Integrating Nanoscale Science and Engineering Concepts into Mechanics and Materials Classrooms

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ABSTRACT

Teaching modules devoted to nanoscale science and engineering concepts have been developed and integrated into key introductory and advanced undergraduate courses in the College of Engineering at the University of Wisconsin - Madison. In addition to one new course that has been created under this effort, existing courses have been modified, removing outdated content and replacing it with cutting-edge content based on current research and emerging applications in nanotechnology. For example, in the Introduction to Engineering course, the traditional dissection laboratory (commonly performed on a toaster or blender) was replaced with dissection of a liquid crystal display watch. In addition to learning about liquid crystals and their properties, students explore how new technology impacts design through this laboratory. Several of the new experiments and demonstrations developed have been contributed to a web-based *Laboratory Manual for Nanoscale Science and Technology* available at http://www.mrsec.wisc.edu/edetc/nanolab/index.html and the Nanoworld Cineplex available on the Internet at http://www.mrsec.wisc.edu/edetc/cineplex/index.html.

1. INTRODUCTION

Nanoscale science and technology are inspiring a new industrial revolution that some predict will rival the development of the automobile and the introduction of the personal computer [1]. The potential of nanotechnology has caught the attention of the Federal government. In December 2003, President Bush signed into law the "21st-Century Nanotechnology Research and Development Act," which authorizes $3.7 billion over the next four years for nanotechnology research [2].

By observing and manipulating materials at the nanoscale, researchers have been able to develop new materials with novel and extreme properties. These properties have been optimized and exploited, allowing industry to realize nanotechnology-based consumer products such as light-emitting diodes (LEDs), self-cleaning windows, and computer hard disks. Because of the diversity of disciplines pursuing research and applications in nanoscale science and engineering, nanotechnology has the potential to make an exceptionally broad impact [3,4].

The importance of this emerging technology to society and industry requires that colleges and universities take steps to adapt their curricula to ensure a capable future workforce as well as a more scientifically literate general population [5-7]. Some experts, including Mihail Roco, the senior advisor for nanotechnology at the National Science Foundation, predict a shortage of qualified and skilled nanotechnology workers in the next 10 to 15 years, when approximately 800,000 to 900,000 nanotechnology workers will be needed in the US [4]. This demand for a skilled workforce coupled with the projected $3 trillion nanotechnology market by 2015 make nanotechnology education a significant issue, one that Roco identifies as one of the "grand challenges" for nanotechnology [4]. Problem-solving will continue to be an important part of undergraduate education, as will the need to cultivate creative, critical, and entrepreneurial thinking [7,9]. Yet, science and engineering undergraduates will need a comprehensive education that includes nanotechnology in order to navigate successfully the challenges of the 21st century. Students need an interdisciplinary education in the basic sciences, the engineering sciences, and the information

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sciences, as well as an understanding of the relationships of these fields to nanotechnology. The interdisciplinary nature of nanotechnology is both a benefit and a challenge as faculty need to balance the breadth and depth of coursework in order to develop a technically-trained workforce [4,6].

A number of colleges and universities are meeting the challenge of integrating nanotechnology into the curriculum. In recent years, numerous education and outreach efforts have been developed to educate and inform students and the general public about nanotechnology [10-12]. In addition, courses in nanotechnology have begun to appear in college catalogs, and nanotechnology concepts have been incorporated into undergraduate general chemistry, physics and engineering courses [6].

This paper describes efforts undertaken at the University of Wisconsin – Madison (UW-Madison) to integrate nanotechnology into the undergraduate engineering curriculum through a National Science Foundation funded grant on Nanotechnology Undergraduate Education. Some modules that were developed are not only applicable to the undergraduate level, but with proper modification are applicable at the graduate level as well. The approach taken is two-fold in that it has impact on both new and existing undergraduate engineering courses. Table 1 lists some of the courses that have been affected by the effort to date. These courses cover a broad cross-section of students in a variety of disciplines. Included in this list is a new mechanics-oriented nanotechnology course, *Micro- and Nanoscale Mechanics*, which was developed in the Department of Engineering Physics and taught over the course of the Spring 2003 semester [13,14].

Integrating nanotechnology-based educational modules into selected existing courses in a manner which is consistent with the goals and structure of the courses is emphasized over injecting nanotechnology activities in an incongruous manner. Tailoring of the chosen modules to fit the needs and level of audience understanding is necessary to maintain the fluidity of the course and to ensure that the nanotechnology-based concepts and examples are incorporated into the curriculum over the long term rather than just making modifications to a course during that particular semester.

Discussion below will focus on three of our experiences of integrating nanotechnology modules into the undergraduate engineering curriculum at UW-Madison. The three activities discussed are: synthesizing nanowires, controlling an AFM remotely over the internet, and fabricating a nanofilter in a microfluidic device.

Table 1. Courses Modified to Integrate Nanotechnology into the Engineering Curriculum

Course Title	Target Audience	Nanotechnology Module Integrated
Introduction to Engineering (EPD 160)	Undeclared freshman	• LCD watch dissection • Careers in nanotechnology
Introduction to Modern Materials (MSE 250)	Undeclared freshman or sophomores	• Intro to nanotechnology • LCD watch dissection • Remote AFM • Synthesis of colloidal gold
Chemistry Across the Periodic Table (Chem 311)	Sophomores and Juniors	• Nickel nanowire synthesis
Materials Laboratory II (MSE 361)	Sophomores in MS&E	• Nanoscale structures using the Bragg bubble-raft • Nickel nanowire synthesis
Materials Laboratory III (MSE 362)	Juniors in MS&E	• Synthesis of nanoparticles • Shape memory alloys • AFM
Micro- and Nanoscale Mechanics (EMA 601)	Seniors and graduate students in MS&E, Engineering Mechanics, and ME	• Synthesis of nanoparticles • Nanofilter device - including surface modification • Nanoscale fracture using the Bragg bubble-raft • Shape memory alloys • AFM
Cellular Scale Explorations (BME 601)	Seniors and graduate students in Biomedical Engineering	• Nanofilter device - including surface modification
Advanced Mechanical Testing of Materials (EMA 611)	Seniors in Engineering Mechanics	• AFM instrumentation • Principles of nanomechanical measurements • Modification of surface properties using self-assembled monolayers
Nanostructures in Science and Technology (Physics 801)	Graduate students in physics and engineering	• Nickel nanowire synthesis • Self-assembled monolayer on silver • Synthesis of colloidal gold

2. Approach and Objectives

Approach

The authors come from a variety of disciplines (Chemical Engineering, Chemistry, Materials Science, Mechanics, and Physics) and all have substantial research experience in nanoscale science and engineering. Teaching experience at the undergraduate level is also included in the background of most of the authors. Their joint experience base also includes background in developing educational modules and dissemination of nanoscale concepts to a wide range of audiences. Additionally, our approach to the integration of nanotechnology into the undergraduate engineering curriculum leverages the experience of one author as the Director of the Interdisciplinary Education Group of the UW-Madison Materials Research Science and Engineering Center (MRSEC) on Nanostructured Materials and Interfaces.

The educational tools and experiments on nanoscale science that have been developed by the Interdisciplinary Education Group have been leveraged by modifying and expanding these materials to make them more relevant to the engineering classroom. New experiments on nanoscale engineering have been developed and are being incorporated into the dissemination avenues developed by the MRSEC. One key component of this existing infrastructure is the MRSEC web site (http://www.mrsec.wisc.edu/nano/), particularly the *Laboratory Manual for Nanoscale Science and Technology*, which currently contains twelve experiments for high school and college level lab classes, and the *Nanoworld Cineplex*, which contains movies of demonstrations of nineteen nanotechnology topic areas. This site is already recognized as a national resource for "Exploring the Nanoworld" [15].

Objectives

The objectives of this work support the general goal of promoting the development of a diverse workforce well versed in nanoscale science and engineering concepts and tools. More specifically, particular objectives of this work include:

- Incorporating nanoscale science and engineering concepts into courses covering several different fields of study;
- Maximizing the impact of the work by obtaining formative and summative feedback;
- Disseminating the results, lessons learned, teaching tools, and experiments developed to other educators;
- Institutionalizing the work into the engineering curriculum to insure the continued development and deployment of nanoscale science and engineering educational tools and experiments in the engineering fields; and
- Fostering interdisciplinary approaches to nanotechnology undergraduate education, particularly amongst engineering disciplines and between chemistry and engineering.

3. Integration of Nanotechnology into Existing Courses

The incorporation of nanoscale science and engineering concepts, educational modules, and educational tools into existing courses provides the most reliable means of institutionalizing the teaching of nanoscale science and engineering concepts to a broad cross-section of students. The advantage of this approach over the development of new courses is that existing courses are already integral components of the engineering curriculum. Because many of the existing nanoscale science and engineering educational tools and experiments available from the UW-Madison MRSEC were developed in collaboration with the chemistry departments at UW-Madison, Beloit College, and Christian Brothers University, the modules had been tailored for use in chemistry education [16]. The translation of these chemistry-based nanoscale science and engineering tools and experiments into the engineering setting has naturally enhanced the interdisciplinary nature of these materials.

The courses modified were selected utilizing two criteria: a diverse cross-section of students and/or large number of undecided engineering students; and whether or not the course could benefit from the integration of nanoscale science and engineering concepts. The courses chosen for modification are, for the most part, required courses for at least one engineering major. Additionally, the freshman-level courses chosen for modification have a large student population. Using existing courses also naturally emphasizes the broad range of subject matter in which nanoscale science and engineering will play an important role in the future.

Courses incorporating these modules include the Engineering Professional Development course *Introduction to Engineering* (for freshman who are interested in learning about engineering as a major); Materials Science courses *Introduction to Modern Materials* (freshman magnet course to expose students to materials science) and *Materials Laboratory II & III* (sophomore and junior lab courses in synthesis, characterization, and understanding of materials and their properties); and the Engineering Mechanics courses *Micro- and Nanoscale Mechanics* (introduction to mechanics on the micro and nanoscale for seniors/1st-year grad students) and *Advanced Mechanical Testing of Materials* (theory and practice in measuring stress, strain, hysteresis energy, and materials properties at deformation and fracture). In particular, the *Introduction to Modern Materials* and *Introduction to Engineering* courses are taken by freshman and have a great potential for impacting a large number of students and attracting them to fields where nanoscale science and engineering is of developing importance. Table 1 shows a sample of the breadth of courses that have been modified. Thus far, 337 UW-Madison students have learned about nanotechnology-related concepts through this project, and 232 of them have done so through a hands-on experience.

In this paper we limit our discussion to three particular modules which are being incorporated into the one or more courses. First, we discuss the integration of a laboratory module in which students use template synthesis to make nickel nanowires and then manipulate them with a magnetic field while observing them under a microscope. Second is a discussion of the integration of a module involving the control of an atomic-force microscope (AFM) through the internet into the freshman-level course *Introduction to Modern Materials*. Third is a discussion of a microfuidic nanofilter lab that was used at the senior-level for both the *Micro- and Nanoscale Mechanics* course and a new biomedical engineering course in *Cellular Scale Explorations*.

<u>Template Synthesis of Nickel Nanowires</u>

Courses impacted: *Chemistry Across the Periodic Table (Chemistry)*, *Nanostructures in Science and Technology (Physics), Materials Science Laboratory II (Materials Science & Engineering)*

The module on Template Synthesis of Nickel Nanowires represents a particularly striking example of the interdisciplinary nature of nanotechnology and of how one laboratory can be integrated into courses over a range of traditional disciplines. This module was successfully utilized in both intermediate-level chemistry and materials-science courses as well as a graduate-level physics course. Another innovative aspect of this module is that it was developed by a research graduate student who saw the opportunity to adapt a portion of her dissertation research into a two-hour laboratory experiment. This laboratory has been included in the *Laboratory Manual for Nanoscale Science and Technology* and is described in more detail in an upcoming issue of *The Journal of Chemical Education* [17].

In this module, a porous-alumina membrane, which is commercially available as a filter at low cost, is used as a template to electroplate nickel into the nano-scale pores of the membrane. A two-electrode cell is utilized with a nickel-wire anode, and an In-Ga eutectic which is applied to the porous membrane is utilized as the cathode. A copper plate insulated with electrician's tape is used as a cathode current collector and for structural support of the alumina membrane/In-Ga eutectic assembly. Since the pores of the membrane are cylindrical, nickel rods are formed in the pores during the electroplating. The membrane filters used in this laboratory experiment have a pore diameter of 200 nm. In order to make these nanowires visible under an optical microscope, enough nickel is electroplated to yield nanowires which are 10-50 μm long (depending upon the deposition time).

The alumina membrane/In-Ga eutectic assembly is freed from the current collector by immersing it in acetone to remove the adhesive from the tape. The In-Ga eutectic is dissolved with nitric acid and then the alumina membrane is dissolved in NaOH. After rinsing with water to dilute the basic NaOH, the nanowires are suspended in water, a drop of which can be transferred to a microscope slide for observation. The students are able to make the nickel nanowires respond to a magnetic field. For visualization purposes, the nanowires in this lab are 200nm in diameter, but much smaller diameter wires can be created with the same technique. The manipulation by magnetic field explored in the lab is related to an important new method developed for the construction of nanoscale devices [18].

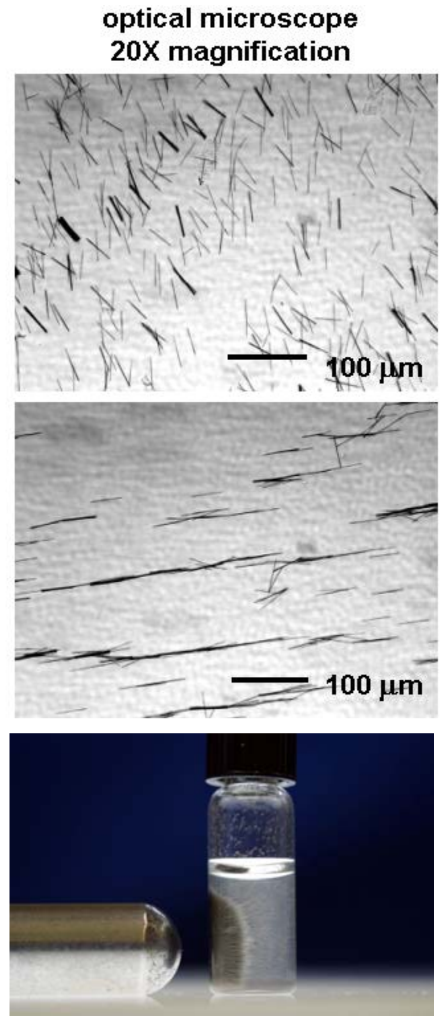

Figure 1. Photographs of nickel nanowires responding to an external magnetic field.

The process of developing this lab was iterative, and assessment was used extensively throughout the process. With the modifications and refinements that evolved out of the development stage, the laboratory can now be performed successfully by the vast majority of students on the first try. Some classes have explored related issues such as the relationship between deposition rate and mass loss of the nickel anode to nanowire length One exciting aspect of the high success rate of student performance in this lab is that it has opened up opportunities for student-initiated inquiry.

As mentioned above, this module has been utilized in several different types of courses. This module was adapted to address the needs of the instructor and the students in each of these courses. For example, in the intermediate-level chemistry course, the nickel nanowire synthesis was used as an example of electroplating techniques. In contrast to this example, when the module was utilized in the graduate-level physics course on nanostructures, the focus of the module was on the fact that this synthesis technique is one which can be used to produce nanostructures and the manipulation technique is one of several available for the assembly of nanoscale devices.

In addition to the traditional paper-based laboratory manuals, this laboratory has explored the use of a video-based format through the *Laboratory Manual for Nanoscale Science and Technology*. In some cases, the video lab manual (which is available at http://www.mrsec.wisc.edu/edetc/cineplex/nickel/index.html) was used as a supplement to a traditional paper-based lab manual. In other cases the video lab manual replaced the printed lab manual entirely.

Remote Internet Control of an AFM

Courses impacted: *Introduction to Modern Materials (Materials Science & Engineering)*

This module was developed to introduce students to the basic theory and operation of an AFM, which is an important forefront research tool in nanoscience and nanotechnology. The students enrolled in the course are generally freshmen and sophomores from a variety of disciplines. In lieu of utilizing the research-based AFMs which are on campus, a teaching-oriented AFM at the IN-VSEE (Interactive Nano-Visualization in Science & Engineering Education) project at Arizona State University was used [19]. This particular AFM is capable of being operated remotely over the Internet. Samples were prepared at UW-Madison by a teaching assistant and then shipped to ASU for the experiment. The sample that was used was a Si wafer spin-coated with a thin layer of PDMS and then plasma-treated to form wrinkles on the surface that are easy to see with AFM. Students took turns outside of normal class periods to conduct the experiment. During the experiment they were able to select several of the AFM parameters and acquire AFM images of the surface.

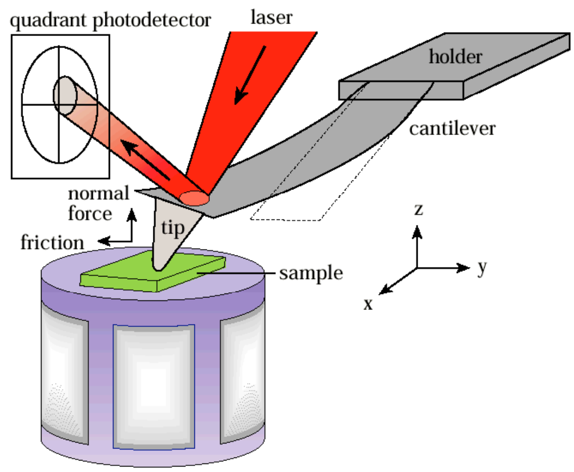

Figure 2. A schematic of AFM operation.

An AFM is a useful tool for studying nanotechnology, not only because it can have atomic-scale resolution, but also because many different types of information can be obtained from its use. An AFM works by using a piezoelectric positioner to move a probe across a surface and measuring the force response of the probe to the surface. The probe consists of a sharp tip integrated with a cantilever beam. The radius of curvature of the tip is typically less than 50 nm. As the tip moves across the surface, the interaction with the surface causes the cantilever beam to be deflected vertically due to normal forces, and twisted torsionally due to lateral (friction) forces. A laser beam is reflected off the back of the cantilever beam and a position-sensitive photodetector is used to detect the magnitude of the deflection and/or torsion. The long optical path length between the cantilever and the photodetector acts to amplify the displacements of the cantilever so that nanometer-scale deflections are observable at a reasonably sized photodetector and correspondingly, nanoNewton forces can be measured.

Deflection of the cantilever beam in the z-direction (normal to the surface) is a measure of the topology of the surface while torsion of the cantilever beam (measured as lateral deflections of the laser beam at the photodetector) can be used to measure the friction between the tip and the surface.

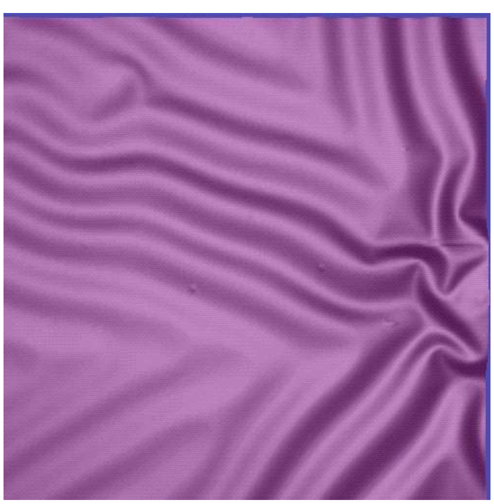

Figure 3. AFM image of a Si-wafer with a plasma-treated layer of PDMS obtained by a student controlling the remote AFM at ASU from UW.

In addition to imaging a surface and measuring its frictional properties, force-versus-distance curves in the z-direction can be measured. In this case, the tip is moved towards the sample. First, the tip makes contact with the sample, then the normal force acting on the tip increases, causing the cantilever to deflect. Once a pre-set amount of deflection is observed, the tip is withdrawn. Hysteresis in the force-versus-distance curve provides information about adhesive force interactions between the tip and the sample. Some of these concepts are beyond the scope of an introductory-level course, but are appropriate for a more advanced course. An example of an image obtained by a student during this module is shown in Fig. 3.

While the module was illustrative of a number of important topics, there were several drawbacks. One logistical issue was the scheduling of time outside of class for the students to conduct the experiment. This involved not only coordinating the instructor's and students' schedules, but also that of the ASU personnel who manage the AFM.

Another logistical problem was the speed of the computers used and the version of the web browser installed on the local machine. The AFM remote-control software is custom-made and not necessarily compatible with later versions of the browser for which it was designed. The software was also limited in the data that it would allow remote users to acquire, which restricted the students to contact-mode or constant-height mode images. A demonstration of tapping-mode imaging as well as lateral-force imaging would have been desirable.

Student feedback was solicited through a survey at the end of the course. Students reported that they were not sure that changes to the parameters that they requested were being implemented by the AFM remotely. An improvement in the software would be to provide the user with a height scale. This is particularly useful to convey the scales involved in the image data (*e.g.* x and y axes typically extend over a few micrometers while the z axis typical extends over a few dozen to a few hundred nanometers). The students' problems with the change in parameters seems to imply that they were lacking a solid context for understanding at what they were looking, and lacking a feel for the "nuts and bolts" issues involved in operating an AFM. Students also reported that they were interested in seeing an AFM close-up and in person which may have given them a better feel for the operation of the instrument.

From this experience, two new approaches to teaching this module have been identified. These alternatives are aimed at providing the students more context for acquisition of their AFM images. The first is a top-down approach where the students begin by viewing SEM images of the sample at increasing magnifications up to approximately 100,000X and then acquire a stereo image at that magnification to give them an estimate of the topology of the surface independent of their AFM images. The AFM would then be used to observe the topology of the same area of the sample that was imaged with SEM. The second is a bottom-up approach where students can view atomic-resolution AFM or TEM images of the sample that begin with high magnification showing individual columns of atoms then going to progressively lower magnifications until it is at the same magnification as the SEM image.

<u>Development of a Microfluidic Nanofilter Laboratory</u>

Courses Impacted: *Micro- and Nanoscale Mechanics (Engineering Physics)*, *Cellular Scale Explorations (Biomedical Engineering)*

The courses *Micro- and Nanoscale Mechanics* and *Cellular Scale Explorations* are two new senior- and graduate-level courses which fall under the auspices of *Special Topics in Engineering Mechanics* and *Special Topics in Biomedical Engineering*, respectively. These courses are designed to introduce students to state of the art engineering topics.

Both courses involve the examination of engineering problems at small scales. Into these two courses a laboratory component was included in which the students construct a microfluidic device designed to filter colloidal gold particles out of suspension. Microfluidics is an area of great interest in biomedical engineering and sensing applications due to the length scales involved in manipulating biological cells and the large surface areas available in such devices. Aspects of micro- and nanoscale mechanics through surface properties of materials and coatings used to control the construction and/or operation of the device.

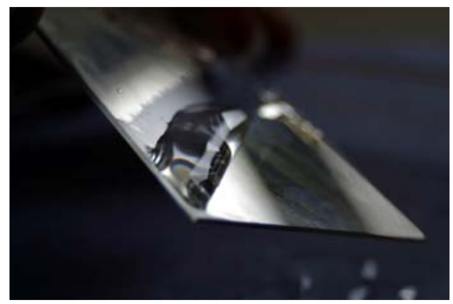

Figure 4. Water is unable to wet the functionalized silver coating resulting in a virtual wall.

This lab was inspired by the research on "virtual walls" in microfluidic devices by Beebe and Moore [20-21] as well as several smaller educational nanotechnology laboratories created by the University of Wisconsin Materials Research Science and Engineering Center (MRSEC) [22]. This lab involves several modules conducted over the course of the semester in which students fabricate microfluidic nanofilters, synthesize colloidal gold suspensions, and test their devices. The modules include 1) silvering and functionalizing glass slides; 2) characterizing the functionalized and unfunctionalized silver coatings (either with AFM or contact-angle measurements); 3) constructing the microfluidic channels; 4) forming a nylon filter membrane and synthesizing colloidal gold; and 5) testing the devices by filtering the colloidal gold from solution with the device

The devices are constructed by creating microfluidic channels on top of a glass slide that has been patterned with silver and functionalized with a self-assembled monolayer of hexadecanethiol. This patterning and functionalizing of the substrate allows the formation of a "virtual wall" at the interface between the hydrophilic untreated glass and the hydrophilic patterned/functionalized glass. The microfluidic channels are constructed so that the intersection of two perpendicular channels is spanned by the hydrophilic-hydrophobic interface. This virtual wall is then used to stabilize the interface between an organic solution of adipoyl chloride and an aqueous solution of 1,6-diammine hexane. A polycondensation reaction occurs at this interface to produce a nylon-6,6 membrane that is used to filter the colloidal gold suspension. This particular lab has been described in more detail in prior proceedings [13,14].

The first use of this module was in the Spring 2003 semester in the *Micro- and Nanoscale Mechanics* course. The students were provided with traditional written instructions for the laboratory modules. Teams of four to five students conducted the laboratory sessions outside of scheduled class time. Since it was impractical to have the students work exclusively on the lab for several days in a row and construct devices in a serial manner, the students constructed devices in parallel with each group began by preparing about 15 glass slides from which they would construct their devices. Not all devices were successfully constructed and several had to be discarded after each module. On average, about 25% of the glass slides with which the students started resulted in devices which successfully altered the appearance of the colloidal gold suspension. This change in appearance was taken to mean that that filtration was successful.

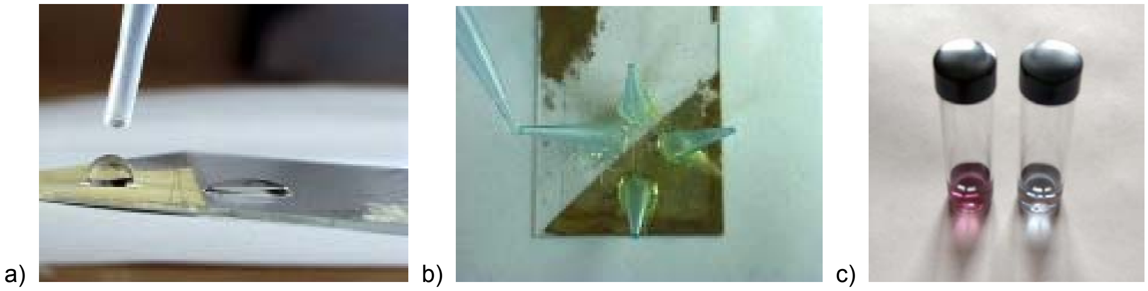

Figure 5. Microfluidic Nanofilter. a) Functionalized and unmodified regions of the glass substrate shown with water droplets; b) Top-view of microfluidic device; c) Colloidal gold –on the left is the suspension before passing through the device, on the right is the suspension collected after passing through the device.

The laboratory was filmed and incorporated in the *Laboratory Manual for Nanoscale Science and Technology,* available at: http://www.mrsec.wisc.edu/edetc/cineplex/fluidics/index.html. The laboratory was utilized in the Fall 2004 semester offering of *Cellular Scale Explorations*. In this iteration of the lab, students were not provided with written instructions. Instead, they were required to utilize the video-based laboratory instructions. Success rates for this iteration were about the same as in the engineering mechanics course. However, some students watched the video lab manual ahead of time, some watched it during their lab sessions, and others just printed out the browser pages for the lab and used that in place of the written lab manual. Some of those students who did not watch the videos, but just read the captions for the videos, indicated in post-course surveys that they did not have a solid understanding of what they were supposed to accomplish in each lab period. More explicit verbal instructions from the instructor as to how to use the video lab manual correctly would probably be helpful in obtaining a more consistent use of the video lab manual amongst the students.

4. CONCLUSIONS

Nanotechnology is an increasingly important aspect in many fields of science and technology. Today's students will be expected to have a background in nanotechnology in order to be effective when they enter the workforce. To this end there is an effort underway nationwide to incorporate nanotechnology into the engineering curriculum. At UW-Madison we have integrated nanotechnology modules into a broad array of courses deigned to affect as many students in as many engineering disciplines as possible. We have discussed three particular experiences in this arena that demonstrate some of the types of activities and methodologies that can be employed in integrating nanotechnology into the classroom.

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