Using Atomic Force Microscopy (AFM) for *Engineering Low-Scatter Thin Film Optics*

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Figure 1. AFM image of the surface structures of a thin LaF_3 film. 500nm scan.

The quality of optical components used in complex applications such as lasers, microscopes, and lithography systems, is critically influenced by surface morphology. The majority of these components – lenses, mirrors, beamsplitters, polarizers, etc.– are covered by thin film optical coatings. Hence, important properties of the optical elements such as optical scattering, are significantly affected by the surface microstructure of the thin film coating. With the ongoing trend of today's optical lithography towards shorter wavelengths (e.g. lithographic objective shifting from 248nm to 193nm), thin film research and industry are facing drastically increasing requirements for low-scatter optics in the UV, and deep UV, spectral region.[1]

The surface microstructure of a thin film coating can be advantageously measured with an Atomic Force Microscope (AFM) and the information obtained can substantially contribute to successful development of low-scatter optical coatings. This, however, requires good understanding of some basic relationships between microstructures and optical scatter, as well as the use of appropriate AFM data analysis and interpretation concepts.

In this application note, we will discuss aspects of thin film and substrate surface microstructures as they relate to scatter losses.

AFM and PSD Measurements

Fluorides play a key role in UV coatings due to their low absorption in the UV, which is particularly important for wavelengths below 200nm. However, all the general aspects and principles demonstrated by using the examples in this application note are valid without restrictions for other coating materials as well. All AFM measurements described here were performed with a Digital Instruments Dimension™ 3100 AFM which was operated with the patented TappingMode imaging technique to prevent damage to the thin films and provide optimal image and data quality.

The AFM image in Figure 1 displays the surface morphology of a thin LaF_3 film (50nm thickness) on a quartz substrate. The surface features result from the columnar structure which is typical for many dielectric thin films. Viewing such an image may result in the assumption that this pronounced structure gives rise to scatter losses. Additional consideration of the increase in rms-roughness (500nm x 500nm scan) from 0.4nm (uncoated quartz surface) to 1.3nm (after coating) would support this assumption.

However, from scattering theories we know that the amount of optical scatter depends not only on the roughness height of a structure but also on its lateral distribution. Any randomly rough surface can be considered as a Fourier series of sinusoidal waves with different amplitudes, periods, and phases. The grating equation shows that a single grating with spacing d causes scatter into the angle, σ, according to: $\sin \sigma = \lambda/d$ where λ is the wavelength of light. d can be considered as one spatial wavelength present on the surface, or accordingly, $f = 1/d$ as one spatial frequency. At a randomly rough surface (such as our thin film component), many different spatial frequencies are present. This is quantitatively expressed by the Power Spectral Density (PSD), giving the relative strength of each roughness component of a surface microstructure as a function of spatial frequency.[3]

The red curve in Figure 2a shows the PSD of the thin film of Figure 1. In order to cover an extended range of spatial frequencies, we combined the PSD curves from 1µm x 1µm and 10µm x 10µm scans. Also given in Figure 2a is the PSD of the uncoated substrate (black curve). It is obvious that at low spatial frequencies (i.e. roughness components of larger lateral extension) the PSD of the coating coincides with the PSD of the substrate, which means that the substrate microstructures replicated by the film determine the PSD in this region. The thin film structure is represented by the "bump" in the PSD at frequencies above $10µm^{-1}$. Now look at the bars indicating the spatial frequency region to which a typical total integrated backscattering measurement (with the scattering angle typically extending from 2° to 85°)[3] would be sensitive when performed in the visible and ultraviolet region (for instance at 633nm, 248nm and 193nm). It is obvious that neither in the visible, nor in the UV, does the film structure cause any measurable scatter; i.e., the scattering is dominated by the substrate. Hence, the PSD reveals that in this case, reduction of scatter loss can only be achieved by improving the substrate polish, not by changing the deposition parameters.

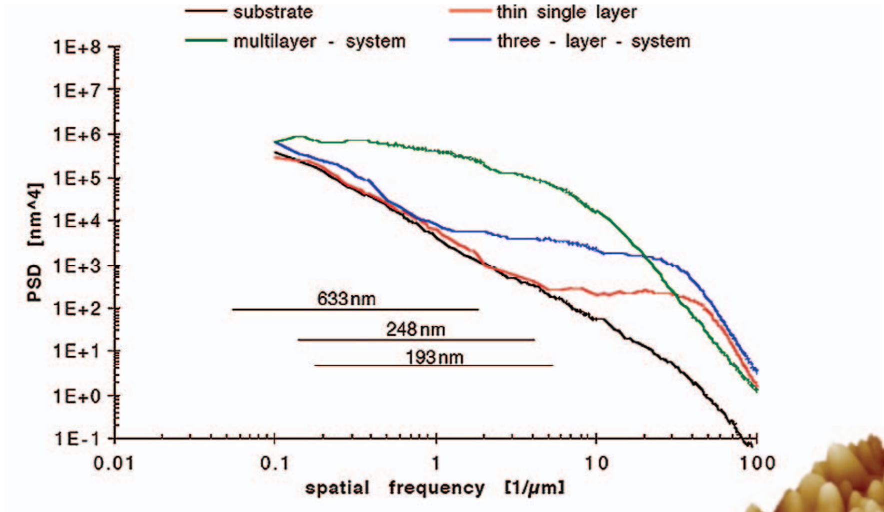


Figure 2a. PSD curves calculated from AFM measurements for an uncoated quartz substrate (black curve), the LaF3 film (red curve), a three-layer fluoride system (blue curve), and a HR multilayer fluoride system (green curve). The bars indicate the spatial frequency ranges to which scattering measurements at various wavelengths are sensitive. See text for useful conclusions drawn from data.

The blue curve in Figure 2a is the PSD for a 3-layer system of alternating LaF_3/MgF_2 layers on a quartz substrate. First, we see the overall increase in roughness – to 2.7nm – relative to the single layer (1.3nm, see above). The most important change, however, is the shift of the "bump" towards lower spatial frequencies. In the visible range, this does not cause any significant scattering effect, but in the UV the effect *is* significant.

Now consider a multilayer system consisting of 42 alternating MgF_2/LaF_3 layers, designed as a HR-mirror for 248nm, again on a quartz substrate. The corresponding AFM image of the film morphology is shown in Figure 2b. The structures have extended both in height and width, with an rms roughness of 6nm (for the 500nm scan size of Figure 2b). In addition, the PSD (green curve) in Figure 2a reveals that the "bump" has significantly broadened and extended to low frequencies, indicating that the film structure is now the dominating factor affecting scatter, even in the visible range.

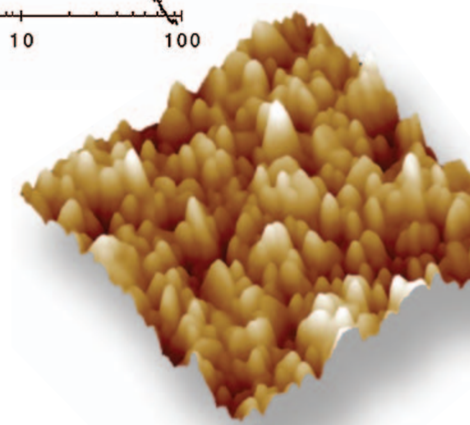


Figure 2b. AFM image of the surface structures of a HR multilayer of 42 alternating MgF_2 LaF_3 films. 500nm scan.

Scattering Measurements

Using a total integrated scattering apparatus (described in detail elsewhere[4]), the total backscattering at 248nm on the multilayer system just described was 1%. The scattering of the uncoated quartz substrate was 0.004%. The increase in scattering, attributed to the enhancement of reflection caused by the mirror system, would result in a scatter value about one order of magnitude lower. Thus, the measured scattering of the fluoride coating is in fact governed by the microstructure of the films.

But does this mean that in the case of a multilayer system the film structures will be the dominant factor determining scatter, whatever the substrate and the film material? Not at all. The same fluoride multilayer system discussed was also deposited onto a MgF_2 substrate, which is useful in certain Excimer laser applications. Figures 3 and 4 show 10µm x 10µm images of the multilayer on quartz and MgF_2, respectively. Differences can be perceived (scratches on the MgF_2 substrate which are replicated by the film), but they do not appear to cause tremendous differences in scattering. Again, the corresponding PSDs provide the answer. Figure 5a and 5b compare the PSDs of the multilayer coating on quartz and MgF_2, respectively. For the coating on MgF_2, the PSD indicates that at 633nm the substrate-related scatter will clearly dominate (note that the small enhancement after coating around 0.1 to 0.2µm^{-1} is caused by formations of larger defects that occasionally occur when the films are deposited on MgF_2 substrates). Even at 248nm, the influence of the substrate is still very significant, and only at shorter wavelengths does the film structure become dominant for the scatter. This has been proven experimentally. The measured total scattering at 248nm was 1% for the system on quartz, and 3% for the same system on MgF_2. So the scatter losses of the two samples differ by a factor of three as a result of the different substrate qualities.

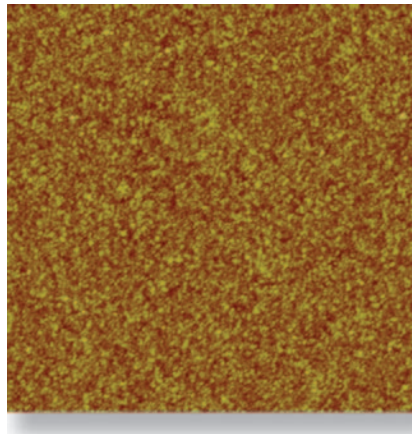


Figure 3. AFM image of the surface of the HR multilayer when deposited on a quartz substrate. 10µm scan.

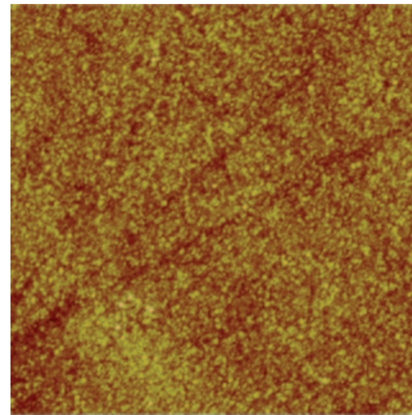
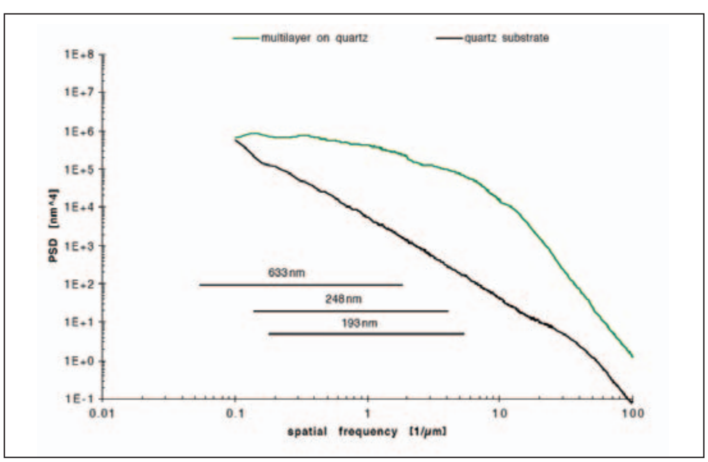


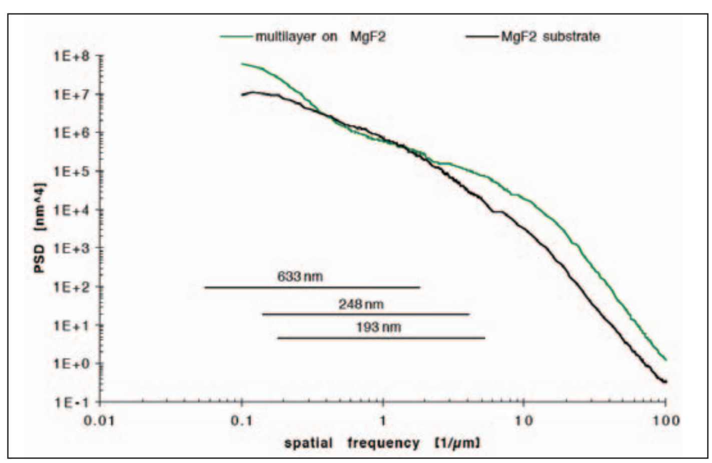
Figure 4. AFM image of the surface of the HR multilayer when deposited on an MgF_2 substrate. 10µm scan.

What the PSDs reveal here is that for the system on the MgF_2 substrate, any improvement of the deposition process would hardly be worthwhile. This substrate topography effect illustrates the influence substrate polish can have on the overall coating microtopography and related scatter in general. For instance, with CaF_2 becoming a material of choice in UV-lithography, the question of how much polishing quality matters relative to thin film microstructure is becoming increasingly important – especially since high-quality polishing of this material is difficult to achieve.

Returning to the case of the multilayer system on the smooth quartz substrate, the height and location of the "bump" in the PSD curve quantify the effect the film structure has on the scattering loss at a particular wavelength. Improvement of the optical coating here requires improvement of the deposition process such that the bump height is reduced (smoother structure), or shifted further out of the spatial frequency region of scattering (growing of structures with lower diameters). Ideally, both improvements should be achieved.



a.



b.

Figure 5ab. PSD curves of the HR multilayers on quartz (a) and MgF_2 (b) together with the PSDs for the uncoated substrates (black curves).

Conclusions

The following general conclusions can be drawn from the above results:

• PSD curves generated with TappingMode AFM data are a valuable and easy-to-handle tool for quantifying the surface microstructure of optical components and for predicting their influence on scatter losses. This is particularly important for thin film optical components, where both the substrate and the film structure can give rise to scatter.

• Once a thin film engineer has become experienced in interpreting PSDs, (s)he can easily determine whether – for the particular film, substrate, and wavelength of application (i.e. where light scatter should be reduced) – the substrate or the film structure or both are the cause of scatter. This helps decide which of the processes, substrate polish or film deposition, has to be improved first.

• If the film microstructure is the dominant factor for scattering, the deposition process has to be optimized with respect to film structure. This can be efficiently controlled by means of the PSD (i.e. "adjusting the bump" towards the region which is out of the "scatter bars") by changing the deposition parameters.

It has been shown how proper AFM data analysis can substantially support predictions about scatter losses in thin film optical coatings and hence, help reduce these losses through PSD-controlled optimization of the processes. Of course, this does not replace the necessity of direct measurement of the scattering losses of the optical components. In fact, combining the PSD method with 2D total scatter loss measurements covering the whole area of the component[4] will result in comprehensive knowledge about the microstructure/scatter loss mechanisms and will improve the ability to effectively engineer low-scatter optics.

References

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