Measuring Surface Roughness with Atomic Force Microscopy

Surface roughness plays a crucial role in determining the functional performance of many devices. This effect of form on function is also present at the nanoscale and below. Understanding and characterizing nanoscale and even sub-angstrom roughness is becoming increasingly important to our ability to continue exploring and building devices at ever smaller length scales.

Nanoscale Roughness

AFM is essential for studying surface roughness (R_a, or average deviation) at the nanoscale, having resolution far exceeding that of other stylus and optical based methods[1]. The measured roughness of any given surface depends on both the spatial and vertical resolution of the instrument. This is because real surfaces exhibit roughness on many length scales and can be thought of as a superposition of these profiles. Consider that even an atomically flat surface has quantifiable roughness when using a high-performance instrument with sub-angstrom resolution, such as the Cypher™ AFM.

There are many examples illustrating the importance of nanoscale surface roughness. In the data storage industry, with areal bit densities surpassing 1 terabyte per square inch, and read/write heads flying mere nanometers above the surface, hard disk platters are now being polished to a roughness of ~1Å R_a.

Likewise, as transistors scale down in accordance with Moore's Law, the ability to measure sub-angstrom surface roughness is becoming increasingly important for the semiconductor industry. Atomically flat silicon has been shown to greatly decrease the transistor noise while increasing reliability and device performance[2]. Figure 1 shows a comparison of chemical-mechanical polished silicon and a single terrace of atomically flat silicon.

There are two important factors which affect the resolution of the surface roughness measurement:

1 AFM instrument noise limits the vertical resolution.

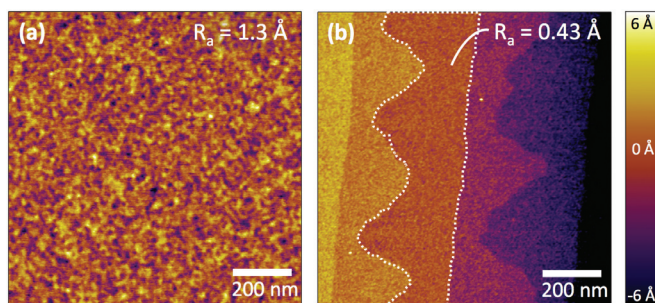2) Tip radius limits the spatial resolution. Tip wear also affects the precision of the measurement.

Figure 1: Surface roughness on a chemical-mechanical polished silicon (a) was measured at 1.3Å and on a single terrace of atomically flat silicon (b) at 0.43Å. Imaged with the Cypher AFM.

Vertical Resolution

Mechanical vibrations in the AFM and random fluctuations in the electrical signals are examples of instrument noise that ultimately translate into a certain amount of variation in the height signal. Height features that are smaller than this are simply "lost in the noise" and cannot be meaningfully resolved.

One commonly employed method to quantify instrument noise is to simply measure the variation in the AFM height signal in the absence of any real signal. For example, many manufacturers set the scan size to zero and report the apparent roughness. Without any features of height, there is no signal; without signal, there is only noise. In theory, this is a seemingly adequate method. In practice, however, this is an unreliable approach since it depends greatly on imaging conditions. In fact, as shown in Figure 2, the measured noise floor could be made arbitrarily small simply by
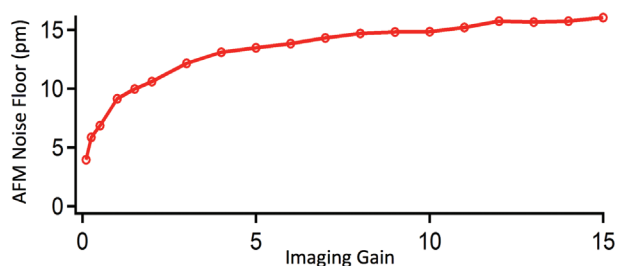

Figure 2: Traditional methods for quantifying the AFM noise floor are flawed in that the measurement depends on the imaging gains that are used.
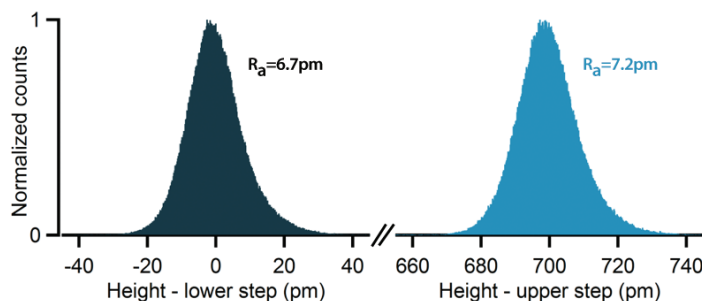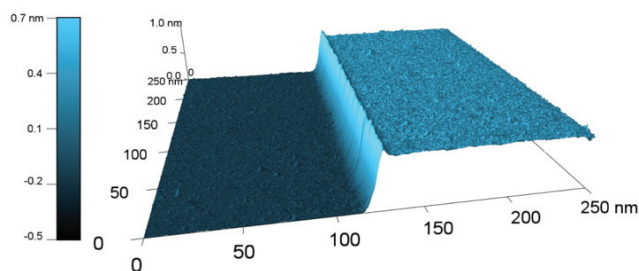
Figure 3: A feature of height such as this single step of MoS$_2$ requires that realistic imaging gains be used during the measurement of the AFM noise floor. The apparent surface roughness of the atomically flat terraces puts an upper limit on the true AFM instrument noise floor. The measured values were 7.2pm and 6.7pm on the upper and lower step, respectively.

lowering the imaging gains or bandwidth to unrealistic values. Since there are no real features to have to track, imaging a flat surface does not require the level of imaging gains or bandwidth that would typically be required for most samples.

The solution we demonstrate here is to scan an atomically flat surface where the scanned area contains a single step edge, and then confine the area for the roughness measurement to a single atomically flat terrace. Molybdenum disulfide (MoS$_2$) was chosen for this task because it is readily available, atomically flat with a moderate density of single steps, and easily cleavable which allows for a chemically clean surface.

Figure 3 shows a 250nm scan taken at 1Hz in tapping mode of a freshly cleaved MoS$_2$ surface with a single step of 6.5Å, imaged with a Cypher AFM. If this surface is to be tracked with any fidelity, the gains and imaging bandwidth must be set appropriately. The realtime height profiles as the tip scans over and then back again should match. After the image is acquired in this fashion, each side is flattened separately and the R$_a$ is measured to be 7.2pm on the upper step and 6.7pm on the lower step. This is a measure of the Cypher AFM's noise floor in tapping mode. The short mechancial path inherent in the Cypher design results in the industry's lowest instrument noise levels (<15pm height noise).

Spatial Resolution and Precision

Measurements of surface roughness are also affected by the radius of the cantilever tip. Compared to other stylus probes used to measure roughness, the relatively small tip radius of an AFM cantilever enables it to image and measure roughness with nanoscale spatial resolution. Furthermore, the precision of the surface roughness measurement also relies on a non-changing tip profile. Quality in instrument design is essential here – specifically the AFM should be very responsive in its mechanical

Z-axis to prevent the tip from blunting, as is the case for the Asylum Research AFM's.

Additionally, small amplitudes can be used to minimize tip wear as shown in Figure 4. Imaging in this fashion prevents the tip from blunting, thereby preserving the spatial resolution of the measurement. This technique is easy to implement and standard on all Asylum Research AFM models.
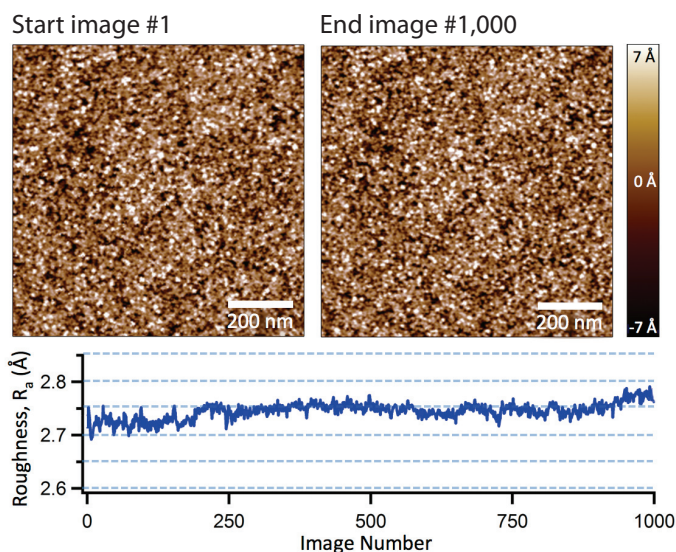

Figure 4: A magnetic hard disk was imaged for 1,000 consecutive images with small amplitudes to preserve the cantilever tip sharpness. There is no discernible tip wear – measured roughness stays relatively constant at an average of ~2.75Å through the entire sequence. The standard deviation is 0.015Å (<0.5% R$_a$).

References

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