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Incorporating Concepts of Nanotechnology into the Materials Science and Engineering Classroom and Laboratory

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Abstract

The National Science Foundation-supported Materials Research Science and Engineering Center (MRSEC) on Nanostructured Materials and Interfaces at the University of Wisconsin – Madison has an extensive and highly successful education and outreach effort. One theme of this effort is the development of instructional materials based on cutting-edge research in nanoscale science and engineering. Nanotechnology examples, such as light emitting diodes (LEDs), shape memory alloys, amorphous metals, and ferrofluids, illustrate interdisciplinary research that provides connections among materials science, chemistry, physics, and engineering. They also highlight the tools of nanotechnology, such as scanning probe microscopy, electron microscopy, self-assembly, x-ray diffraction, and chemical vapor deposition, associated with the preparation and characterization of nanostructured materials. These and other nanotechnology concepts are illustrated with video demonstrations in a web-based resource called the "Nanoworld Cineplex," which contains movies of experiments and demonstrations that can be brought into the classroom. Numerous experiments are also available in the "Nanotechnology Lab Manual," which can be used as either a virtual laboratory or as a web-based video lab manual. These resources for using nanotechnology to teach fundamental materials science and engineering principles are available at <http://www.mrsec.wisc.edu/nano>.

Introduction

Nanotechnology touches our everyday lives. Its impact is growing in magnitude every day. A new industrial revolution that some predict will rival the development of the automobile and the introduction of the personal computer is being inspired by nanotechnology.[1] Nanotechnology examples, such as light emitting diodes (LEDs), shape memory alloys, amorphous metals, and ferrofluids, illustrate the increasing impact of this field.

The importance of this emerging technology to society and industry requires that undergraduate institutions take steps to adapt their curricula to ensure a capable future workforce as well as a more scientifically literate general population.[2-4] Undergraduate science and engineering majors need a comprehensive education that includes nanotechnology in order to successfully navigate the challenges of the 21st century. Students need an interdisciplinary education in the basic sciences, the engineering sciences, and the information sciences, as well as an understanding of the relationships of these fields to nanotechnology. This has motivated the National Science Foundation-supported Materials Research Science and Engineering Center (MRSEC) on Nanostructured Materials and Interfaces at the University of Wisconsin – Madison to create an extensive education and curriculum development effort focused on nanotechnology. One theme of this effort is the development of instructional demonstration and laboratory materials based on cutting-edge research in nanoscale science and engineering.

The challenge of integrating nanotechnology into the curriculum is being met by a number of colleges and universities. In recent years, numerous education and outreach efforts have been developed to educate and inform students and the general public about nanotechnology.[5-6] In addition, courses in nanotechnology have begun to appear in college catalogs, and nanotechnology concepts have been incorporated into undergraduate general chemistry and physics courses as well as materials science and engineering courses.[3,7]

Nanotechnology Instructional Materials from the UW-Madison MRSEC

The University of Wisconsin – Madison (UW) MRSEC is addressing the challenges of integrating nanotechnology into the science and engineering curriculum. The UW MRSEC carries out forefront research in nanoscale materials and interfaces, and is composed of approximately 40 faculty participants organized into three major research areas, exploratory seed projects, and the education/outreach effort. As part of this effort, UW MRSEC has created numerous kits, distributed at cost by the Institute for Chemical Education (http://ice.chem.wisc.edu/); the *Nanoworld Cineplex*, a web-based resource that contains movies of experiments and demonstrations that can be brought into classrooms and laboratories; and the *Laboratory Manual for Nanoscale Science and Technology*, a web-based manual that provides movies of laboratory experiments for teaching nanotechnology at the high school and college level. The experiments available in the laboratory manual illustrate synthetic methods, nanoscale phenomena, and nanotechnology applications. These laboratory experiments are unique because of the web-based video laboratory manual that has been developed for student use, which allows this resource to be used as a virtual laboratory or as a web-based video lab manual.

UW MRSEC instructional materials have been incorporated into introductory and advanced chemistry and materials science courses at a number of colleges and universities, including UW, Beloit College (Beloit, WI), Christian Brothers University (Memphis, TN), and Lawrence University (Appleton, WI). These institutions represent a broad range of learning environments, demonstrating the adaptable nature of the instructional materials developed. UW introductory chemistry and engineering courses often have large 250-350 student lecture sections that are offered as either mathematics-intensive classes designed for science and engineering majors, or as less mathematical classes for non-technical majors who need to satisfy a college distribution requirement. Beloit College, a liberal arts college with module-based introductory chemistry classes of 24 students, uses MRSEC educational materials in a guided inquiry format. Christian Brothers University, a small, private university, has a more traditional laboratory and lecture-based introductory chemistry course of 20-30 student lecture sections that services engineering majors. Lawrence University, a small liberal arts school, has an introductory chemistry course of 50-60 students and another introductory course on materials science in which nanotechnology components have been incorporated. UW MRSEC materials have also been integrated into upper division and graduate courses in chemistry, physics, materials science, and engineering mechanics at the UW and upper division chemistry classes at CBU.

The following sections provide brief introductions to several of the nanotechnology laboratories that have been developed. A complete listing of instructional resources developed by UW MRSEC for teaching about nanotechnology is available on the Internet at <http://www.mrsec.wisc.edu/nano/>.[8]

Optical Diffraction Experiments to Explore Characterization by X-Ray Diffraction

Optical Transform slides, the focus of two UW MRSEC kits, have been used in lectures and laboratories to illustrate X-ray diffraction, an important tool used to characterize nanoscale materials.[9-10] Laser printer written, photographically-reduced patterns on 35-mm slides like the one shown in Figure 1 contain a variety of arrays that mimic the packing of atoms in common metal and mineral structures.[11-12] Because the spacing of dots on the slide is similar to the wavelength of visible light, diffraction occurs when coherent light from a hand-held laser is passed through the slide. Students can measure the feature spacings on the slide using a plastic ruler and hand lens and then compare this value with that obtained in a simple diffraction experiment using the Fraunhofer equation. This inquiry-based approach permits students to explore X-ray diffraction and appreciate the manner in which structural information is acquired from diffraction data. The observation and investigation of diffraction works well as a classroom demonstration and as an inquiry-based activity.

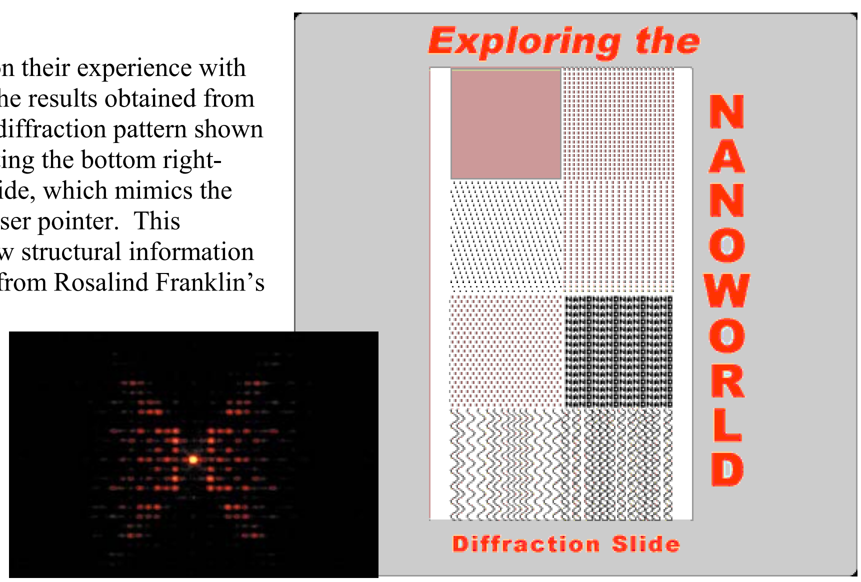

Figure 1. Students can build on their experience with simple patterns to understand the results obtained from more complex structures. The diffraction pattern shown in the inset is seen by illuminating the bottom right-hand panel of the diffraction slide, which mimics the double helix of DNA, with a laser pointer. This particular pattern illustrates how structural information about DNA was first obtained from Rosalind Franklin's x-ray diffraction experiments.

Ferrofluid Synthesis Laboratory

One popular experiment from the *Laboratory Manual for Nanoscale Science and Technology* is the preparation of ferrofluids, which comprise nanoscale particles of magnetite suspended in water with the aid of a surfactant. Since the ferrimagnetic mineral magnetite possesses the spinel structure, containing iron atoms in both the divalent and trivalent oxidation state, the stoichiometry of Fe^{2+} and Fe^{3+} utilized in the synthesis needs to be controlled in order to obtain a final product that is ferrimagnetic. Agglomeration of the particles is prevented through the use of an ionic surfactant (tetramethylammonium hydroxide). The surfactant ions coat the surface of the magnetite nanoparticles and electrostatically isolate the particles from one another. This concept-rich experiment can be used to illustrate principles of stoichiometry, oxidation state, crystal structure, magnetism, and surfactant chemistry.[13] Figure 2 shows several images taken from the manual's collection of videoclips. Applications of ferrofluid, ranging from computer hard disk drives and loudspeakers to research on magnetically-controlled drug delivery, show the real-life relevance of nanoscale materials. This laboratory has been successfully performed at all of the institutions listed above in traditional chemistry undergraduate laboratories. It has also been successfully performed in outreach venues such as *Grandparents University* which brings 6th graders and their grandparents into the lab.

a) b) c) d)

Figure 2. Images from the web-based video laboratory experiment "Aqueous Ferrofluid Synthesis" in the *Laboratory Manual for Nanoscale Science and Technology* developed by the UW MRSEC are shown in (a-d). a) A solution of nanoparticles formed by mixing Fe(II), Fe(III) precursor solutions. b) A suspension of nanoparticles is formed by adding ammonia to the solution. After an initial brown precipitate, a black precipitate will form (magnetite). c) After the magnetite has settled the clear liqid can be decanted and surfactant added. d) The ferrofluid can be observed to form spikes in response to a magnetic field.[14-15]

Nanorod Template Synthesis Laboratory

Recently, a nanowire synthesis lab has been developed that can be incorporated into introductory science and engineering classes and adapted to students at a number of different educational levels.[16] In the experiment, students prepare nickel nanowires using a common template synthesis technique and then characterize them. Electrodeposition of nickel into the 200 nm-diameter pores of a commercially available alumina filtration membrane is accomplished using a nickel salt solution and an AA battery. The nanowires (which are 200 nm in diameter and up to 50 μm long) are liberated from the membrane by dissolving both the silver cathode and the alumina template itself. Suspensions of nanowires are dispersed on a microscope slide and observed using an optical microscope with a 10X or 50X lens. The alignment and movement of the magnetic nanowires are controlled using common magnets, as shown in Figure 3a.

Advanced students can analyze their nanowires using Scanning Electron Microscopy (Figure 3b) and powder X-ray diffraction techniques. This lab has been incorporated into two courses at UW-Madison: Materials Science and Engineering 361 (Materials Laboratory II) and Chemistry 311 (Chemistry Across the Periodic Table). Demonstration of the steps in the full laboratory experiment is included in the *Laboratory Manual for Nanoscale Science and Technology.*

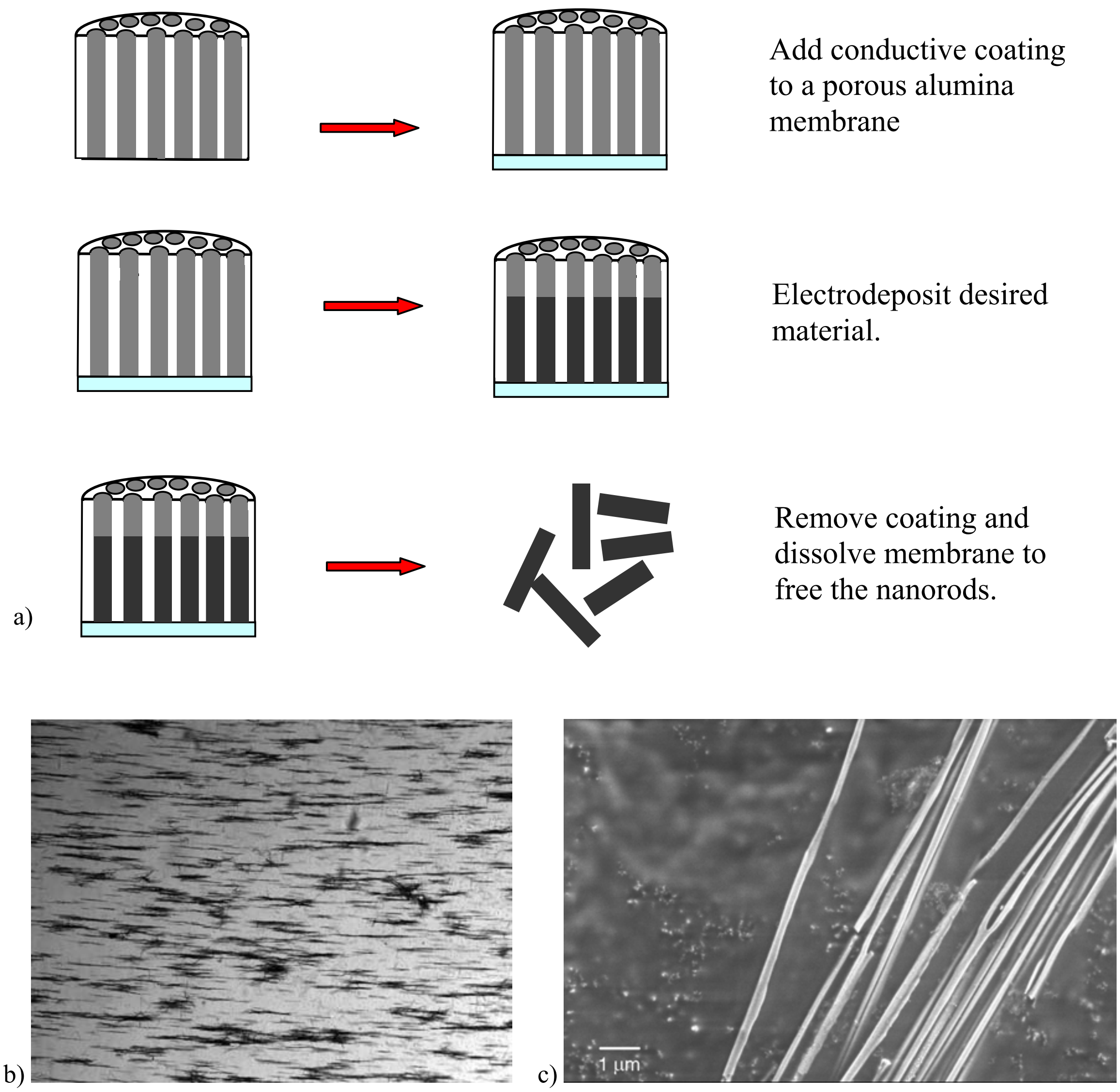

Figure 3. This experiment involves the preparation of nickel nanowires by template synthesis using electrodeposition of nickel into a commercially available alumina filtration membrane, as shown schematically in (a). The nanowires (which are 200 nm in diameter and up to 50 μm long) are liberated from the membrane, and their alignment under a magnetic field can be observed by optical microscopy. The alignment of nickel nanowires (black rods) in a magnetic field, as observed using an optical microscope, is shown in (b). Each individual nanorod is approximately 50 μm in length. SEM image of the same nanowires (white rods) is shown in (c). The scale bar represents 1 μm.

Colloidal Gold Synthesis Laboratory

Figure 4. A reddish suspension of gold nanoparticles is produced by reduction of a gold (III) salt. The presence of the gold colloid can be detected by the scattering of a laser beam by the nanoparticles.[29]

In another *Laboratory Manual for Nanoscale Science and Technology* experiment, colloidal gold is prepared from a fairly simple synthesis involving the reaction of sodium citrate and hydrogen tetrachloroaurate. Sodium citrate reduces the gold(III) ions to form a reddish colloidal suspension of gold nanoparticles. The presence of gold colloid can be investigated by shining a laser pointer through the solution. In certain orientations, the laser light is scattered by the gold colloid, allowing the laser beam to be observed in the suspension, as shown in Figure 4.[14] This is a demonstration of the Tyndall effect. A simple rotation about the axis of a polarized laser pointer beam causes the laser beam to gradually disappear and reappear in the solution. This is due to differences in scattering of the polarized beam by the colloid as the polarization direction is altered. Topics such as redox chemistry, colloids, electromagnetic radiation, and polarization effects can be introduced with this experiment.

Laboratory on the Construction of a Microfluidic Nanofilter Device

A number of the experiments in the *Laboratory Manual for Nanoscale Science and Technology* have also been incorporated into a more comprehensive laboratory that allows students to construct a microfluidic device that filters nanoparticles from solution. The device utilizes a nylon membrane formed by an interfacial polycondensation reaction between two immiscible solutions, diaminohexane and sebacoyl chloride. These solutions are brought into contact at an interface within a microfluidic device. The interface where this reaction occurs is stabilized by the surface treatment of the device substrate with a self-assembled monolayer to create neighboring hydrophilic and hydrophobic regions. The membrane forms at the "virtual wall" where these regions intersect and allows the device to be used as a filter capable of separating gold nanoparticles from an aqueous solution. Several laboratory periods are required to complete the device and conduct analyses on its components. The construction and testing of this device, shown in Figure 5, provides the students with an opportunity to investigate several nanotechnology and microfluidic phenomena during the course of the semester. Each module of the lab is connected to nanotechnology and microfluidic concepts, such as atomic force microscopy, self-assembled monolayer deposition, and microfluidic technology, providing hands-on experience with synthesis techniques, nanoscale materials characterization, and microfluidics.

This laboratory series was incorporated into a new course on "Micro- and Nanoscale Mechanics" taught at UW-Madison in the spring of 2003. This graduate/senior undergraduate level course provided an introduction to nanoscale engineering with a direct focus on the critical role that mechanics needs to play in this developing area. Along with two 75-minute lectures per week, numerous demonstrations and experiments were used throughout the course, including synthesis and fabrication techniques for creating nanostructured materials, and bubble raft models to demonstrate scale effects in thin film structures. Details of this course are presented in a separate paper in these proceedings titled "A Course in Micro- and Nanoscale Mechanics".

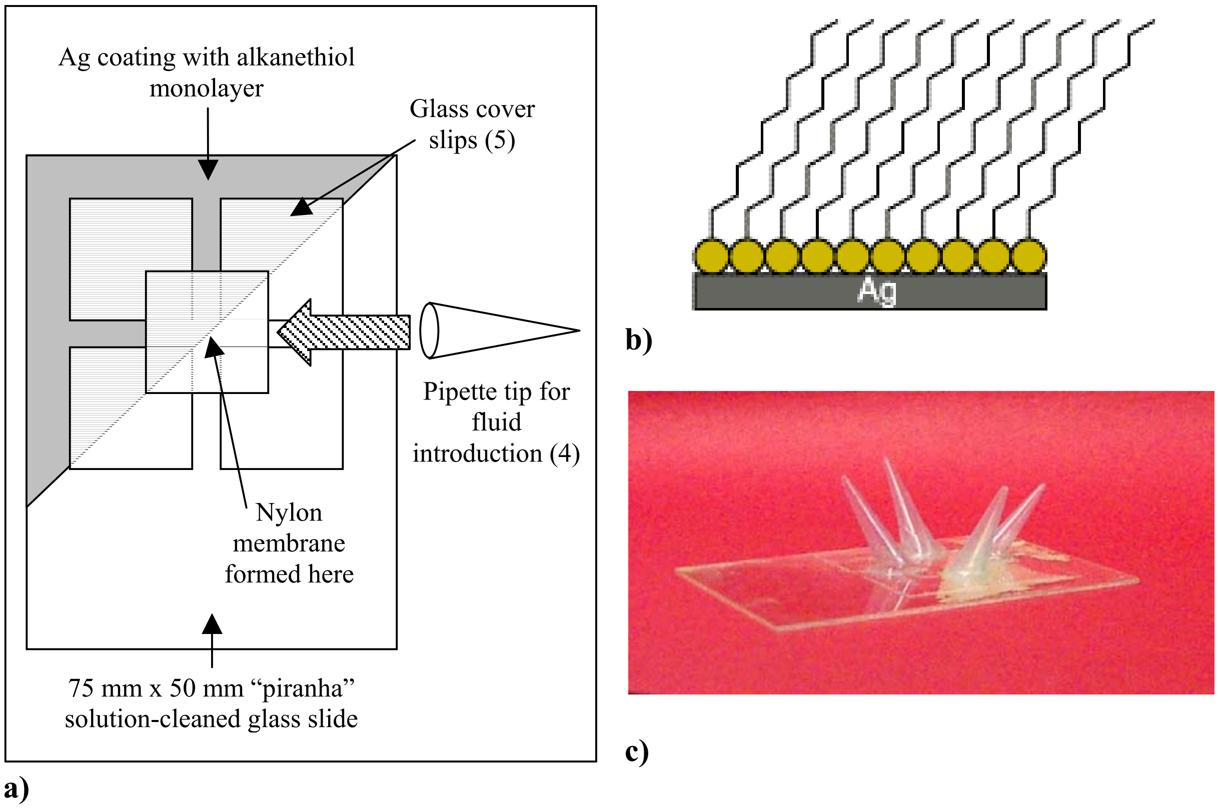

Figure 5. This laboratory allows students to construct a microfluidic device that filters nanoparticles from solution using a nylon membrane formed by an interfacial polycondensation reaction between two immiscible solutions. The solutions are brought into contact at a "virtual" interface within a microfluidic device. The schematic shown in (a) provides an overview of the construction process. After silvering the glass substrate, an alkanethiol self assembled monolayer, shown schematically in (b), is created. The device is constructed on top of the modified substrate by arranging four glass cover slips to form two intersecting channels. A fifth glass cover slip is placed over the top of the intersection of these channels to provide a "roof" for the channels. Plastic pipette tips are affixed with epoxy onto the coverslips such that the pipette tips act as conduits for the introduction of fluids into the microchannels of the device. Image (c) shows a side view of the microfluidic device after the construction process. The construction and testing of this device provides students with an opportunity to investigate several nanotechnology and microfluidic phenomena.

Liquid Crystal Watch Dissection Laboratory

The last *Laboratory Manual for Nanoscale Science and Technology* experiment highlighted in this paper incorporates aspects of nanoscale science and technology with the dissection of a common wristwatch, and testing of its nanoscale component, the liquid crystal display (LCD).[17-18] This laboratory includes dissection of the watch, followed by hands-on experiments exploring the polarization of light, liquid crystal phase changes, and the relationship of these concepts to the operation of the LCD. This dissection lab, followed by reassembly of the LCD watch, has been incorporated into classes ranging from *Introduction to Engineering* at UW to *General Chemistry* at Christian Brothers University (Figure 6). Introductory engineering courses often include dissection of a traditional consumer product such as an electric blender or an electric can-opener, and can be easily modified to include this LCD watch dissection, which provides the opportunity to introduce nanotechnology concepts.[17-18]

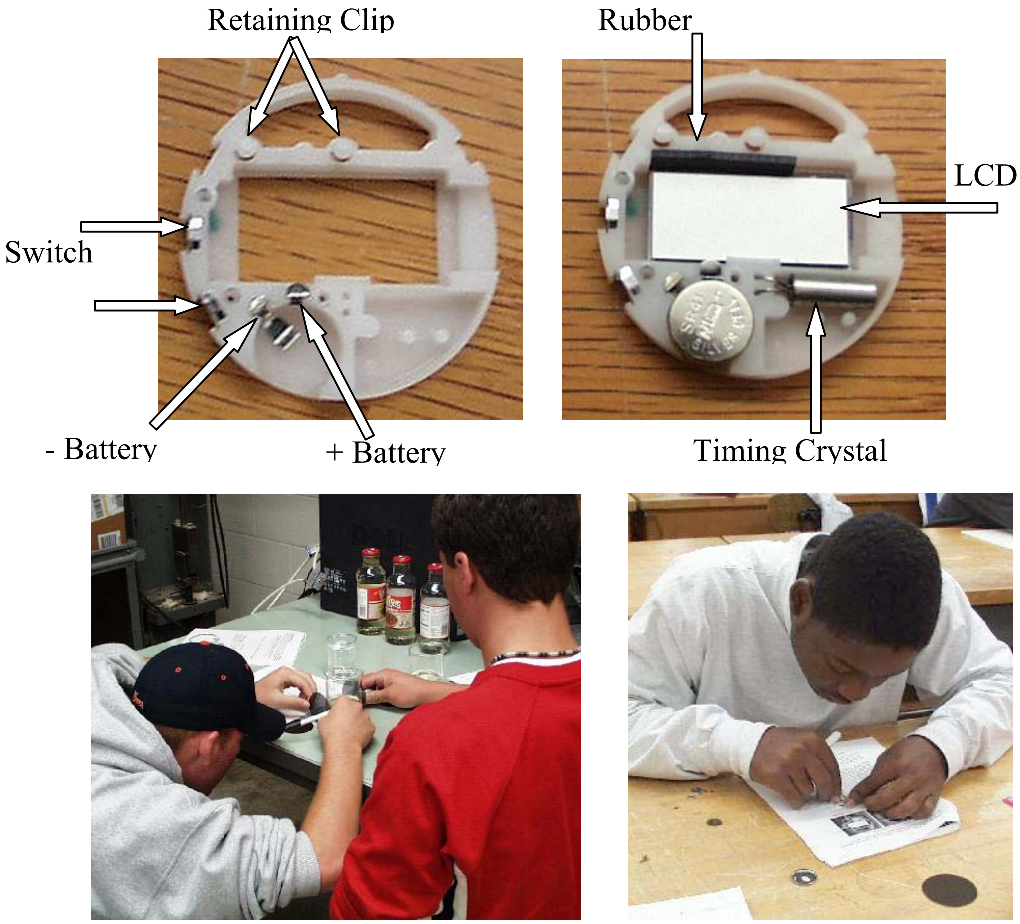

Figure 6. This experiment deals with the disassembly of an inexpensive liquid crystal display (LCD) wristwatch and the testing of several of the properties of the LCD panel. The top images shows the watch components identified by the students during the dissection. In the lower images, students are shown in a laboratory section of UW's *Introduction to Engineering* participating in the LCD watch disassembly-reassembly experiment.[14]

Conclusion

Nanotechnology is at the cutting-edge of science and engineering disciplines and will have a broad impact on society. It is essential that we as educators begin to prepare our students to meet the intellectual challenges posed by this technology so they can make successful contributions as members of the technical workforce. The educational materials created by UW MRSEC are focused on helping students understand the concepts and principles of nanotechnology in a variety of ways, from traditional written materials, to kits and, most recently, to a web-based video laboratory manual. The laboratories presented above have been used in a variety of institutional settings at both the undergraduate and graduate level. They have been successfully incorporated into engineering, materials science, mechanics, chemistry, and physics courses. The laboratory experiments have been used independently as an introduction to nanotechnology in a variety of courses and together as an in-depth laboratory component accompanying courses on nanotechnology, such as Chemistry 801 *Nanostructured Materials and Interfaces* and EMA 601 *Micro- and Nano-scale Mechanics* both taught at the University of Wisconsin – Madison. In addition to introducing concepts of nanoscale science and engineering, the use of a video-based lab manual has been found to be superior delivery method. The Ferrofluid Synthesis Laboratory has been done at all author's institutions, in courses taught by a variety of faculty (engineering, inorganic chemists, organic chemists, biochemists). Using text-based directions gave about 50% success rate; with the video prelab the success rate increased to over 90%.

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