Nanotechnology for the 21st Century
Lecture-Demonstration

University of Wisconsin-Madison
Materials Research Science and Engineering Center on
Nanostructured Materials and Interfaces

in Partnership with the National Science Foundation

Talking Points and Demonstrations

1. Title slide. We are in the midst of a technological revolution. There are new materials and tools that give us unprecedented control over synthesizing and manipulating matter, leading to a steady stream of new devices and technologies. Increasingly, we can design materials with desired properties, often aided by the computer, and construct them virtually atom by atom. By controlling combinations of materials and their interfaces, we can customize devices.

2. Population Density. This illustration is emblematic of what we can do today: On the left is an 8-inch diameter silicon wafer used in the computer industry, and each box on it is a Pentium microprocessor. There are more electronic components on this 8-inch diameter wafer than there are people on Earth! As humans, we have probably now built more transistors than any other "thing" - including bricks! Small as these features are, making them smaller yet requires thinking on the scale of individual atoms - the nanoscale.

3. Scale. Nanotechnology is the study and design of systems at the nanoscale - the scale of atoms and molecules. The ability to manipulate materials on the scale of the nanometer could revolutionize the way that almost everything is designed and made. Nano means one billionth: That's a thousandth of a thousandth of a thousandth. There are one billion nanometers in a meter. The diameter of a pin is on the millimeter scale at 1.4 mm in diameter. A single strand of human hair is on the micrometer scale and has a diameter of 40 micrometers. Even smaller is DNA, whose cross-section is on the nanoscale with a diameter of about 2.5 nanometers.

4. Materials Science. This pyramid summarizes the storyline of this presentation. While we might think of materials as an old science in some ways (Stone Age, Iron Age, Bronze Age, e.g.), in many respects they represent a young science with tremendous vitality. The four corners of the pyramid symbolize the idea that different aspects of designing and building materials are interdependent.

We begin at the top of the pyramid with "structure." How do we know how atoms are arranged? We have tools that are atomically sharp - they let us "see" and manipulate matter on a material's surface, atom by atom.
To the left is "synthesis and processing." We can make and process materials that have novel properties that depend on the size of the material, as illustrated by the ferrofluid that we will discuss. At the right are "properties." Carbon nanotubes are a newly discussed form of carbon, like graphite and diamond, which have been measured to be stronger than steel of the same weight. And finally, at the bottom is "performance." We can create devices like light-emitting diodes, LEDs, that enable us to redefine old technologies like traffic lights.

5. Scanning Tunneling Microscope. The circles in this diagram represent atoms. We have a technology that lets us sharpen some materials like electrical wires so that their end terminates in a single atom, as shown in the upper part of this figure. We are also able to move this upper wire in atomic-scale increments across the bottom surface. The closer the atomically sharp tip is to atoms on the bottom surface, the more electricity will flow between the two when we make them part of an electrical circuit. By measuring the electricity as the tip and surface are moved relative to one another, we can "see" how atoms are arranged on the bottom surface. The instrument that is used for these measurements is called the scanning tunneling microscope, or STM.

6. Silicon. This illustration, from the laboratories of Max Lagally at the University of Wisconsin-Madison, highlights some of the capabilities of the STM and foreshadows emerging technologies. The tiny bumps are individual silicon atoms on a silicon wafer. The darker left-hand side of this figure is a plane of silicon atoms that is one atomic level higher than the silicon atoms on the lighter right-hand side, defining an "atomic terrace."
Occasionally a dark spot is seen - these are missing silicon atoms. If we imagine occasionally "crashing" our atomically sharp tip into the surface to kick out a silicon atom, we can imagine creating patterns on the scale of individual atoms. The occasional white streaks are rows of silicon atoms yet one atomic level higher. Imagine putting some metal at each end of such a row - these would be wires that are one atom thick! We can imagine constructing electrical circuits with unusual properties from such structures.

Demonstration with Refrigerator Magnets

Hand out these to the audience.
Speaker may want to hold an enlarged version of the same magnet.

7. Imaging. We will do an experiment together that illustrates a related kind of atomic-scale imaging. The refrigerator magnet (RM) has been scored on its right-hand edge so that if you bend it a few times along the edge, it can be ripped off cleanly. This is what we will call the "probe strip."

8. Imaging. Turn the RM over so that you are looking at the dark, unprinted side. Put the dark sides of the RM together. Drag the probe strip slowly in the two perpendicular directions shown on the slide and ask: "Is there any difference in what you hear, see, and feel?" The probe strip provides a way to map the magnetic field of the RM. *Encourage members of the audience to share their observations with the person(s) next to them.*

9. Which Best Represents the Poles? Which of the three pictures of the magnetic pole arrangements shown is most consistent with what you experienced?
How many choose:

(a), which has a completely uniform magnetic field - all north pole, e.g.?
(b), which has stripes of magnetic poles, alternating as north-south-north, etc.?
(c), which is a checkerboard arrangement of magnetic poles, alternating north-south in both directions?

Almost everyone will choose the correct answer, which is b).

Now imagine that the probe tip is sharpened to a single atom and dragged in atomic-scale increments across the bottom surface. We could "map" the bottom surface, atom by atom. There is another kind of microscope, called the atomic force microscope, or AFM, that works on a similar principle. The RM demonstration also helps us understand how we can "see" something (like atoms or magnetic fields) that is invisible to the naked eye.
If you keep a refrigerator magnet, be sure that it is kept away from credit cards or magnetic keys.

Demonstration with Optical Transform Slides.

Hand out these to the audience and collect them at the end of the talk. You should have a pocket laser and minimaglite available and the room should be as dark as possible. A white screen can help to make the demonstration easier to observe. SAFETY WARNING: USE THE POCKET LASER WITH CARE TO ENSURE THAT THE BEAM DOES NOT SHINE DIRECTLY OR THROUGH REFLECTION INTO ANYONE'S EYES!!!

10. Structure Determination. We will do a second experiment that illustrates another method for determining where atoms are located relative to one another. The top part of this diagram shows how much of our present information on atomic positions was obtained. X-rays, like those used by doctors and dentists, are a form of electromagnetic radiation that can be described as a wave with a very short wavelength between crests. Because this wavelength is about the same size as the spacing between atoms in a crystal, when the X-rays strike the crystal they are scattered into patterns through a phenomenon called diffraction. It is then possible to take the patterns and to work backward to determine what atoms are present and how they are arranged.

The bottom part of the figure indicates that we can make this phenomenon visible to the eye. Visible light has wavelengths thousands of times longer than X-rays. When red light from a pocket laser strikes slides bearing computer-printed features that have been photographically reduced, similar diffraction effects to those seen with X-rays striking crystals are observed.

11. Diffraction Conditions. To appreciate what we are about to see, when the pocket laser strikes the 35-mm slide, the red beam will be separated into a pattern of red spots against a dark background. A visible spot of light is a result of waves having been scattered so that they are marching in step (crests match up on the top half of the slide), which is called constructive interference. Everywhere darkness is seen, the waves are marching out of step (crest and trough of two waves match up on the bottom half of the slide) and effectively canceling each other, which is called destructive interference.

12. Nanoworld Slide. Remove the slide from its plastic envelope. The slide the audience is holding is shown. To match this orientation, the word "Nanoworld" should be at the top of the slide. These lines and dots might represent different kinds of atomic arrangements. These features can easily be observed with an inexpensive hand lens or Radio Shack microscope.

First demonstration: Shine the pocket laser through the eight different arrays to see eight different diffraction patterns.

Different arrangements give different diffraction patterns. For example, (1) compare the two arrays on the left. Does the smaller or larger array give a smaller or larger diffraction pattern? (2) Compare the two arrays in the upper left. When a square is stretched vertically into a rectangle, how does the diffraction pattern change? (3) Any repeating pattern will work, even the word NANO. (4) The two patterns on the right show the difference between a single and a double DNA helix. These are patterns similar to what Rosalind Franklin saw when working on discovering the structure of DNA.

Second demonstration: Shine the pocket laser beam on a screen (not through the slide).

Everyone raise your slide in front of your eyes and view the laser beam through different parts of your slide. You should see the same diffraction patterns I just showed you.

Third demonstration: Unscrew the cap from a minimaglite so that this point source of white light can be seen (Mimic the Statue of Liberty.). View the white light through your optical transform slide. Why is the diffraction pattern from a single color light source like the laser easiest to interpret than the pattern from the white light source?

Demonstration of Ferrofluid

The ferrofluid cell, cow magnet, and overhead projector are used here.

13. Liquid or Solid? *Hold the ferrofluid cell up and move it back and forth to demonstrate the fluid-like properties of ferrofluid.* Do you think that this black material is a solid or a liquid? Let's see what happens when we hold a magnet up to this material, called ferrofluid. *Hold a magnet up to the ferrofluid on an overhead projector*. The spikes that appear follow the lines of the magnetic field emitted by the magnet. Ferrofluid contains nano-sized particles with flow properties of liquids and magnetic properties of solids. They were originally discovered in the 1960s at the NASA Research Center, where scientists were investigating different possible methods of controlling liquids in space.

14. Ferrofluids. This ferrofluid cell contains a suspension of tiny particles (each approximately 10 nm in diameter) of magnetite, a magnetic compound found as black sand on some beaches, suspended in a liquid. These nano particles are covered in a surfactant (a detergent-like molecule) to provide the flow properties of ferrofluid. Ferrofluid can be made by mixing appropriate amounts of Fe (II) salt and Fe (III) salt in a basic solution. Ferrofluid is used in low friction seals and loud speakers. Scientists and doctors are now trying to find a new application of ferrofluid in the delivery of drugs. By combining drugs with ferrofluids and controlling the material's location with a magnetic field, researchers hope to find a new method of drug delivery.

15. Cadmium Selenide Nanoparticles. These test tubes contain suspensions of cadmium selenide nanoparticles with a surfactant, similar to ferrofluid. The top view is under black light and the bottom view is under normal room light. By tuning the particle size the color of the solution can be changed. All the particles have the same chemical composition, but as the particle size increases from left to right (4 nm to 50 nm) the material emits and absorbs light of different colors.

16. Carbon Nanotubes. Graphite and diamond are two forms of carbon that have drastically different properties. Graphite is soft, whereas diamond is strong enough to scratch glass. This dramatic difference is due to the molecular structures of the materials. Other new forms of carbon have been discovered recently. Fullerenes are soccer-ball-shaped molecules that were named after the architect, Buckminster Fuller, who created the geodesic dome. (Think of the Epcott Center in Florida.) Carbon nanotubes have a tubular shape and are stronger than steel. There are three types of carbon nanotubes called armchair, zig-zag, and chiral.

Demonstration with Carbon Nanotube Pencils
Hand out these to the audience.

17. Name that Nanotube. The structure of a carbon nanotube is printed around the circumference of the pencil in front of you. Which of the three types of carbon nanotube is printed on your maroon pencil (or black pencil)? Twist the pencil around its circumference (the direction of twist, around the long axis, needs to be demonstrated) and compare the pattern on the pencil to the patterns of armchair, zig-zag, and chiral.
How many choose (a), which is armchair?
How many choose (b), which is zig-zag?
How many choose (c), which is chiral?
Almost everyone should choose the correct answer, which is a) for the maroon pencil or b) for the black pencil).

18. Nanotube Pencil Answers. Armchair nanotubes are printed on the maroon pencils, and zig-zag nanotubes are printed around the black pencils. Armchair nanotubes are metallic, and zig-zag and chiral nanotubes can be either metallic or semiconducting. Carbon nanotubes have various applications and are being used in flat panel display screens and in tips for atomic force microscopes. Nanotubes can act as nanothermometers, as they can be partially filled with gallium metal. When the temperature changes, the gallium metal expands or contracts to fill or empty the carbon nanotube. The gallium level in the carbon nanotube varies almost linearly with temperature. This new device may find use in certain microscopies.

Demonstration of LEDs.
The color strip of 4 LEDs (red, orange, yellow, green), a blue LED, and tricolor LED are used, each powered by a standard 9-V battery.

19. LEDs. The light-emitting diode and pocket laser illustrate our ability to customize semiconductor materials to control the color of light they emit. The electrons in these solids can be excited simply by connecting the materials to a common 9-volt battery. The electrical energy provided by the battery is converted into the energy of light, optical energy. A schematic of an LED is shown, illustrating the two electrical leads, a glowing red semiconductor, and a gold wire completing the circuit, all held within a transparent lens.

A representation in the upper left corner of the slide shows the arrangement of atoms in the semiconductor. By varying the sizes of the atoms used in constructing the semiconductor solids and their relative numbers, the color of light they give off can be tuned across the visible spectrum. Atoms of an element called gallium can be combined with mixtures of atoms of the elements arsenic and phosphorus to obtain colors from red to orange to yellow to green. As the atoms decrease in size, the energy of the light emitted increases from red to orange to yellow to green. In a very recent breakthrough, by combining gallium with nitrogen, blue light can be obtained.
These LEDs can be connected to a battery and passed around for the audience to see.

20. Solid Solutions. **A**s shown in this figure, specific colors in the visible spectrum can be obtained by mixing gallium atoms with various ratios of phosphorus to arsenic atoms. The extreme left side might correspond to having exclusively phosphorus atoms (shown in blue) in a solid sample, and the extreme right side to having exclusively arsenic atoms (shown in yellow). An 80%-20% solid solution with random placement of 80% phosphorus atoms and 20% arsenic atoms is pictured, as are 60%-40% and 20%-80% combinations.

21. Tricolor LEDs. The recent availability of blue LEDs makes it possible to obtain any color in the visible spectrum by adding colors together. Combinations of red, green, and blue light can produce all other colors, and white light. By placing all three LEDs in a single housing, this additive color mixing can be observed.
Pass the color mixing board around for the audience to see.

You can produce different colors by turning each color knob individually to produce a single color - red, green, or blue - or combine colors to make new ones. If you take an inexpensive hand lens or Radio Shack microscope and look at a computer monitor you can see the red, green and blue picture elements (pixels) on the screen.

Diode lasers use similar materials. These advances in light-emitting diodes may revolutionize many display and communication technologies. For example, compact disks (CDs) that operate with blue diode lasers are estimated to be able to hold at least four times as much information as current CDs.

22. LED Traffic Signal. Traffic lights and automobile brake lights are examples of exciting new applications of LED technology. Replacement of a traditional incandescent light bulb used in traffic lights by hundreds of LEDs has at least two major advantages. One is safety: the light does not fail catastrophically, i.e., all at once. A second advantage is energy savings, as LED traffic lights cost about a tenth the energy to operate. LEDs are also used in the red brake lights of motor vehicles (the spoiler bar on the rear of cars, e.g.). Their use in this capacity is particularly advantageous when replacement is difficult. They can also light up faster, which means people will know to brake sooner.

23. Additional Resources. The National Nanotechnology Initiative website at http://www.nano.gov provides additional information on these and related technologies. Additional activities and materials to further explore the nanoworld can be found at http://www.mrsec.wisc.edu/NANO. *Generous support from the National Science Foundation permitted development of this presentation, but opinions expressed herein are those of the authors.*

<u>List of props for the 'take-out' talk</u>

a darkenable room
overhead projector and projection wall or screen

one large refrigerator magnet for speaker
small refrigerator magnets for audience

optical transform slides for the audience
laser pointer for speaker
minimaglite for speaker

ferrofluid cell with cow magnet

Carbon nanotube pencils

LED reference strip
blue LED
tricolor LED
one or more 9-volt batteries

All of the items above will be supplied except an overhead projector. The speaker is encouraged to give away the refrigerator magnets, which contain the NSF-MRSEC website address. All other items should be collected and re-used, although we can provide replacements for lost items if necessary.