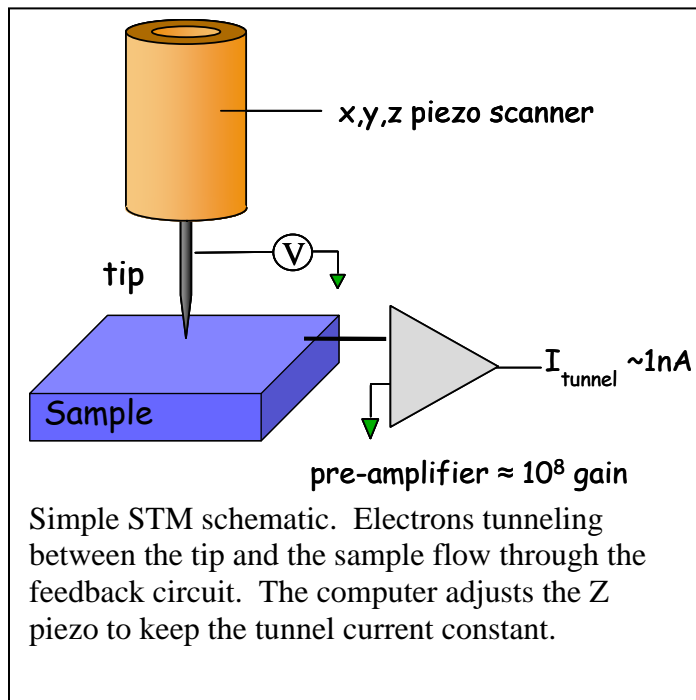


Atomic Resolution with Scanning Tunneling Microscopy

Andrew Parella, Monica Plisch

Introduction

One of the triumphs of the scanning tunneling microscope (STM) is the ability directly image atomic structure. The precise mechanical control allowed by piezo electrics and exponential dependence of the tunneling phenomenon on distance make atomic resolution with STMs commonplace in modern laboratories. In this lab the goal will be to obtain an atomic-resolution image of a graphite surface, filter it to remove noise, and determine the closest distance between two neighboring carbon atoms.



Electrons are allowed to be in either the STM tip or the sample. The space between the two is a barrier. However, if the distance between the two is small enough, electrons will tunnel from one to the other (see Appendix A). If no voltage applied between the tip and the sample, electrons will tunnel back and forth with equal probability and no net current will flow. However if a voltage is applied, electrons will prefer to tunnel from the lower voltage to the higher one. This flow of electrons is the tunnel current and is exponentially sensitive to the distance between the tip and the sample.

In normal operation, the STM maintains a constant tunnel current, and thus a constant distance between the tip and the sample, as the tip scans back and forth. If the tip scans across the surface and encounters a high point, the computer will send a signal to the scan head to retract the tip in order to keep the tunnel current constant.

The STM scan head is based on piezoelectric ceramics, which can be precisely compressed or stretched on the nanoscale by applying modest voltages to the material. Separate voltage signals control the X, Y, and Z motion of the tip. The topographic image in the STM software is a recording of the change in Z voltage required to keep the tunnel current constant as a function of X and Y.

Procedure

Obtaining Atomic Resolution Images

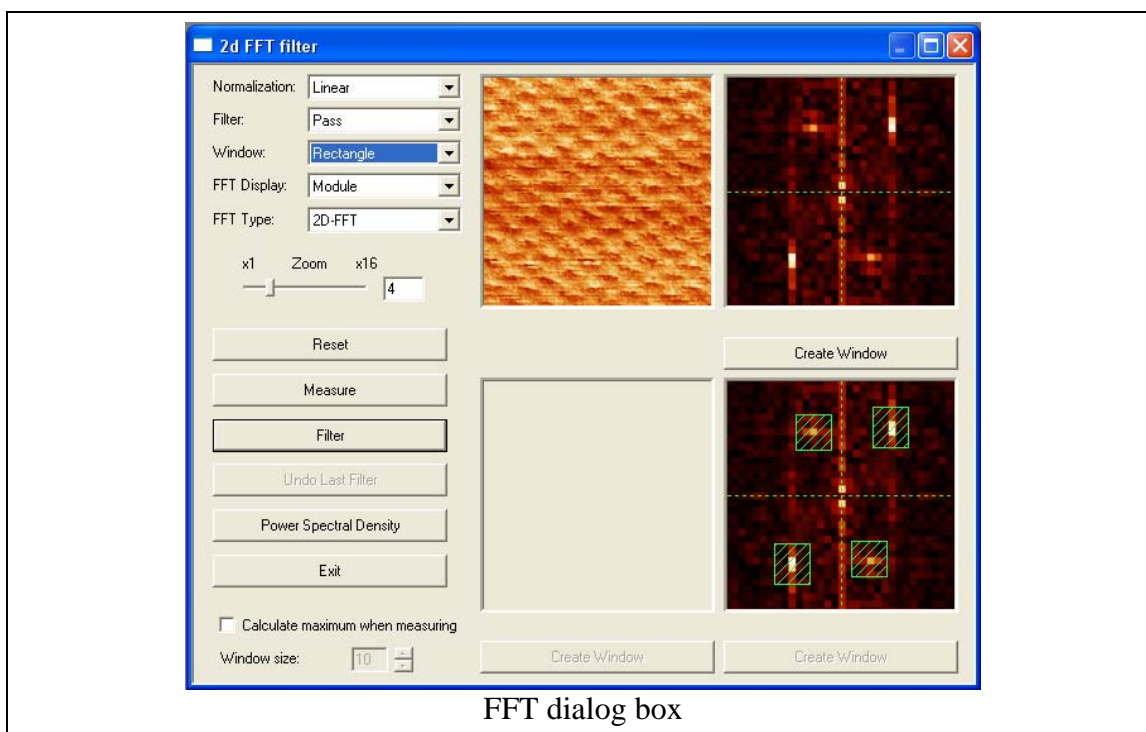
Follow the instructions in the *Nanosurf STM system* manual for obtaining atomic resolution images of graphite (pg. 17). It may take some time to obtain a high quality, defect free image. Even if the tip is sharp and the area is flat, thermal and electrical drift may take some time to fade away. Page 28 of the manual shows some examples of other kinds of experimental artifacts you may encounter. Work on obtaining as clear an image as you can.

Optimize the “I-gain” and “P-gain” values to get as clear an image as possible. These values control error correction in the feedback loop maintaining constant current. A useful strategy is to increase one parameter slowly and watch for spikes to occur in the linescan, indicating that unwanted oscillations are occurring in the feedback loop. Then back off one or two steps until the linescan becomes smooth again. This will be the optimum value.

When you get images that you are satisfied with, capture two subsequent images, one scanning down and the other scanning up the screen to check for drift. Save both images (see instructions on p. 27).

Filtering Noise from Images

The typical STM image has artifacts such as random noise and scan lines. These artifacts can be removed so the real data is more easily seen and measured. Begin by opening the program WsXM. Open one of the graphite images that you saved. You may need to



change the 'file type' menu to "all files" in order to see the *.ezd file which contains your data.

Press the Fast Fourier Transform (FFT) button to activate the FFT dialog box. See Appendix B for a slightly more detailed explanation of Fourier transforms. When the dialog box opens, press "filter." You may have to change the Zoom in order to see the features of the FT of your image.

The bright points in the upper right hand FT image indicate that there are features in the real image that occur with a specific period. To remove every other signal and keep only the signals with the frequency represented by the bright points, press the "Filter" button. Select the frequencies you want to keep by holding the left mouse button over the center of the bright spot and dragging a small box around it. Do this with any signal that appears in the image. Then activate the filter by right clicking anywhere on the FT. You should see a new image appear where the atomic lattice has greater clarity than your raw data. This processed image can now be more easily analyzed.

Line profiles are commonly used analysis tools in topographic measurements. These profiles produce plots of height vs. distance along a section of the image. To get to the line profile tool, select "profile" from the "process menu." This will allow you to draw a line across the image. As you draw the line, a plot should form. You can use this to accurately measure the distance between atoms as well as observe the apparent height of each carbon atom. Use the line profile tool to measure the atomic spacing along different directions.

Analysis and Discussion

1. Typically, most samples must be imaged in vacuum with the STM. Why? What properties of graphite allow us to image it in air?
2. For scanning a sample, the STM needs to position the tip less than 1 nm from the sample. Explain how the nanoSurf STM decreases the tip-sample distance from ~1 mm down to <1 nm without crashing the tip.
3. Explain the concept of constant current imaging. What does it mean if two regions of your image are the same brightness?
4. Name and explain at least three factors that are essential for achieving atomic resolution with this STM.
5. Attach the two subsequent images of graphite that you acquired (raw data, not filtered). Report any evidence of drift. Describe any steps that you can take to minimize the effect of drift on the accuracy of your atomic measurements.
6. Attach at least one filtered image to your report. What is the purpose of filtering an image?
7. Draw a hexagon on one of your images that shows the location of an individual hexagonal ring of carbon atoms. (Hint: see p. 33 in the STM manual for help with interpretation of your graphite image.)
8. Using your best filtered image and the WsXM software, determine the distance between a carbon atom and its nearest neighbor. How does it compare with the accepted value of 0.14 nm?

APPENDIX A
Brief Introduction to Quantum Mechanical Tunneling

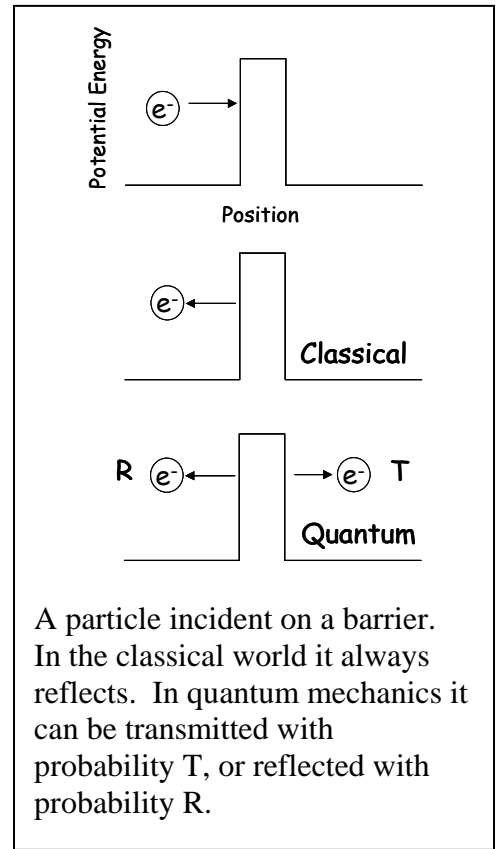
The scanning tunneling microscope (STM) is based on a quantum mechanical phenomenon known as tunneling. In tunneling, a particle, in this case an electron, can jump from one location to another without spending any time in between. An example of tunneling can be seen in the figure to the right. If a particle is incident upon a barrier in the familiar macroscopic world it will always reflect from the barrier. In other words, its probability of reflecting from the barrier R is $R=1$. In the microscopic world of quantum mechanics, that same particle will not necessarily reflect; rather, it has some probability T of tunneling through the barrier. The probability of reflecting from the barrier R is less than one. R and T are related by:

$$R+T = 1$$

The probability of transmission, or tunneling, is

$$T \propto e^{-\beta w}$$

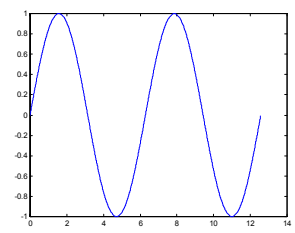
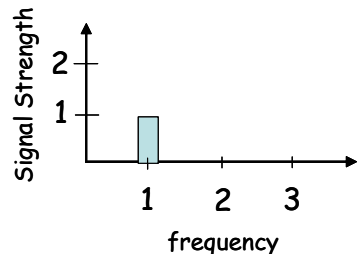
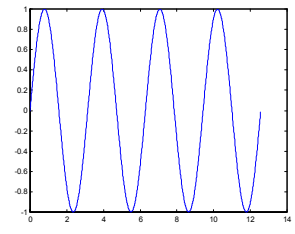
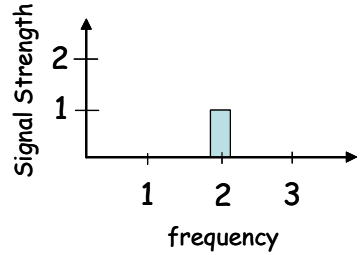
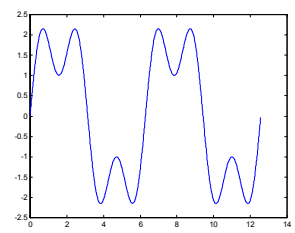
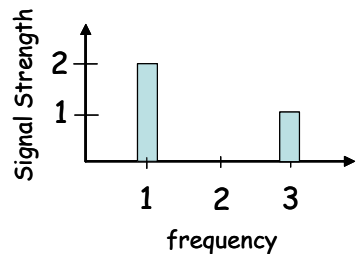
Where β is a constant that depends on the energy of the particle and the barrier, and w is the width of the barrier. This exponential dependence on distance is what makes the STM such a sensitive instrument for exploring surfaces.



APPENDIX B

Brief Introduction to Fourier Transforms

This is a basic conceptual introduction to the fourier transform (FT), which can be useful in understanding the FFT data processing step for removing noise from images. The idea behind the FT is that any signal can be written as the sum of sine waves, with each frequency sine wave having its own amplitude. The FT signal is the amplitude corresponding to each frequency. For example:

Signal	Plot of signal	Fourier Transform
$y = \sin(x)$		
$y = \sin(2x)$		
$y = \sin(3x) + 2\sin(x)$		

In WsXM, the software goes through the image and breaks it into sine waves (in the case of a spatial image the ‘frequency’ has units of 1/length) and maps the amplitude of each sine component. Since the image is two dimensional, the FT is also two dimensional. Features with regular spacing will appear much brighter than those without regular spacing. You can choose to keep only those signals with a specific frequency by selecting them on the FT. Since graphite has a regular structure that repeats spatially, this is a good strategy. Such frequency filtering tends to remove noise, which appears at all frequencies.

Additional information on Fourier transforms

<http://www.med.harvard.edu/JPNM/physics/didactics/improc/intro/fourier1.html>

<http://www.cs.unm.edu/~brayer/vision/fourier.html>

<http://online.redwoods.cc.ca.us/instruct/darnold/laproj/Fall98/KrisCrg/Fourier.pdf>

APPENDIX C
Answer Key

- 1. Typically, most samples must be imaged in vacuum with the STM. Why? What properties of graphite allow us to image it in air?** Most surfaces will contaminate very quickly in air and form a non-conducting surface layer (e.g. oxidize) that will prevent tunneling. Graphite is very stable and will not oxidize due to the planar nature of the carbon-carbon bonds, so that when the sample is cleaved there are no “dangling bonds” at the surface that are highly reactive.
- 2. For scanning a sample, the STM needs to position the tip less than 1 nm from the sample. Explain how the nanoSurf STM decreases the tip-sample distance from ~1 mm down to <1 nm without crashing the tip.** The STM uses a combination of an inertial stepper motor and a piezo to bring the tip within tunneling range without crashing. First the piezo extends the tip towards the surface while testing for a significant tunneling current. If the piezo reaches its maximum extent without the tip getting within tunneling range of the surface, it retracts the tip. Next, the inertial stepper moves the sample one step closer to the tip. Then the piezo extends the tip once again. The cycle repeats until the tip reaches tunneling range.
- 3. Explain the concept of constant current imaging. What does it mean if two regions of your image are the same brightness?** Constant current imaging means that the position of the tip is adjusted closer or farther from the surface of the sample so that a constant tunneling current is maintained as the tip is scanned across the surface. If two regions of an image are the same brightness, the probability of finding an electron at each location is the same.
- 4. Name and explain at least three factors that are essential for achieving atomic resolution with this STM.** Some factors essential for achieving atomic resolution include: (1) an atomically sharp tip, formed by cleaving PtIr wire, (2) a three-dimensional piezoelectric positioning system capable of moving the tip with subatomic precision, (3) good mechanical stability, achieved by a short mechanical path from tip to sample and a vibration damping platform (granite block on rubber-like viton feet), and (4) a low-noise current amplifier that can magnify the ~1 nA tunneling current and allow monitoring.
- 5. Attach the two subsequent images of graphite that you acquired (raw data, not filtered). Report any evidence of drift. Describe any steps that you can take to minimize the effect of drift on the accuracy of your atomic measurements.** If the regular features of the two images do not look the same (e.g. in one scan the atoms appear compressed while in the other the atoms appear stretched out), there was drift during the imaging. Since the scan lines are horizontal, in general horizontal measurements will be less affected by drift (each scan takes only ~0.1 s to complete in which time the drift is minimal). Also, averaging measurements taken in several directions on both images can help minimize the effects of drift.

- 6. Attach at least one filtered image to your report. What is the purpose of filtering an image?** Filtering is used to remove noise. Since graphite has a regular, periodic structure and noise is typically not periodic, the FFT filtering technique is used to keep the periodic signals and reject the aperiodic signals (noise).

- 7. Draw a hexagon on one of your images that shows the location of an individual hexagonal ring of carbon atoms. (Hint: see p. 33 in the STM manual for help with interpretation of your graphite image.)** Even though the hexagonal rings of carbon atoms lie all in the same plane, some of the atoms appear higher in the STM image due their location relative to the underlying sheet of carbon atoms. Therefore, each hexagonal ring contains three “bright” atoms and three “dull” atoms in images where brightness corresponds to topography. The center of each hexagonal ring occurs in the darkest regions of the image. See the explanation in the STM manual for more information.

- 8. Using your best filtered image and the WsXM software, determine the distance between a carbon atom and its nearest neighbor. How does it compare with the accepted value (0.14 nm)?** One of the easiest lengths to measure on an image is the distance between the “bright” atoms, which show as clearly defined peaks. Bright atoms are not nearest neighbors; rather they are second-nearest neighbors. Using the geometry of the hexagon, if nearest neighbors are 0.14 nm apart, then second-nearest neighbors must be 0.25 nm apart. It is best to average distances in different directions and different images if possible as discussed in question 5.