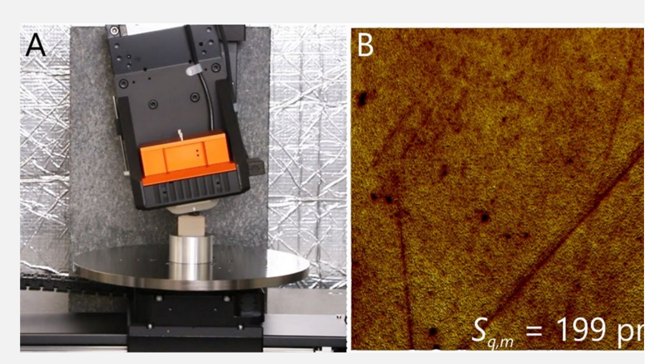

Figure 6: Roughness analysis of a concave surface an optical component with radius of curvature of 28 mm. A) AFM Setup with translation and rotation stage enabling the complete lens surface to be approached perpendicularly B) 20x20 µm^2 image showing pits and trenches in the surface and exhibiting a roughness of 199 pm. Image z-range: 5 nm.

representative for the complete surface. For the example below it requires the imaging of multiple areas to obtain the average roughness and variation in roughness between different areas.

Other roughness parameters from the ISO25178 class can be used to quantify surface with irregular features. The skewness S_{sk} can differentiate between protrusions and pits or S_p and S_v give the highest and lowest point in an image, respectively.

Conclusion

The AFM is uniquely suited to measure roughness accurately in the high spatial frequency range (HSFR) taking advantage of its high lateral and vertical resolution. With unparalleled resolution below 10 nm in the x and y-axis and <50 pm system noise in the z-axis, the AFM can measure 3D maps and roughness at the highest spatial frequency range below 100 pm. While multiple roughness parameters can be extracted from the data, the most common being the standard deviation of heights (S_q). The AFM measurement is sufficiently accurately that the roughness can be corrected for the system noise. When comparing roughness values among images or samples, it is important to note that imaging parameters such as scan size and resolution are selected carefully and that the parameters are kept constant that govern the AFM tip-sample interaction. Finally, the noise floor of the AFM system must be well below the roughness of the sample, which is demanding for smooth samples.

Finally, to analyze samples with large dimensions or that are not flat, special stage designs are required that not only reach the desired system noise specifications, but also fulfill other requirements concerning safety or EUV compatibility.

References

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