WHITEPAPER

Atomic Force Microscopy for Advanced Optical Components

New applications for optical components place ever-higher demands on surface roughness and finish specifications. Current-generation atomic force microscopy (AFM) techniques provide accurate 3D images with sub-angstrom accuracy in less than a minute. These advancements make AFM ideal for applications requiring more detailed information than available with optical interferometry techniques.

The Importance of Surface Characterization

Components in optical and photonic applications typically consist of a substrate and one or more coatings to achieve the desired functionality. In these components, the microstructure of both the substrate and coating can be a critical factor in overall quality and performance. Features with nanometer or even smaller vertical dimensions can cause light loss through scattering.[1] Optical scattering reduces efficiency and output power, degrades image quality, and lowers the laser damage threshold.

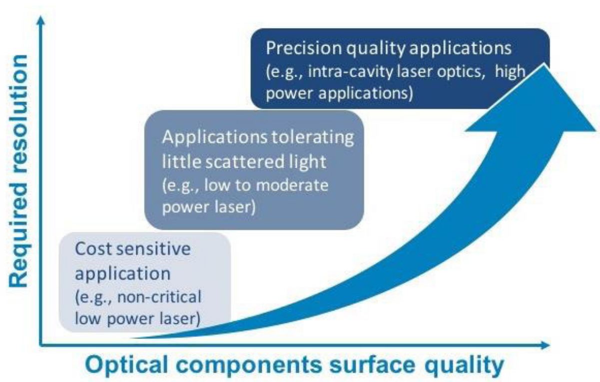

Figure 1: The trend towards improved surface quality for more demanding applications of optical components requires improved spatial resolution.

Despite already stringent requirements on optical scattering, many emerging applications demand even lower values. Examples include optics for high-power lasers, x-ray mirrors, and extreme-UV lithography.[3] As a result, surface specifications for features with high spatial frequencies (roughness) to low frequencies (form) continue to shrink. While current roughness requirements may typically be a few angstroms, sub-angstrom values are becoming more frequent.

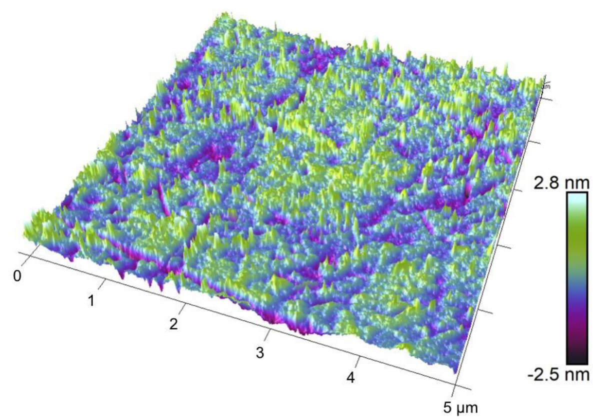

Figure 2: High-resolution 3D image of surface topography obtained with AFM for an optical blank with 20-10 scratch-dig rating.

To keep pace with this trend, better surface characterization of both substrate and coatings is needed (Figure 1). Besides higher spatial resolution, 3D surface information is increasingly needed, rather than simply a 2D parameter like arithmetical mean roughness R_a.[1,4] This is because a single number cannot tell the whole story. For instance, R_a cannot distinguish between peaks and pits, nor between a few large features and many small ones.[5] Thus two surfaces can have the same roughness value yet differ dramatically in optical performance.[6] This 3D information is also needed across a wide range of spatial frequencies in order to evaluate roughness, midrange waviness or figure, and form simultaneously.

For many years, optical interferometry methods were thought adequate for industry needs, and atomic force microscopy (AFM) was considered too slow for industrial use. But tighter requirements plus recent AFM improvements mean these ideas should be reconsidered. Here, we explain the benefits of AFM for high-resolution surface characterization (Figure 2).

Optical Interferometry Techniques

White light interferometry (WLI) and phase shifting interferometry (PSI) are two popular techniques for surface characterization based on optical interferometry. Both can be used to determine roughness variations of a few angstroms or greater (Figure 3). Measurements can take only a few seconds, but spatial resolution affects image acquisition time. Images with high lateral and spatial resolution can take substantially longer, typically a minute or more.

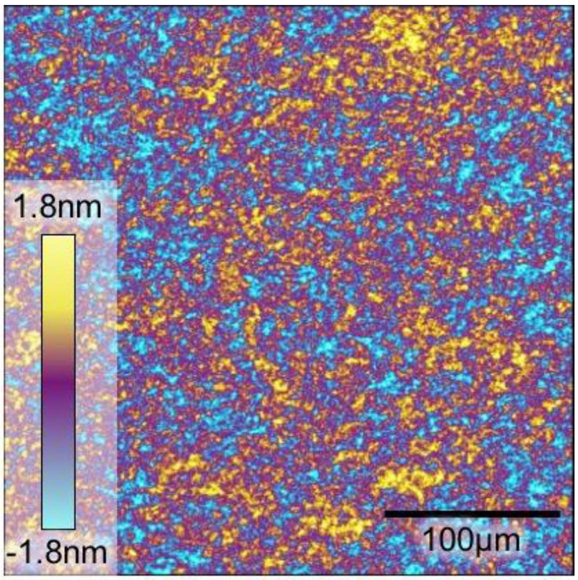

Figure 3: WLI image of uncoated ultraviolet-grade fused silica (UVFS) with 10-5 scratch-dig rating. On this very smooth surface, the measurement yields a value of arithmetical mean height R_a = 4.64 Å but does not allow the observation of individual scratches.

Although interferometric methods such as WLI and PSI yield good results on rougher surfaces (see Figure 5 next page), they are not suited for every application. For example, coatings such as those used in interference filters can introduce phase distortions or extra interference fringes that can lead to inaccurate results. Samples containing regions with very different optical properties can also produce measurement errors. Coatings with high transmission over a wide wavelength range, for instance antireflective coatings, may not reflect sufficiently for good measurements. Dynamic range limitations are also a consideration on highly curved surfaces or ones with sharply varying features. With PSI, height variations greater than a few hundred nanometers between adjacent pixels can cause measurement problems.

Atomic Force Microscopy

AFM[6] is an alternative technique for nanoscale surface characterization that overcomes some limitations of WLI and PSI. One of its most valuable features is routine, accurate measurement of sub-angstrom height. In AFM, a cantilever probe containing a sharp tip is used to sense the interaction forces between the tip and the sample surface (Figure 4). The interactions at play are atomic and do not rely on optical or electrical properties of the sample. By raster scanning the tip across the sample, data is acquired to directly map the surface, capturing its complete topography within measurement resolution. Automated software provides many capabilities for display and analysis of these maps, including calculation of the full range of 3D surface parameters (e.g., S_a, S_q, skewness, kurtosis).

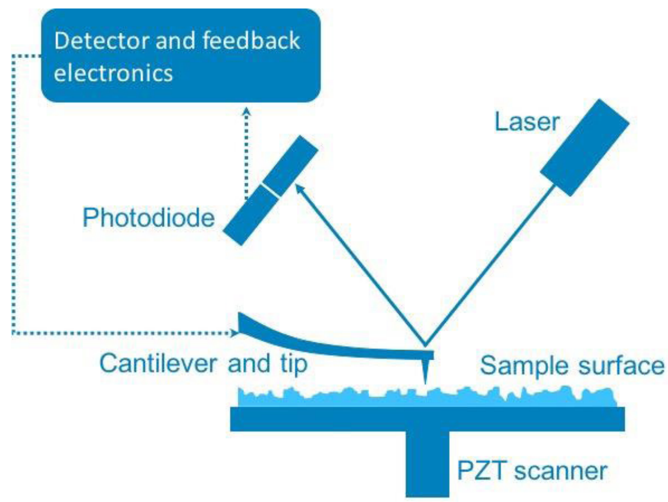

Figure 4: Schematic of key AFM components.

AFM provides additional benefits for surface characterization. Because imaging does not depend on the sample's optical or electrical properties, it works on optically reflective, transparent, or low-reflection samples as well as both insulating and conducting ones. AFM measurements can also be integrated into other experimental setups, for instance to examine laser damage in situ. Experiments can be performed in ambient conditions and typically require little or no sample preparation, unlike electron microscopy techniques (SEM and TEM).

A hallmark of new-generation AFM instruments is their significantly increased imaging speed. A complete image of 512x512 pixels can now be acquired in less than 1 min. Images with pixel densities up to 4096x4096 are possible for high-resolution zooming and take longer. Image sizes of ~90 µm and inspectable ranges of 150-200 mm in each direction are also typical.

Although often classified as a stylus technique, AFM is usually nondestructive. Current instruments have exquisitely precise control of forces as low as piconewtons. Thus, topographic imaging in “tapping” (intermittent contact) or pulsed modes enable extremely gentle imaging without sample damage.

Comparison of WLI and AFM Spatial Resolution

Since the values of many roughness parameters depend on scan size,[4] it is more meaningful to compare the spatial resolution of different techniques. Table 1 shows that AFM presents distinct advantages over WLI/PSI in this regard. Vertical (Z) resolution, often the main specification of interest for surface characterization, is significantly higher (3-20x). It should be noted that current AFM instruments can routinely achieve this sub-angstrom resolution not just in a tightly-controlled research lab environment, but also in noisier settings.

Table 1: Comparison of spatial resolution for optical interferometry (WLI/PSI) and AFM. Values are intended as general guidelines and are not exact specifications of a particular brand or model.

Technique	Vertical (Å = 0.1 nm)		Lateral (nm)	
	Best	Standard	Best	Standard
WLI/PSI	1	10+	200	500+
AFM	0.3	0.5	2	5-10

Table 1 also shows that AFM provides even more substantial improvements in lateral (in-plane or XY) resolution. At 25-100x higher lateral resolution, AFM enables nanometer-scale characterization of small features including grains, pits, and surface contamination while still measuring longer-range features such as waviness (Figure 5). Recent improvements in AFM scanner performance have also increased imaging fidelity and enable highly accurate offsets and zooms.

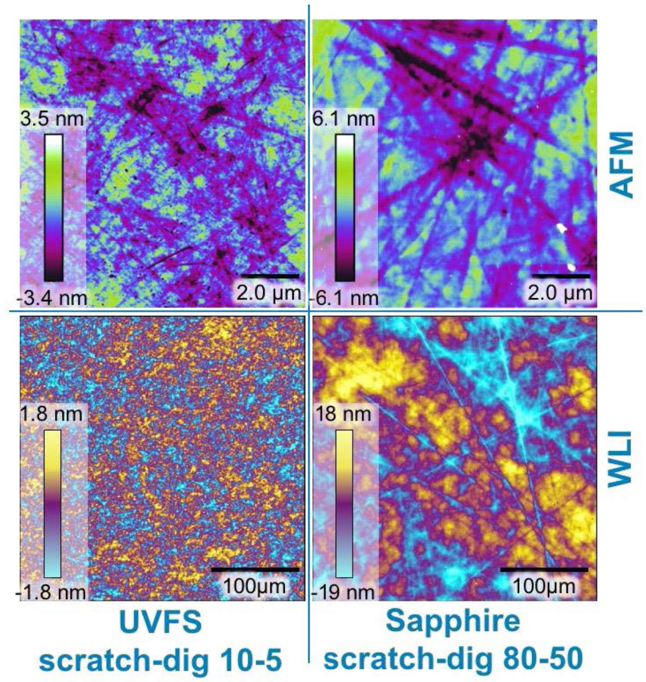

Figure 5: AFM and WLI results for two materials with different surface qualities. Even on a very smooth material (left), the AFM image reveals individual defects at much higher resolution, while the surface appears random with WLI. The AFM measurement of 10-5 scratch-dig surface revealed fine scratches left over from the polishing process. On the rougher sample with 80-50 scratch-dig (right), AFM clearly detects scratches just barely visible with WLI.

Optical scatter depends on the lateral distribution of surface structure as well as the overall height. Thus 3D surface imaging provides a richer understanding of scattering sources than a single roughness value. High lateral resolution can be particularly valuable for this application. Concepts such as the power spectral density (PSD) function have been developed to better quantify surface microstructure and its effect on optical scattering. The range of length scales probed by AFM techniques mean they provide information about PSD curves and other functions over a much wider range of spatial frequencies.[1,4]

The Role of AFM in Characterizing Optical Components

AFM offers many potential benefits for surface characterization of optical components (see sidebar). In particular, its exquisite spatial resolution holds promise for applications requiring ultra-smooth substrates and films. The ability to provide 3D images with extremely high lateral resolution over a wide spatial wavelength range also presents many possibilities. Although AFM imaging rates have improved dramatically in recent years, it generally remains slower than optical techniques for the same area. Thus it is typically better suited to high-value applications than high-throughput ones. For example, AFM can reveal the effect of process variables on microstructure when developing a new film deposition process or a new substrate polishing method.

Surface Characterization of Optical Components with AFM

Process development and optimization

- Film deposition parameters: temperature, deposition rate, etc.
- Substrate polishing variables
- Surface treatments
- Contamination, cleanliness
- Before and after comparisons

Dimensional measurements

- Film thickness, trenches, gratings, patterned film uniformity, etc.

Failure analysis and long-term reliability

- Adhesion and wear
- In-situ experiments in relevant environments: high temperature, liquids or gase

Nanoscale property mapping

- Mechanical properties
- Tribology and surface adhesion
- Electrical, magnetic, piezoelectric response

Better, Faster, Cheaper AFM

Development of reliable, high-performance optical components requires increasingly detailed surface characterization of both coatings and substrates. Recent innovations make AFM even more powerful for this purpose, including higher spatial resolution than optical interferometry, direct 3D visualization of surfaces, and greatly faster imaging rates. To learn how AFM can help in your application, contact Covalent Metrology.

About Covalent Metrology

Covalent Metrology is an advanced materials science and analytical services platform headquartered in the heart of Silicon Valley.

We have a proven track record of helping scientists and engineers from many of the most influential companies in the world better understand the optical, chemical, physical, and electrical properties of their new products and technologies. Covalent Metrology succeeds through a unique combination of cutting-edge analytical instruments and a world-class team of scientists: enabling us to provide our clients actionable, accurate and affordable data and insights to accelerate the development of product and technology innovations.

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