

Lab Report 1 - Atomic Force Microscopy

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Abstract

In this work, we aim to better understand the mechanisms of Atomic Force Microscopy (AFM) and how they can be used to analyze samples at the nanometer scale. We examine the surface topography in both 2D and 3D for three samples and explore how the AFM operating conditions contribute to obtaining clear scans. More specifically, we analyze the surface roughness, structure, and feature dimensions of a given sample. All image analysis and correction were performed using Gwyddion software. Below is a comprehensive report of AFM procedure, instrument performance, and the image analysis acquired from Gwyddion.

1 Atomic Force Microscopy

1.1 Background

Atomic Force Microscopy (AFM) is one of many scanning probe techniques used to acquire precise, high-resolution images that can be used to evaluate various aspects of a given sample. The basic procedure of AFM involves the scanning probe moving in the x, y, and z directions, where the tip of the probe interacts with the sample surface; the interaction force detected between the tip and sample produce the final result imaged. AFM is capable of imaging objects across a wide range of length scales, from nanoscale features to micrometer-scale structures. Due to its high-resolution technique, it is primarily designed for small samples. The very largest scan range is on the order of $150\mu\text{m}$ by $150\mu\text{m}$ in the x and y directions and about $28\mu\text{m}$ in z. However, it is more typical for the sample to be of a size that allows for a maximum scan range of approximately $100\mu\text{m}$ by $100\mu\text{m}$ or less in x and y, with the z-range being less than $10\mu\text{m}$. As a result, AFM can image objects ranging from nanometer-scale particles and molecular features up to surface structures on the order of up to hundreds of micrometers, depending on the scan range of the instrument.

1.2 AFM Set-up

The main elements to the AFM include the chip, the laser, the photo-diode, the piezoelectric scanner, and the feedback mechanism. There are many other parts that incorporate the AFM such as the software used for scanning and imaging, the stage, motors, camera, and the various samples used. The chip, is the force transducer, which most notably includes the cantilever with a tip. The force between the probe and the surface is measured by the force transducer. Depending on the probe, the force transducer can measure forces as low as 10 piconewtons between the probe and sample surface. When the tip interacts with the sample surface, the cantilever deflects, and this deflection is what is ultimately measured to determine the topography and any other properties one hopes to measure. The measurements acquired by the scan vary based on the mode used. Most notable AFM applications are: EFM, PFM, KPFM, MFM, cAFM, and TFM. There are many other specialized modes that can be used with the correct parameters and probe.

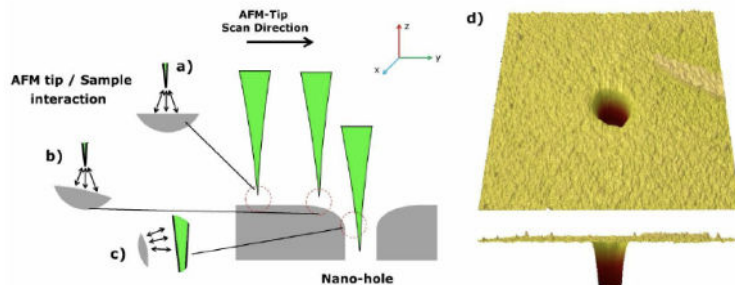


Figure 1: Tip-sample interaction

The laser and photo diode detection system work together to monitor the cantilever motion. The laser is reflected off the back of the cantilever and onto the photo diode; changes in the reflected position of the laser correspond to changes in cantilever deflection. This indicates changes in force between the tip and the sample. The signal that comes from the detection system is recorded and saved by a computer. The piezoelectric scanner is another major element of the AFM. Piezoelectric materials convert electrical potential into mechanical motion; this allows for very small and precise movements of the probe relative to the surface being scanned. These scanners are used to move the probe across the sample surface in the x-y directions. They also control the distance between the tip and sample in the z direction. The feedback mechanism is one of the most critical operations of the AFM. The feedback mechanism uses the signal from the force transducer and feeds it back to the piezoelectric scanner to maintain a fixed force between the tip and the sample. If the measured force between the tip and sample increases, the feedback system moves the probe away from the surface; conversely, if the force decreases, the probe is moved toward the surface. There are constant adjustments being made by the feedback loop such that the AFM maintains the interaction force at a set value (the set point) when scanning. The behavior of the feedback loop is highly impacted by integral gain, which corrects the cumulative error between the system and its target state (in this case the tip-sample force to the set point). There is also the proportional and derivative gain that play a role in determining how quickly and accurately the system responds to deviations from the set point. The feedback loop continuously compares the measured force signal to the desired value set and adjusts the z position in real time such that the tip to sample distance changes so as to compensate for the change. The set point is the value of force that the feedback system attempts to maintain between the tip and the sample during scanning. The set point is usually manually set by the user, but in some newer AFMs there are automated options. Depending on the mode you are imaging in, the set point corresponds to different feedback parameters.

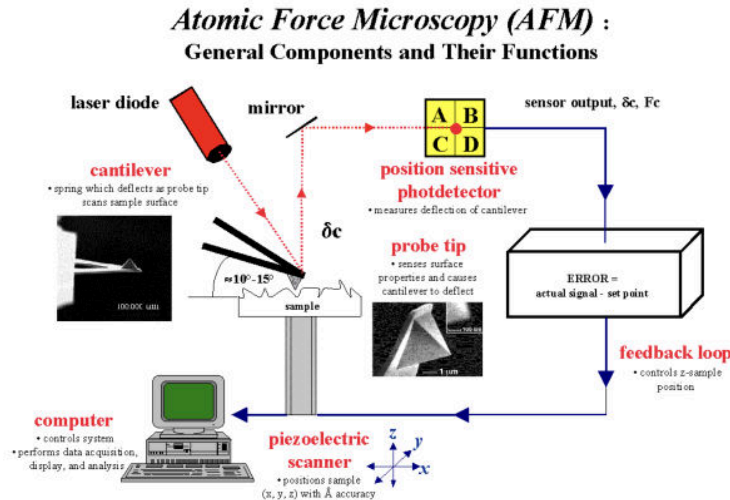


Figure 2: AFM Mechanisms

1.3 AFM Modes

The main modes of AFM operation are contact mode and tapping mode, also known as intermittent contact mode. Contact mode was the first mode developed for AFM. In contact mode, the tip of the probe remains in continuous contact with the sample surface while scanning. The feedback system maintains a constant deflection force on the cantilever; as mentioned earlier the feedback system keeps the cantilever deflection at a certain value determined by the set point. In tapping mode, the cantilever is driven to oscillate such that, while scanning, the probe moves through the “attractive and repulsive regimes” so that the tip is periodically in contact with the surface. The interaction with the surface causes changes in oscillation amplitude, which is used by the feedback system to generate the images seen on the software. There is additionally non-contact AFM (NCM) where the probe oscillates close to the surface within the attractive force regime but does not make physical contact with the sample. NCM is often used to locate the region of interest (ROI) on your sample before switching to another mode for data collection.

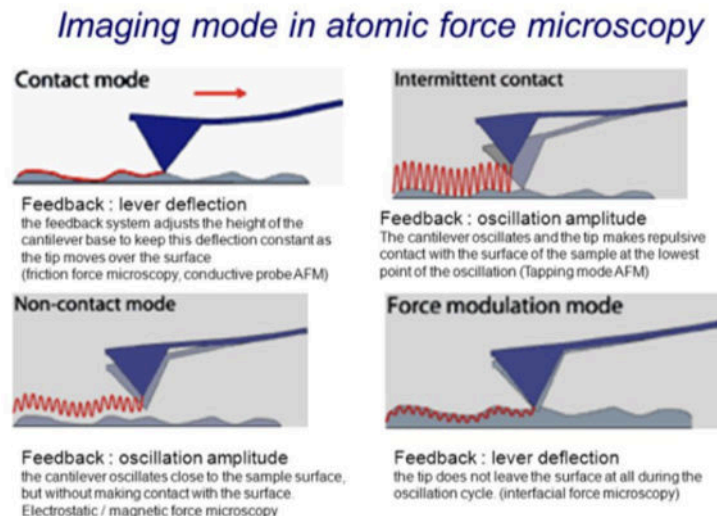


Figure 3: AFM Scanning modes

A major advantage of the AFM is that it requires little to none sample preparation and you can still acquire very clear and accurate images. Contrasty, SEM and TEM typically require vacuum conditions and conductive samples. Additionally, AFM can operate in “any” sample environment and it can image both conductive or insulating materials; the SEM and TEM generally require conductive samples. Another advantage is that AFM can provide 3 dimensional measurements as it has the ability to magnify in the X, Y and Z axes, as will be seen in this report. Further, the force the AFM applies during imaging is very small ($10 \times 10^{-9}\text{N}$ or less). This greatly reduces sample damage and increases the longevity of a sample. Lastly, but very importantly, the cost of an AFM is relatively very low in comparison to the others. Despite the lower cost, the AFM still provides highly accurate positioning of the probe and high sensitivity while imaging.

2 Methods

The data produced for this report was composed in three, two hour lab sessions over the course of three weeks. Each lab session a different sample was imaged, while the AFM procedure for data acquisition was kept almost identically the same. All AFM use was conducted on a Next II NT-MDT AFM Microscope and supervised by Dr. Sean O'Neill, Sean Lannon, and Professor Svetlana Lukishova.

2.1 Procedure

1. Turn Power on.
2. Log into Computer using URNano log in.
3. Open door.
4. Flip up head.
5. Replace probe if needed using camera to adjust as needed.
6. Stick sample to disc mount using double-sided carbon tape.
7. Place sample on stage.
8. Return head to proper position.
9. Use **Move** to increase stage height till sample is roughly a millimeter from the head
10. Close door.
11. **Aim** tab - **Scan** button, select visible area, drag over old region, **Scan**.
12. Manually adjust laser using X/Y (Laser value on aim tab must be less than 16).
13. **Aiming** button (check that LTF and LF values are close to zero).
14. **Resonance** tab - click **Auto** and check resonance value. Resonant frequency graph should resemble a Gaussian curve and the phase response graph should resemble a sigmoid curve.
15. Turn **Feedback** on and set to 0.7 for now.
16. Set **Set Point** to 50-60% of Magnitude.
17. **Approach** tab - click **Landing**, adjust gain as needed (no less than 0.1).

18. To find ROI, click **Remove** 2-3 times (varies based on sample flatness) and then use X/Y on camera.
19. Once ROI is located, perform **Landing** again and adjust gain as needed.
20. Go to **Scan** tab - **Area** button, change size and rate as needed.
21. Select **Run** - adjust order as needed (the lower the order the better).
22. Once scan complete go to **Data** tab to save and analyze data.

The size and rate of the image vary based on both the scanning region, material of sample, and time available for scanning. Problems with the landing and gain resulted in scanning problems that will be described later in the report.

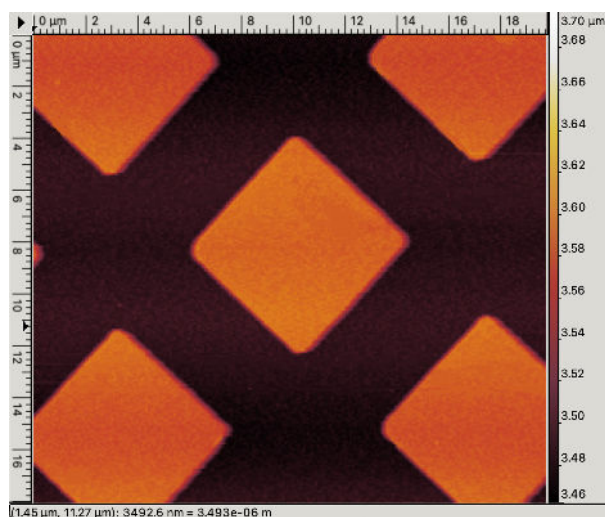
3 Results

The images and analysis below are the results of three different samples with differing nanoscale features and various configurations. Images were processed, corrected, and analyzed by Iliana Balaskas using Gwyddion software on a computer running macOS.

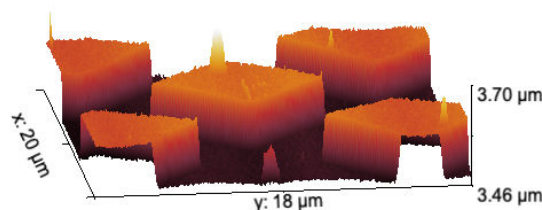
3.1 Nanosurface Testing Grid

The first week of lab was spent imaging a sample containing various nanostructures including: square pillars, circular pillars, circular holes, and diagonal grating structures. Due to time limits and poor image quality, only a portion of the possible structures are featured in this report.

All images were initially edited by applying a Plane Level and a background correction via **Data Process** → **Correct Data** → **Align Rows...** → Median of differences. Then using the **Mask** feature, minimal adjustments were made to edit feedback instability, contamination, and tip artifact. It is important to weight the quality/clarity of the image to the possibility of over-correction that can effect data analysis.

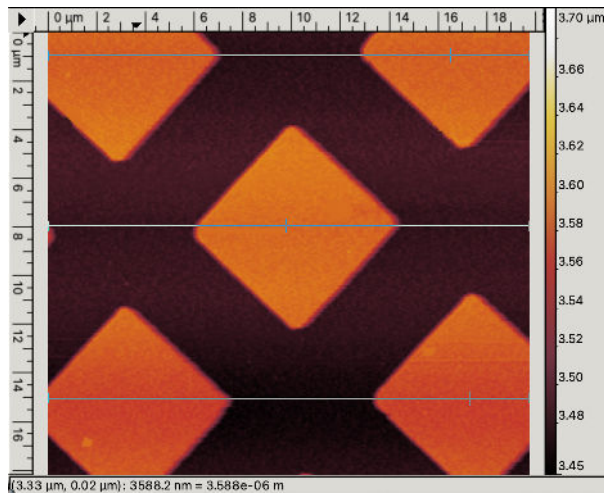


(a) 2D square pillar topology

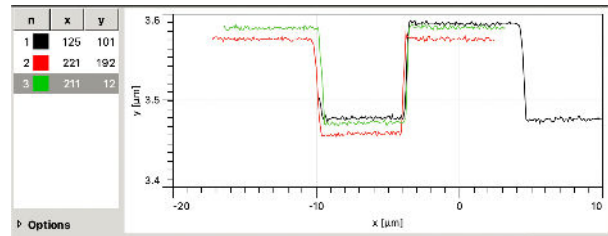


(b) 3D image of square pillars

Figure 4: Topology of square pillars in 2D and 3D.

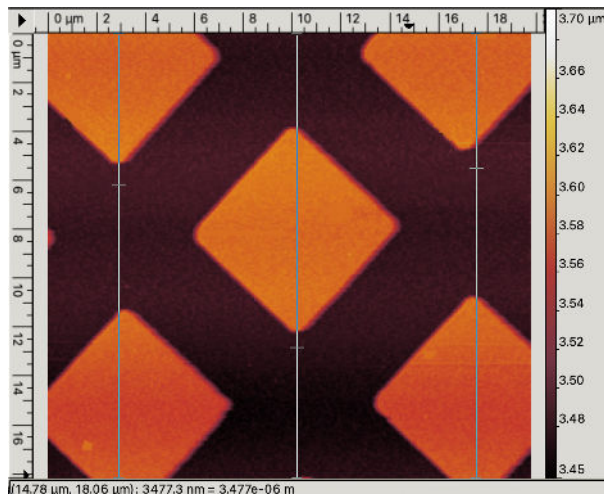


(a) Horizontal Profile

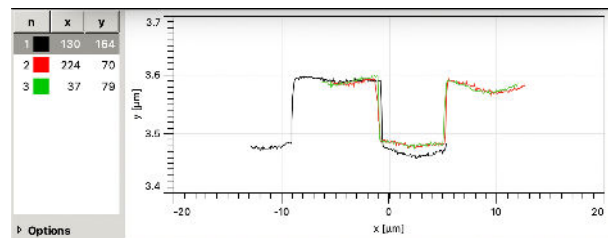


(b) Graph of Horizontal Profile

Figure 5: Horizontal profile and corresponding graph for square pillars.



(a) Vertical Profile



(b) Graph of Vertical Profile

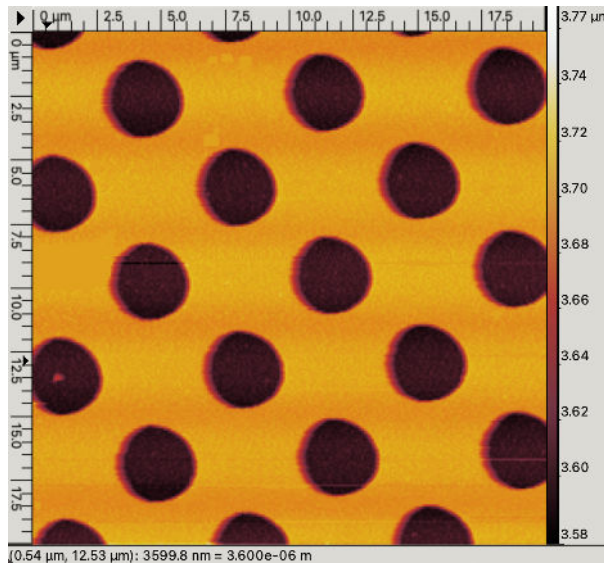
Figure 6: Vertical profile and corresponding graph for square pillars.

The first scan was of a 20μm x 20μm region of square pillars. The image has been cropped to 20μm x 18μm using Gwyddion to remove feedback instability at the start of the scan. Heights of the background and pillars were obtained using **Profile Along Axes**. Both horizontal and vertical profiles were conducted at multiple places with a line thickness of 5 pixels to acquire accurate measurements. The horizontal profile revealed a height of ~0.120μm; from the vertical profile we find a height of ~0.135μm. Differences in these heights can be due to a number of factors from tilt of the scan to the line selected for the profile. These numbers match the 3D graph configured in Gwyddion.

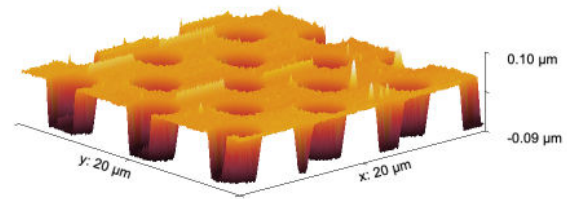
The roughness of the image was determined in Gwyddion via **Calculate Roughness Parameters** and selecting a region of the pillars and background. The roughness average

(R_a) and the root mean square roughness (RMS) were then found for each given region. It was found for the pillars that $R_a = 1.668 \text{ nm}$ and $\text{RMS} = 2.254 \text{ nm}$. For the background, we found $R_a = 2.044 \text{ nm}$ and $\text{RMS} = 3.113 \text{ nm}$. As expected, there is a change in roughness between the pillars and background.

The same procedure was repeated for other nanostructures on the sample. Next we analyze circular holes.

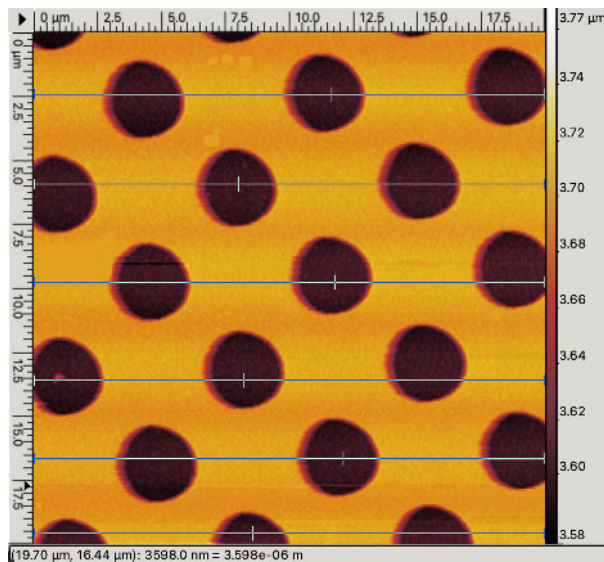


(a) 2D circular holes topology

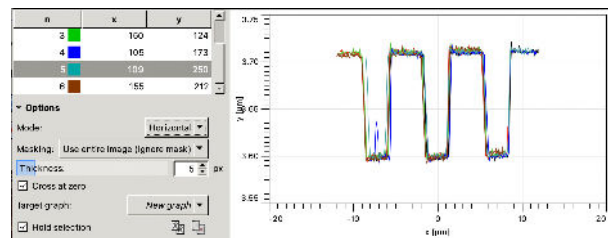


(b) 3D image of circular holes

Figure 7: Topology of circular holes in 2D and 3D.

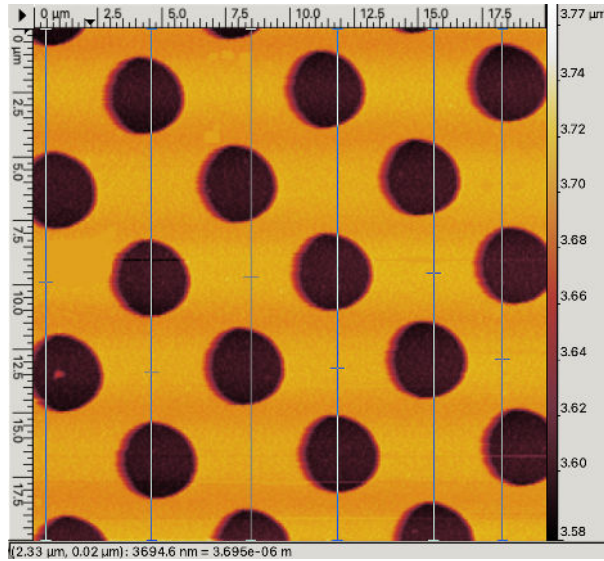


(a) Horizontal Profile

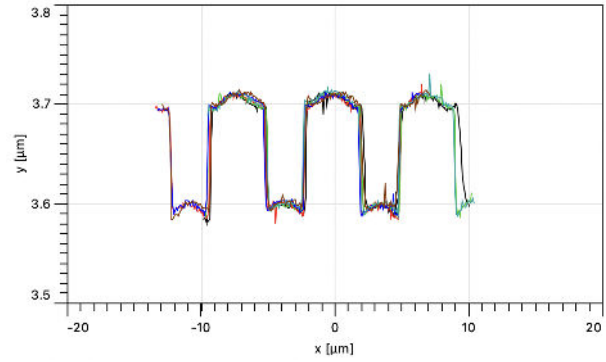


(b) Graph of Horizontal Profile

Figure 8: Horizontal profile and corresponding graph for circular holes.



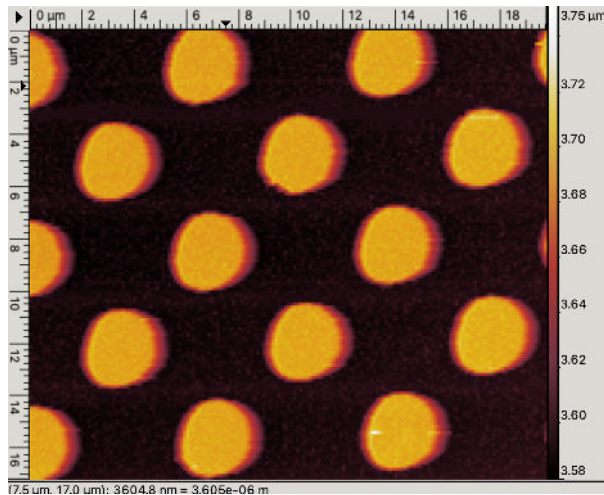
(a) Vertical Profile



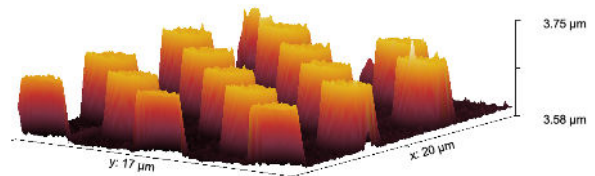
(b) Graph of Vertical Profile

Figure 9: Vertical profile and corresponding graph for circular holes.

The circular holes were imaged as a 20μm x 20μm scan; there was no feedback issue in this scan and as a result no cropping was needed. The holes were found to have a vertical depth of $\sim 0.120\mu\text{m}$ and horizontal depth of $\sim 0.113\mu\text{m}$. The roughness of the holes was found as $R_a = 2.104\text{ nm}$ and $\text{RMS} = 2.223\text{ nm}$. For the background, we found $R_a = 2.441\text{ nm}$ and $\text{RMS} = 2.563\text{ nm}$. Next circular pillars were imaged and analyzed using the same process.

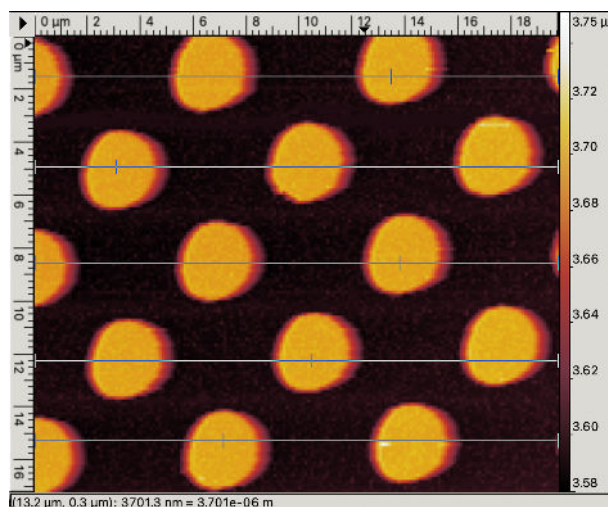


(a) 2D circular holes pillars

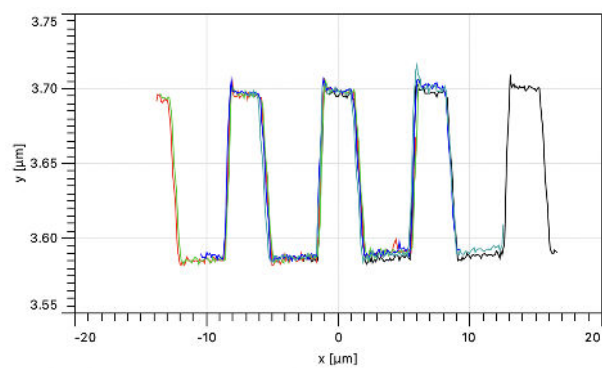


(b) 3D image of circular pillars

Figure 10: Topology of circular pillars in 2D and 3D.

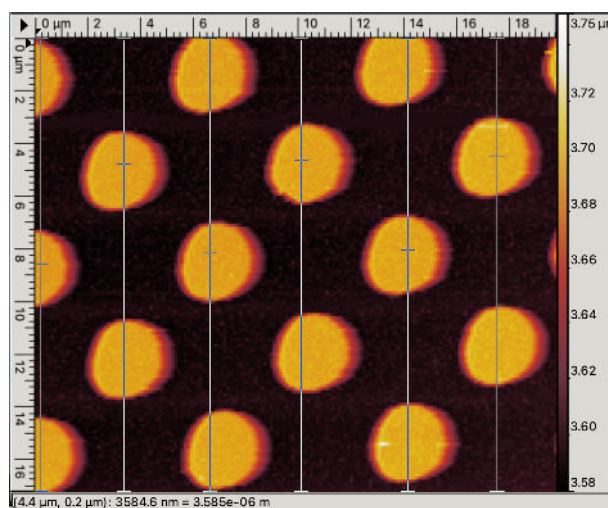


(a) Horizontal Profile

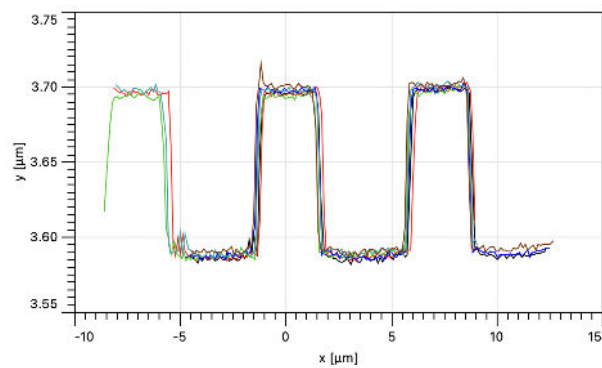


(b) Graph of Horizontal Profile

Figure 11: Horizontal profile and corresponding graph for circular pillars.

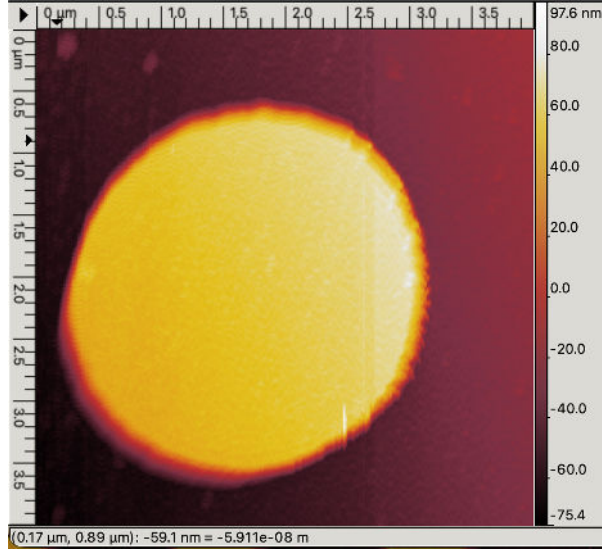


(a) Vertical Profile

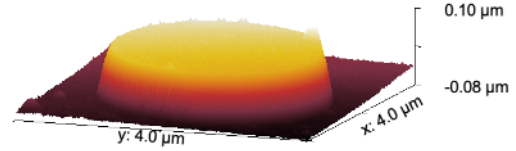


(b) Graph of Vertical Profile

Figure 12: Vertical profile and corresponding graph for circular pillars.



(a) 2D circular pillar topology



(b) 3D image of circular pillar

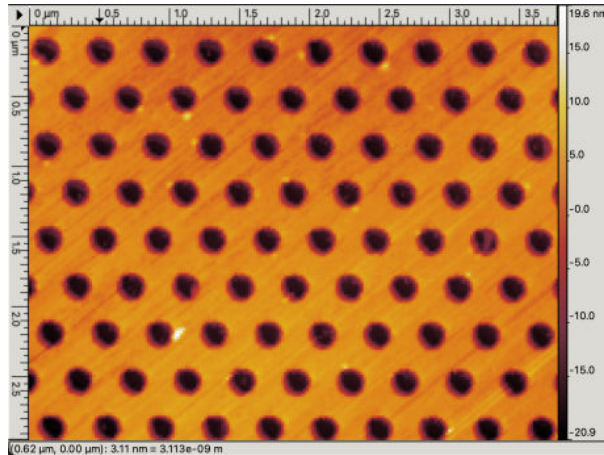
Figure 13: Topology of one circular pillar in 2D and 3D.

The circular pillars were initially a 20μm×20μm scan cropped to 17μm×20μm. The pillars were found to have a vertical height of $\sim 0.115\mu\text{m}$ and horizontal height of $\sim 0.121\mu\text{m}$. The roughness of this region was found using the image of a singular pillar. A 4μm×4μm image of one pillar was taken. Roughness of the pillar was found as $R_a = 2.806\text{ nm}$ and $\text{RMS} = 3.227\text{ nm}$. For the background, we found $R_a = 1.734\text{ nm}$ and $\text{RMS} = 2.189\text{ nm}$.

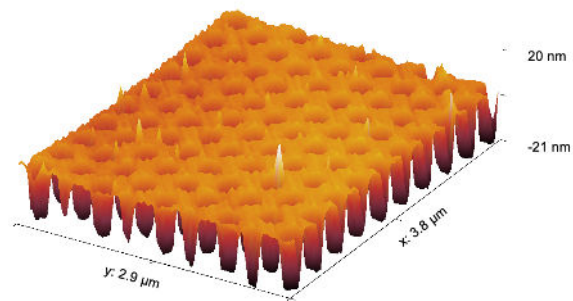
3.2 Silicon Photonic Band Gap Structure

The second week of lab was spent imaging a sample containing a nanophotonic bandgap structure. The structure was composed of circular holes. Due to time limits and poor image quality, only one set of viable images was taken for processing.

As with the first samples images, all scans from Lab 2 were analyzed in Gwyddion using the same process as the Lab 1 scans. The initial scan of the circular holes was a $5\mu\text{m} \times 5\mu\text{m}$ that was cropped to $2.9\mu\text{m} \times 3.8\mu\text{m}$ due to feedback instability in the image.

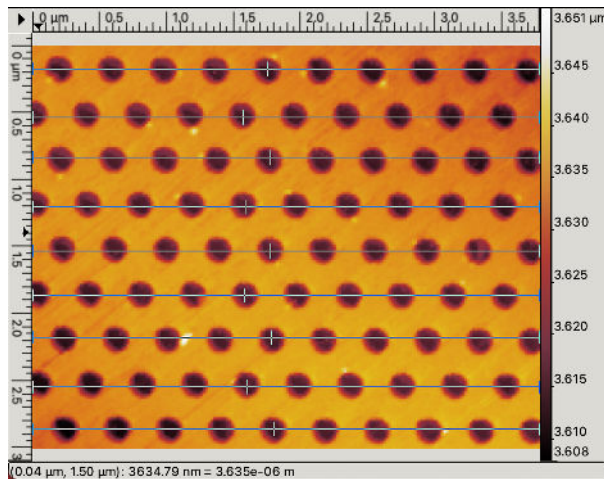


(a) 2D square pillar topology

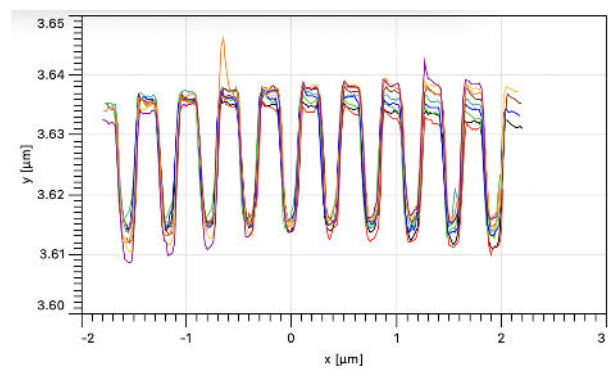


(b) 3D image of square pillars

Figure 14: Topology of square pillars in 2D and 3D.



(a) Horizontal Profile



(b) Graph of Horizontal Profile

Figure 15: Horizontal profile and corresponding graph for square pillars.

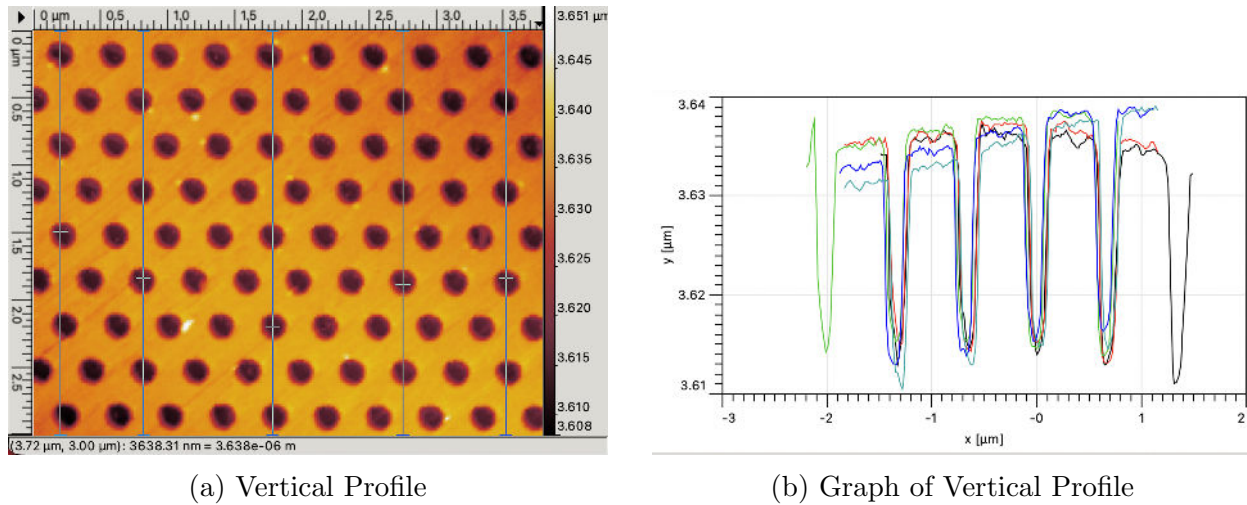
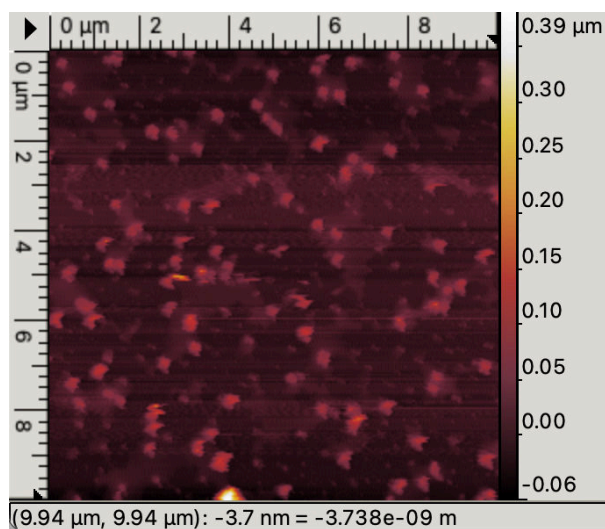


Figure 16: Vertical profile and corresponding graph for square pillars.

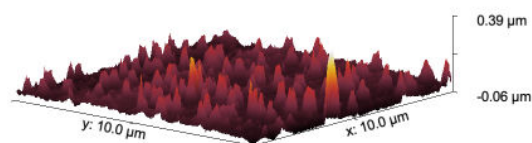
The holes were found to have a vertical depth of $\sim 0.028 \mu\text{m}$ and horizontal depth of $\sim 0.025 \mu\text{m}$. The roughness of the holes was found as $R_a = 2.003 \text{ nm}$ and $\text{RMS} = 2.379 \text{ nm}$. For the background, we found $R_a = 2.328 \text{ nm}$ and $\text{RMS} = 2.715 \text{ nm}$.

3.3 Silver Nanocubes

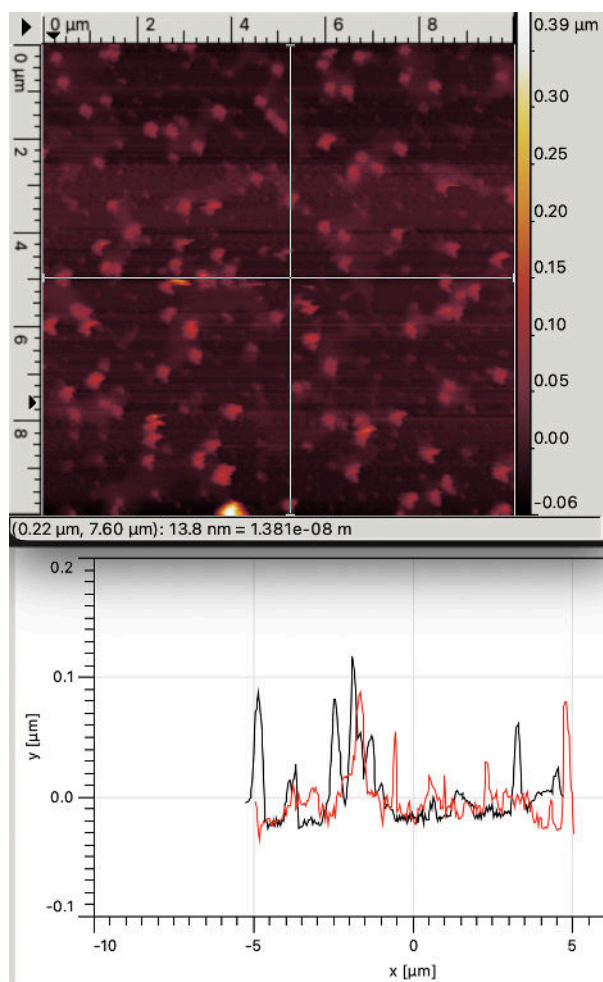
The final week of lab was spent imaging silver nanocubes that contained a protective polymer layer. Imaging of the clusters of nanocubes was found to be very difficult due to equipment issues. With a scan size too large, the nanocubes were not easily visible. With a small scan size, clarity and visibility decreased. A higher gain of 0.521 was used to image the nanocubes as a faster feedback response allows for more quality results with such a structure. The issue arises when the gain is too might too develop a high quality image, and instead, noisy, feedback oscillation arise, as we will see.



(a) 2D topography of nanocubes



(b) 3D image of nanocubes



(c) Horizontal and vertical profile of nanocubes

Figure 17: Topology and profile analysis of nanocubes in 2D and 3D.

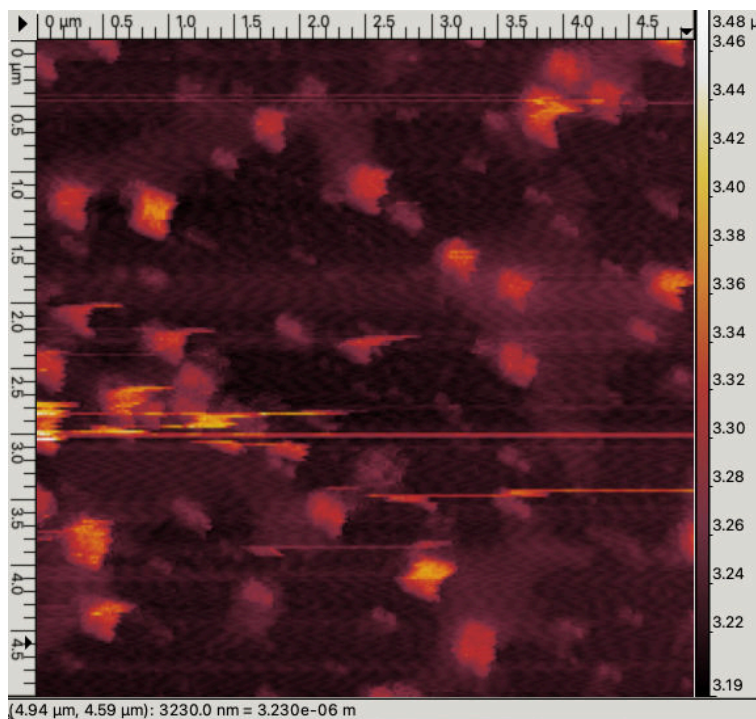
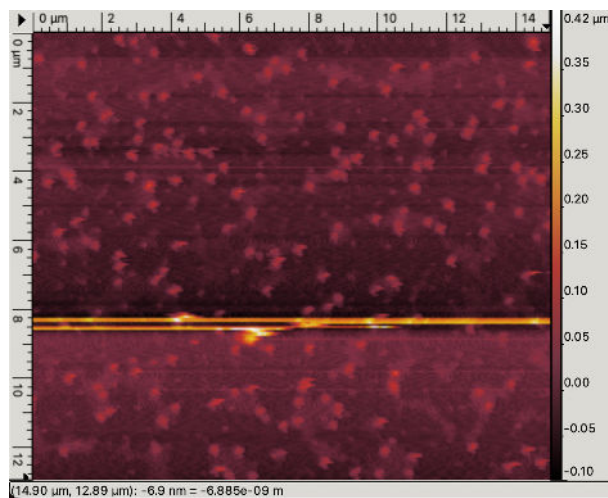
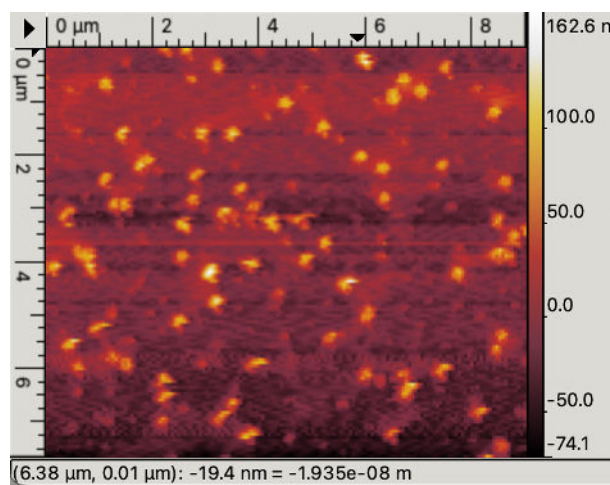


Figure 18: Cluster of nanocubes



(a) Before cropping noise



(b) After cropping noise

Figure 19: Change in color scale by cropping out noise.

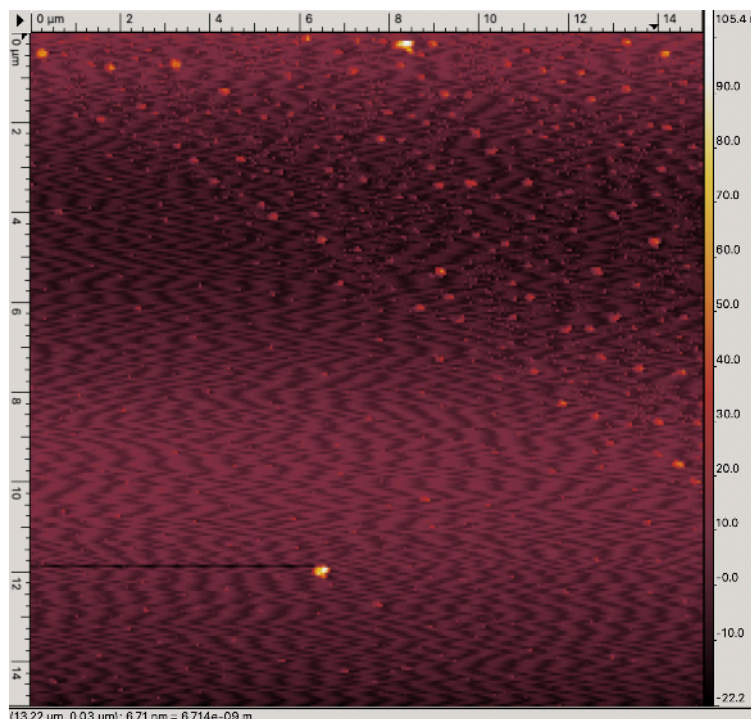


Figure 20: Visible oscillations due to noisy feedback from high gain.

The nanocubes were found to be difficult to image. The AFM does not respond well to high gain, likely due to its old age. As a result, problems arise as one tries to image the clusters. A height profile is difficult to determine but taking the raw data into excel, it is found that we can very roughly estimate a cube height of 0.13μm. Noise makes it difficult to be accurate, but this is close enough to what we expect from the sample. As seen in Figure 17, the oscillations on the image are not actually on the sample, but instead a result of feedback noise from the AFM. The images can be improved using simpler techniques to Labs 1 and 2. In addition, cropping large regions of noise can also help improve the quality of the image.

4 Discussion

The data analysis above follows our previous understanding of AFM. As seen, we can use the 2D topological images, along with their 3D configurations, to determine many aspects of the structures. While a lot of useful analysis was discovered, we can also observe the distortions that arise due to instrument limitations. As previously mentioned, some of the features observed in the images are not actually a part of the sample, but instead are artifacts, blurs, distortions, and oscillation created from effects of the feedback, gain, and environment. In many of the images, the gain could not be set to a high value due to distortion of the signal during landing when it was raised to high. A low gain can cause the tip to "lag" on the sample, resulting in some of the distortion or "drag" seen in the scans. While we also see in Lab 3, that with a high gain we can get a different problem; high gain can cause feedback noise that results in oscillations in the scan. The sensitivity of the probe means that these changes in the gain can have a large effect of the results produced. It could even be seen during scanning that raising ones voice or hitting the table has an impact in the outcome of the scan. This simply shows that the AFM is sensitive tool that requires the correct parameters to properly scan a region with complete clarity.

5 Conclusion

Atomic Force Microscopy is an innovative approach to scanning features of structures on the nanoscale. With proper understanding of the AFM mechanisms and procedure, very accurate and useful scans can be produced. This report demonstrates how basic parameterization can be implemented to acquire clear, high-resolution topological scans that can be analyzed and edited. To further improve results, consider the preparation of the sample, scanning environment, probe selection, and scanning time. All these parameters play a large role in one's success to well curated images.

References

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