Customizing Materials 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 yet smaller requires thinking on the scale of individual atoms - the nanoscale.

3. 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 and composition.” We have tools that are atomically sharp - they let us “see” and manipulate matter, atom by atom.
To the left is “synthesis and processing.” We can make and process materials that have novel properties, as illustrated by this foam that we will discuss.
At the bottom is “performance.” We can create devices like light-emitting diodes, LEDs, that enable us to redefine old technologies like traffic lights.
And finally, at the right are “properties.” Eyeglasses that retain their shape are representative of new classes of so-called “smart” materials that respond to a stimulus - bending, for example - in a predictable way.

4. 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 this 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.

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

6. 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." *If there is a printed message on the strip like a website address, you can call attention to this.*

7. Imaging. Turn the RM over so that you are looking at the unprinted side. Put the unprinted side of the probe strip against the unprinted side of the RM. Drag the probe strip 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.*

8. 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.?
How many choose b), which has stripes of magnetic poles, alternating as north-south-north, etc.?
How many choose 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 that works on a similar principle.
If you keep a refrigerator magnet, be sure to keep it away from credit cards or magnetic keys.

Demonstration with Optical Transform Slides.

Hand these out 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!!!

9. 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 using computers 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 35-mm slides bearing computer-printed features that have been photographically reduced, similar diffraction effects to those seen with X-rays striking crystals are observed.

10. 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. Everywhere a spot of light is seen, it is because the waves have 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 cancel each other, destructive interference.

11. Discovery Slide. This slide shows what is on the 35-mm slide the audience is holding. To match this orientation, the word “ICE” should be at the top of the slide, as shown. 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 arrangments give different diffraction patterns.

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 such as the laser easiest to interpret than the pattern from the white light source?

Demonstration of Re-Entrant Foam.

Samples needed are a thick rubber band and untreated and treated re-entrant foam. For a large audience, the overhead projector is an effective way to present the demonstration. A Hoberman sphere, obtainable from a toy store, can be used as a model for the processed foam.

As an illustration of new, customized materials, let’s begin by taking a thick sample of a rubber band and stretching it. Does its cross-section become wider or thinner during the stretching? *The audience should note that it becomes thinner.* Let’s try the same thing with a sample of foam (polyurethane) used in air filters. Note its very porous nature. Like the rubber band, its cross-section constricts when the foam is stretched.

Processing is a way to change properties of materials. When the sample of foam is squeezed by wrapping it in aluminum foil and tying off the ends and heated (about one hour at 200 degrees Centigrade), the same atoms are present and linked to their immediate neighbors the same way. But on a scale of millionths of a meter (microstructure), they form different shapes. This treated “re-entrant foam” is much denser and less porous looking.

Does its cross-section become wider or thinner during the stretching? When stretched it does something counterintuitive - it expands in cross-section!

12. Re-entrant Foam. The explanation of this remarkable effect is that if we think of the pores as cubes, the combination of squeezing and heat causes the pores to, in effect, implode. From the sketch, stretching in any direction will cause the entire imploded cube to open up, leading to the macroscopic effect of seeing a bulge in the cross-section when the sample is stretched.
Can anyone suggest a use for such a material? One possibility is ropes for rock climbers - when such a rope is placed in a crevice and tension applied, its swelling could help reinforce its placement in the crevice.

13. Hoberman Sphere. A Hoberman sphere also expands on stretching and illustrates how a pore of re-entrant foam behaves.

Demonstration of LEDs.

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

14. LEDs. The light-emitting diode and pocket laser illustrate our ability to customize semiconductor materials to control the color of light they emit. These solids can be excited simply by connecting them 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.

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

16. Tricolor LEDs. The recent availability of blue LEDs provides the possibility of obtaining any color in the visible spectrum by adding colors, as 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 trying 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 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.

17. 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 these cost about a tenth the energy to operate. LEDs are also finding use 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.

Demonstration of Memory Metal.

Strips of this metal should be given to the audience and a source of heat is needed - either very hot water or a hot air gun such as is used to dry hair, in which case a piece of scotch tape is also useful. If time permits, a candle and match can be used to conduct a follow-up demonstration.

Show the audience a linear strip of memory metal and ask for a volunteer from the audience to: Wrap the strip around your finger as though you are making a spiral or helix. Remove the strip from your finger and return it to me. What happens when we heat the sample? *You can then tape the strip onto the overhead projector and heat it with the hot air gun, causing it to revert to its linear shape. Alternatively, the strip can be dunked in very hot water, coffee, or tea (heated to at least 60 degrees Celsius, e.g.). Depending on how large the audience is and how many containers of hot water are available, it may even be possible for everyone in the audience to do this at the same time. In the case of using hot water, there are safety issues: a sturdy cup (ceramic, preferably) should be used, and the audience members should be instructed to remove the wire from their finger and hold one end very firmly as the other end is dunked in the hot water. The wire exerts a substantial force as it returns to its original shape.*

This experiment characterizes a smart material: in response to a stimulus, a change in temperature, this material will change its shape. The composition of the material is nickel-titanium with almost exactly a 1:1 ratio of atoms. Neither pure nickel nor pure titanium has this kind of property.

18. Atomic Ballet. Underlying the smart material's behavior is the kind of change that takes place when ice melts to become liquid water. Before and after, only water molecules are present, but there is a different kind of ordering of the molecules, with greater order in the solid. As the slide shows, when the memory metal sample is warmed to hot air or hot water temperature, a more symmetric ordering of the atoms results that makes the warm form of atoms relatively rigid. When the sample is cooled to room temperature, this kind of atomic ballet is reversed and the transformation leads to a less ordered, more flexible structure. In the slide the two kinds of atoms are represented by the two colors. The slightly offset pairs of atoms represent corners of a three-dimensional box that comprise the structure.

Optional: The sample of memory metal can be "re-trained" by heating it to candle flame temperature. By lighting a candle or using the match itself, the center part of the linear strip is heated. After a few seconds it can be bent into a V-shape and then withdrawn from the flame. It will quickly cool to room temperature where its new shape can be shown to the audience. The same volunteer can now be asked to bend the wire into some other shape. When the bent wire is now heated with hot air or hot water again, it will transform back *into the V-shape! The effect of much higher temperatures (the candle flame is about 500 degrees Celsius) is that large groups of atoms can be moved around (a kind of processing as discussed earlier with the re-entrant foam) to imprint the metal with a new shape that it "remembers."*

Possible applications are intriguing: Imagine making a car out of this material - if you have an accident, the car will return to its original shape simply by heating it! Another example is from the art world…

19. Memory Metal Sculptures. The left-hand part of this slide is Olivier Deschamps' sculpture of a mother holding a child. When it is cold outside, the mother is bent over as shown. When the sun comes out, the right-hand part of the figure shows that the warmer temperature causes the mother to hoist her child into the air! When cooler temperatures return, gravity will cause the sculpture to return to the original shape.

20. Memory Metal Products. Not only does memory metal undergo a structural change induced by temperature, but pressure can also trigger such a change. The young lady in this picture is wearing orthodontic braces whose arch wire is made of memory metal. The metal is biocompatible and its attempted phase transition can be used to apply uniform pressure to teeth. Eyeglass frames made of memory metal pass through their phase change with bending but revert to their original shape after the pressure is removed. By varying how much nickel there is to titanium over a small range of compositions, the temperature at which the smart metal goes through its transformation can be altered. Setting it to very low temperatures permits the bent eyeglass frames to return to the shape in which they were set at very high (candle-flame-like) temperatures.

21. Additional Resources. The National Science Foundation's website of MRSECs (Materials Research Science and Engineering Centers) at http://www.nsf.gov/mps/dmr/mrsec.htm provides additional information on these and related technologies. *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 audience
laser pointer for speaker
minimaglite for speaker

thick rubber band
untreated foam
re-entrant foam
optional: Hoberman sphere toy

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

memory metal strips

hot air blower (hair dryer) or container with very hot water, coffee, or tea
optional: match and small candle for retraining the strip

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