Lesson 4:
Tools of the Nanosciences

Student Materials

Contents

Name_________________________________ Date_____________________ Period ______

Black Box Lab Activity: Student Instructions and Worksheet

Purpose

To use different probes to determine the layout of objects on the bottom surface of a closed box, and to consider the limitations and challenges in using probes to "see."

Materials

- One black box
- One pencil and magnet probe
- One cotton swab probe
- One skewer probe

Instructions

1. Obtain from your teacher a box, pencil and magnet probe, a cotton swab probe, and a barbecue skewer probe.

2. Place the pencil and magnet probe into the center hole, and determine as best you can what the surface of the bottom of the box looks like. Draw your best guess below.

3. Replace the pencil and magnet probe with the cotton swab probe, using the swab end as the probe. Is there any additional information you are able to conclude about the surface of the bottom of the box? Draw your best guess below.

4. Replace the cotton swab probe with the barbecue skewer probe, using the pointed end of the skewer as the probe. Is there any additional information you are able to conclude about the surface of the bottom of the box? Draw your best guess below.

Questions

1. Describe the technique you used to investigate the surface of the bottom of the box.

2. What kinds of information about the bottom surface were you able to deduce?

3. How accurate do you think your drawing is?

4. What could you do to get a better idea of what the bottom surface looks like, besides opening the box?

5. What if a ping-pong ball was attached to the probing end of the skewer? How might this have affected your interpretations?

6. What difficulties did you encounter in using this probing technique to “see” the unknown? Or what challenges could there be in using such a technique?

Seeing and Building Small Things: Student Reading

How Do You See and Build Things That Are So Small?

Although **Richard Feynman** launched the idea of **nanotechnology** way back in his 1958 speech, it wasn't until decades later that we were actually able to create things at the **nanoscale**. Why did it take so long? Because we didn't have the right tools until then. We had lots of tools to make small devices, but these tools didn't operate at a small enough scale—until now!

Scanning Probe Instruments

In recent years, new tools have been developed that make it easier for scientists to measure and manipulate atoms and molecules. Some of the first tools were scanning probe instruments, developed in the early 1980s. The idea behind these instruments is simple: If you close your eyes and slide the tip of your finger across a surface, you can tell tree bark from satin from peanut butter. The tip of your finger acts like a probe that measures the force that it takes to move across the surface. It's easier to slide your finger across satin than across peanut butter because the peanut butter exerts a drag force that pulls the finger back. You can even rearrange the peanut butter by dragging it this way.

Scanning probe instruments are like your finger, but reduced to the nanoscale. They have probes that slide across surfaces and measure properties like force—but the very tip of such probes are often only a single atom in size! With this tiny tip, these instruments can "feel" the force of one atom on the surface and from that, be able to tell what kind of atom it is. They can even be used to move atoms around and arrange them in a preferred order, just as you can move peanut butter with your finger.

What Are Some Types of Scanning Probe Instruments?

One type of scanning probe instrument is the atomic force microscope (AFM). The AFM uses a tiny tip that moves in response to the **electromagnetic forces** between the atoms of the surface and the tip. Tips are usually made of silicon, though sometimes carbon nanotubes are used for the tip. As the tip is scanned across a surface, the AFM measures the tiny upward and downward deflections of the tip necessary to remain in close contact with the surface. Alternately, the tip can be made to vibrate and intermittently "tap" the surface. In this case, the AFM senses when the tip (briefly) contacts the surface and uses this information to generate a topographical images.

Another type of scanning probe instrument is the scanning tunneling microscope (STM). With this instrument, the "tunneling" of electrons between the tip and the atoms of the surface being viewed creates a flow of electrons (a current). Tungsten is often used for STM tips because it is strong, electrically conductive, and easy to electro-chemically etch to a fine point. Carbon nanotubes may also prove to be suitable for use as STM tips, given their remarkable electrical and mechanical properties.

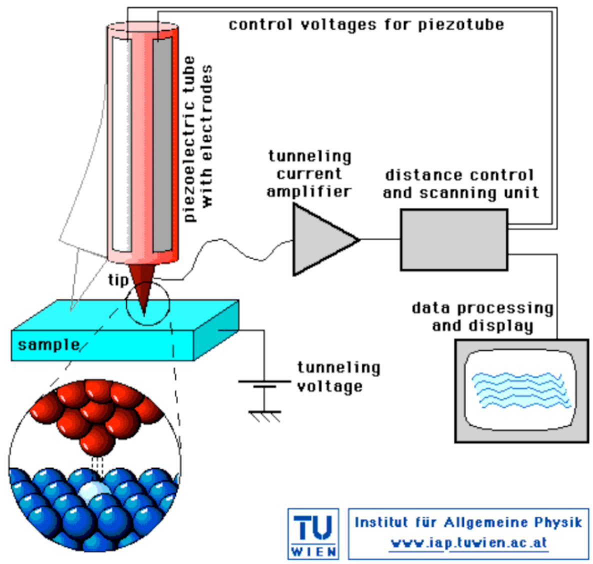


Figure 1. Scanning tunneling microscope (STM) [1].

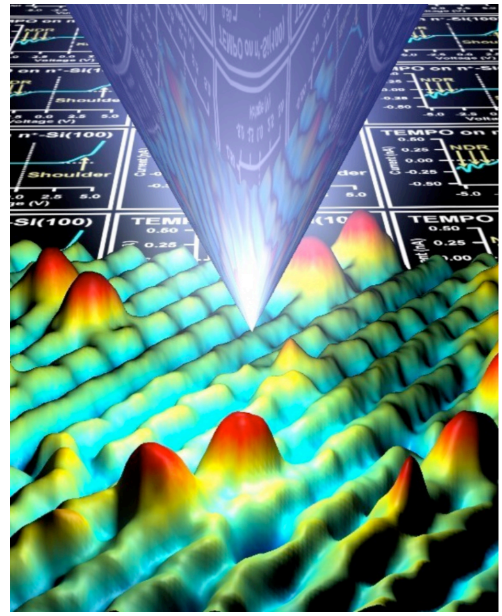


Figure 2. Tip of a scanning probe instrument [2].

The AFM was invented to overcome the STM's basic drawback: it can only be used to sense the nature of materials that conduct electricity, since it relies on the creation of a current between the tip and the surface. The AFM relies on actual contact rather than current flow, so it can be used to probe almost any type of material, including **polymers**, glass, and biological samples.

The signals (forces or currents) from these instruments are used to infer an image of the atoms. The tip's fluctuations are recorded and fed into computer models that generate images based on the data. These images give us a rough picture of the atomic landscape.

You Mean I Can *Move* Things Too?

But these microscopes can do much more than just "see": their tips can form bonds with the atoms of the material they are scanning, and *move* the atoms. Manipulation of atoms by an STM is done by applying a tiny pulse of charge through the tip of the instrument. For example, hydrogen can be removed from hydrogen-silicon bonds by scanning a STM tip over the surface while applying rapid pulses, which pulls the bonds apart.

Once an atom has been lifted, it can be deposited elsewhere. Using this method with xenon atoms, IBM created the tiniest logo ever in 1990. In 1996, the tiniest abacus was also created by arranging **buckyballs** on a copper surface.

Figure 3. Nano logo [3].

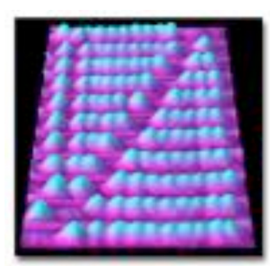


Figure 4. Nano abacus [4].

Is This a Good Way to Make Things?

Creating devices and materials atom-by-atom is more than an academic exercise; it paves the way for the next wave of nanotechnology research. But producing a material one atom at a time is not great for satisfying mass demand, because it's expensive and slow. For example, using the fastest techniques we have today, it would still take over 60 million years to assemble one aspirin table atom-by atom, because there are a lot of aspirin molecules (about 3.5×10^{20} to be precise) in one aspirin tablet that would need to be assembled! So how else can we manipulate atoms?

What is Nanoscale Lithography?

A "lithograph" originally referred to an image made by carving a pattern into a stone, applying ink to the stone "mask," and then pressing the inked stone onto a paper. Lithography was first used in the 18th century by artists to print music and art on paper. The lithography process was adapted in the late 20th century to imprint patterns on semiconductor materials to be used as integrated circuits. In this case, the "mask" is made using chemical methods, and light "ink" passes through the mask to produce the circuit structures.

Nanoscale lithography adapts this process once again. But nanoscale lithography can't use visible light, because the wavelength of visible light is 400 **nanometers**, which is too big. It would be like trying to engrave your name on your watch with a shovel. Doing lithography on the nanoscale requires new methods.

One way to get around the problem of visible light waves being too big is to use smaller wavelengths of light at the nanoscale. But smaller wavelength light is also higher energy, and that energy could cause damage to a feature that you're trying to make. One of the early approaches to get around this problem was to use electrons instead of light. This is called e-beam lithography.

A more recent (and some argue, better) approach is to use something called dip pen nanolithography (DPN), which writes structures to a surface the same way that we write ink using a pen. In this approach, a reservoir of atoms or molecules (the "ink") is stored in the tip of an AFM. The tip is then moved across a surface, leaving the structures behind on the surface.

In this schematic of DPN, the wiggly lines above the substrate are the atoms and molecules that make up the "nanoink."

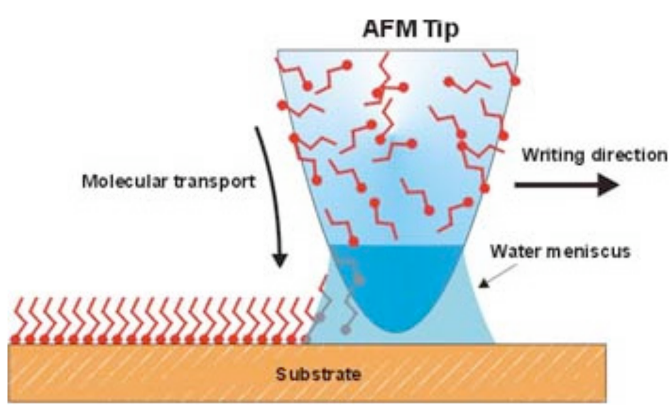


Figure 5. Transporting molecules to a surface using dip-pen nanolithography [5]

These techniques are clearly better and faster than manipulating atoms one by one. But it still would be wonderful if we could just mix chemicals together and have nanostructures just assemble themselves? This is what nature does, after all.

What is Self Assembly?

Self assembly is the process by which molecular building blocks "assemble" naturally to form useful products. Molecules try to minimize their energy levels by aligning themselves in particular positions. If bonding to an adjacent molecule allows for a lower energy state, then the bonding will occur. We see this happening in many places in nature. For example, the spherical shape of a bubble or the shape of snowflake are a result of molecules minimizing their energy levels. In cells, DNA is self-assembled from the atomic particles available to the cell. **Photosynthesis** is a process of self assembly. In fact, all the functions of the cell are variations of self assembly.

Is Self Assembly a Good Way to Build Things?

Through self assembly, large structures can be prepared without the individual tailoring that is required in the methods mentioned above. Just toss atoms or molecules onto a surface, and stand back. Of course it's not quite that simple—they don't always go in the places that you want them to! But because of the large number of structures one could create quickly with this method, it will probably become the most important nanofabrication technique.

One particular type of self-assembly is crystal growth. This technique is used to "grow" **nanotubes** and **nanowires**. In this approach, "seed" crystals are placed on some surface, some other atoms or molecules are introduced, and these particles mimic the pattern of the small seed crystal. For example, one way to make nanotubes is to create an array of iron **nanopowder** particles on some material like silicon, put this array in a chamber, and add some natural gas with carbon to the chamber. The carbon reacts with the iron and **supersaturates** it, forming a precipitate of carbon that then grows up and out. In this manner, you can grow nanotubes like trees!

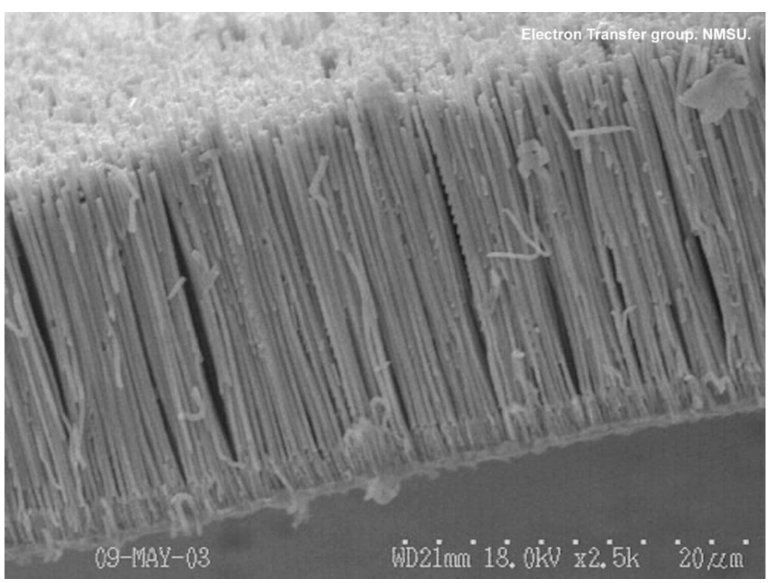


Figure 6. Growing nanotubes like trees [6]

Summary

The size limit of the smallest features you can create depends on the tools that you use. We've seen that STM and AFM's can be used to measure and manipulate atoms, either in a one-by-one fashion, or through nanolithography methods like DPN. In contrast to this "positional" approach, self-assembly is carried out largely by nature, usually through a chemical reaction. We can use self-assembly to create new structures if we set up the conditions just right. Although there are many examples of self-assembly around us in nature (including ourselves!), the rules that govern these assemblies are not fully understood. Our ability to create nanostructures improves as we gain understanding of biological self-assembly, the chemical development of new molecular structures, and the physical development of new tools.

References

(Accessed August 2005.)

[1] http://www.iap.tuwien.ac.at/www/surface/STM-Gallery/stm_schematic.html

[2] http://www.hersam-group.northwestern.edu/cover-figure.jpg

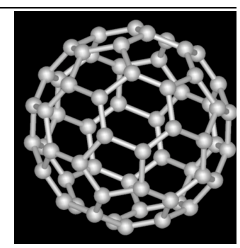
[3] http://www.almaden.ibm.com/ vis/stm/images/stm10.jpg

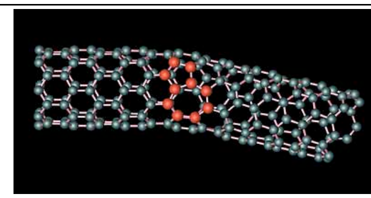
[4] http://www.research.ibm.com/atomic/nano/roomtemp.html

[5] http://www.chem.northwestern.edu/~mkngrp/dpn.htm

[6] http://www.chemistry.nmsu.edu/~etrnsfer/nanowires/

Glossary

Term	Definition
buckyball	A soccerball-shaped molecule made up of 60 carbon atoms. Also known as Buckminsterfullerene.  Image from http://en.wikipedia.org/wiki/Image:Fullerene-C60.png
electromagnetic forces	Particles with charge (or areas of charge) exert attractive or repulsive forces on each other due to this charge. Particles with magnetic properties exert attractive or repulsive forces on each other due to these magnetic properties. Since magnetism is caused by charged particles accelerating (for example by the electron "spin" in materials such as iron), these forces are considered to be two aspects of the same phenomenon and are collectively called electromagnetic forces.

Feynman, Richard (1918-1988)	One of the most influential American physicists of the 20th century, Richard Feynman greatly expanded the theory of quantum physics and received the Nobel Prize for his work in 1965. He also helped in the development of the atomic bomb and was an inspiring lecturer and amateur musician.  Image from http://en.wikipedia.org/wiki/Image:Nobel_feynman.jpg
nanometer	One-billionth of a meter (10-9m). The prefix 'nano' is derived from the Greek word for dwarf because a nanometer is very small. Ten hydrogen atoms lined up side-by-side are about 1 nanometer long.
nanopowder	A dry collection of nanoparticles.
nanoscale	Refers to objects with sizes in the range of 1 to 100 nanometers in at least one dimension.
nanotechnology	The design, characterization, production and application of structures, devices and systems that take advantage of the special properties at the nanoscale by manipulating shape and size.
nanotubes	Carbon nanotubes are cylindrical molecules made up of carbon bonded in a hexagonal formation. They are unusually strong, efficient conductors of heat and exhibit unique electrical properties. These characteristics make them potentially useful in extremely small scale electronic and mechanical applications.  Image from http://en.wikipedia.org/wiki/ Image:Louie_nanotube.jpg
nanowires	A "nanowire" is a wire of dimensions of the order of a nanometer (10 − 9 meters). At these scales, quantum mechanical effects are important - hence such wires are also known as "quantum wires".
photosynthesis	A biochemical process in which cells in plants, algae, and some bacteria use light energy to convert inorganic molecules into ATP (a high energy storage molecule) which they can use for energy later.
polymer	A generic term used to describe a substantially long molecule. This long molecule consists of structural units and repeating units strung together through chemical bonds.
supersaturation	Supersaturation (or oversaturation) refers to a solution that due to special conditions contains more of the dissolved material than could be dissolved by the solvent under normal circumstances.

Name__________________________________ Date______________________ Period ______

Seeing and Building Small Things: Student Quiz

1. Name the scanning probe instrument that uses electrical current to infer an image of atoms. Briefly describe how it works.

2. Name the scanning probe instrument that reacts to forces inherent in atoms and molecules to infer an image of atoms. Briefly describe how it works.

3. Scanning probe instruments can also be used to create things atom by atom. Briefly summarize the downside of using such tools to create an aspirin tablet.

4. How does dip pen nanolithography (DPN) work? Using a drawing in your explanation.

5. Name two things in nature that are created by self-assembly processes.

1:

2:

6. Circle true or false for each of the following.

E-beam lithography is a type of self assembly.	True	False
One type of self-assembly is crystal growth.	True	False
Nanotubes can be grown like trees from seed crystals.	True	False
The rules governing self-assembly are fully understood.	True	False