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Teaching a Multidisciplinary Nanotechnology Laboratory Course to Undergraduate Students

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Here we report our efforts to teach the first multidisciplinary undergraduate nanotechnology laboratory course in the College of Engineering at North Carolina State University (NCSU). The course was designed to provide undergraduate students with hands-on experience in nanoscience and nanotechnology. The theme of this laboratory course is the integration of nanotechnology with microsystem technology, i.e., bottom-up synthesis meeting top-down fabrication. This course consists of seven carefully designed lab modules that bridge the major "pillars" of nanotechnology–nanomaterials, nanofabrication, nanoscale characterization, and nanodevices. Final projects provide students opportunities to conduct nanotechnology research through problem-based learning and to improve their communication and presentation skills for educating the public about nanotechnology. A pedagogical approach that features problem-based learning, group learning, visual/tactile assistance and interdisciplinary interaction was employed during the offering of this course.

Keywords: Nanotechnology, Undergraduate Education, Top-Down, Bottom-Up, Nanomaterials, Nanodevices.

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1. INTRODUCTION

Since the initiation of the National Nanotechnology Initiative (NNI) in January 2000, tremendous efforts have been spent to pursue nanotechnology related research and education that will help meet the economic, health, national security, and energy needs of the 21st century. As of 2009, about a quarter of a trillion dollars worldwide market was taken by nano-enabled products, of which about $91 billion was in the US. About 2 and 5 million workers will be needed worldwide in nanotechnology by 2015 and 2020, respectively (Roco, 2011). Educators must respond by organizing engineering courses and curricula to train this new workforce (Englander & Kim, 2011; Hersam et al., 2004; Winkelmann et al., 2011).

According to the Roadmap for Nanotechnology in North Carolina's 21st Century Economy, North Carolina has >70 companies working in nanotechnology. A large number of these companies are located in the research triangle park (RTP) area served by North Carolina State University (NCSU). Technically, these companies cover one or more aspects of nanotechnology such as nanomaterials, nanofabrication, nanoscale characterization, and nanodevices, following either the top-down or the bottom-up approach. Notable companies include Coventor and MEMSCAP, which are the world leaders in microelectromechanical systems (MEMS) design and fabrication, nCoat, which is specialized in nano-coating technologies, and Liquidia, which is using polymer nanoparticles for biomedical applications. Research consortia and government labs that are involved in nanotechnology include the Semiconductor Research Corporation (SRC) and NIH-National Institute of Environmental Health Sciences. These companies and research entities in North Carolina need employees who have received education about nanotechnology to assist with their research and technological innovations. Thus, there was an imperative need to develop nanotechnology undergraduate curricula at NCSU.

2. BACKGROUND

2.1. Bottom-Up Meeting Top-Down: Nanotechnology Advancement and Challenges

Richard Feynman's talk "There Is Plenty of Room at the Bottom" in 1959 has since inspired tremendous efforts

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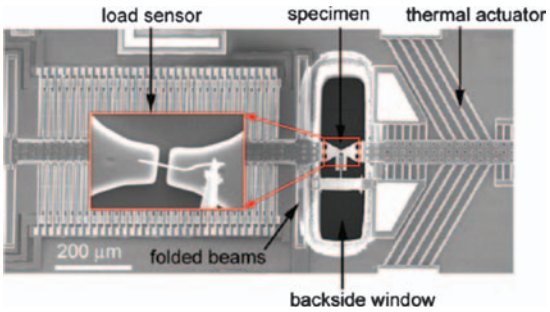

Fig. 1. MEMS-based nanoscale material testing platform to measure mechanical properties of nanomaterials (Zhu & Espinosa, 2005). Inset shows a CNT being mounted onto the platform.

in miniaturization. In the last three decades, MEMS have seen rapid progress with many successful military and commercial applications. Commercial products include the accelerometers from Analog Devices, the Digital Light Projector (DLP) projectors from Texas Instruments, inkjet printers from HP and the Nintendo Wii. Top-down fabrication has enabled the remarkable success of MEMS and now continues its stride to the nanoscale. Almost in parallel, advances in nanoscience and nanotechnology have enabled a multitude of technological innovations, especially in the area of nanomaterials. A large number of nanomaterials such as carbon nanotubes (CNTs) (Baughman et al., 2002), metal and semiconductor nanoparticles and nanowires (Xia et al., 2003), and graphene (Geim & Novoselov, 2007) are commercially available. A large number of nanomaterial-based products have also been successfully developed into products, such as nanotube-reinforced tennis rackets, coatings, sunscreens, and cosmetics that incorporate nanoparticles. In most of these products, however, nanomaterials are randomly accumulated, rather than assembled into devices.

Integrating nanomaterials into functional devices could further advance the progress of nano-technology. One route of integrating nanostructures is through molecular self-assembly defined by lithographic techniques such as micro-contact printing (Xia & Whitesides, 1998) and dip-pen nanolithography (Piner et al., 1999). Another route is through top-down fabricated micro/nano systems. MEMS offer unparalleled capabilities in manipulating, assembling and controlling nanoscale matters. A number of hybrid devices have been developed combining individual nanostructures with micro/nano fabricated structures, such as a transistor made of a single CNT lying between source and drain (Bachtold et al., 2001), a CNT-based nanoelectromechanical systems (NEMS) motor (Fennimore et al., 2003) and a MEMS-based nanoscale material testing platform to measure mechanical properties of nanomaterials (Zhu & Espinosa, 2005). Top-down approaches (micro/nano fabrication) hold great promise to enable the assembly of nanomaterials prepared using bottom-up approaches (chemical synthesis and self-assembly) into functional devices.

2.2. Nanotechnology Research and Education at Ncsu

The NCSU Nanotechnology Initiative promotes and encourages multidisciplinary partnerships in nanotech research and education. An aim of the Initiative is to expand hands-on engineering experiences in nanotechnology for undergraduate and graduate students. Within the College of Engineering, nanotechnology is one of the strategic thrust areas. Several courses in nanotechnology topics have been offered by different departments for junior and senior undergraduates. However, undergraduate students have not had access to a nanotechnology laboratory course.

Extensive research on how students learn about nanotechnology, nanoscale science, and concepts of size and scale has been carried out at NCSU. For example, co-author Jones and collaborators developed *the nanomanipulator* for students and museums to use to control the atomic force microscope (AFM) from remote locations. Jones has studied the impact of interactions with nanoscientists on students' concepts of science and scientists (Kubasko et al., 2008), differences in African-American and female students' perceptions of nanoscale investigations (Jones et al., 2007), the impact of haptic (tactile) sensory perception of nanoscale materials (Jones et al., 2003; Jones et al., 2006), and strategies to teach nanoscale science to students (Jones, 2008; Taylor et al., 2008). Findings from these studies suggest that teaching nanotechnology through problem-based contexts and providing students with direct experiences with tools and techniques are highly effective (particularly in comparison to simulations).

These studies of nanoscience education have shown that meaningful understandings of nanoscale phenomena result from the use of problem-based, active learning strategies. This type of learner-centered pedagogy promotes student engagement and connected knowledge. In recent years, engineering education has moved towards an interdisciplinary approach.

3. GOAL AND OBJECTIVES

In response to the national and local need in nanotechnology education, four faculty members from the College of Engineering and one member from the College of Education at NCSU have employed their collective knowledge in nanotechnology and education to develop a multidisciplinary nanotechnology laboratory course to help introduce undergraduate students to this field of nanoscience and nanotechnology. This course was made possible by a NSF Nanotechnology Undergraduate Education (NUE) award. Our goal was to provide undergraduate students at NCSU with hands-on experience in nanoscale science and engineering.

The theme of this laboratory course is the integration of nanotechnology with microsystem technology, i.e.,

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bottom-up synthesis meeting top-down fabrication. It bridges the major "pillars" of nanotechnology–nanomaterials, nanoscale characterization, and nanodevices. This lab course has an emphasis on size-dependent properties at the nanoscale, which is critical as novel properties enable new applications. The NUE program was designed to encourage more undergraduate students in the US to pursue graduate study related to nanotechnology and to train a workforce for the emerging nanotechnology industry. The objectives of this laboratory course are for students to:

(1) become knowledgeable about key areas of nanotechnology (nanomaterials, fabrication, characterization and devices) with the bottom-up meeting top-down concept;
(2) understand how size affects the properties of nanomaterials and the performance of nanodevices through hands-on experiments and real-time observations;
(3) become familiar with and able to use nanoscale instrumentation and techniques;
(4) conduct nanotechnology research through problem-based learning in the final projects;
(5) be prepared for more advanced degree and/or nanotechnology-related work.

4. NANOTECHNOLOGY LABORATORY COURSE

The multidisciplinary nanotechnology laboratory course includes classroom instruction, seven lab modules, and final projects. The lab modules are designed based on the instructors' expertise and the effective learning strategies learned from previous pedagogical research such as problem-based learning, group learning, visual/tactile assistance and interdisciplinary interaction. Final projects are designed to further enhance the problem-based learning of students.

The nanotechnology laboratory course was first taught at NCSU in the Fall 2011 semester. Senior-level undergraduates from all engineering departments were invited to enroll in the class. Consistent with the multidisciplinary appeal of nanotechnology, the course attracted sixteen undergraduate students from a variety of departments including electrical and computer engineering, mechanical and aerospace engineering, materials science and engineering, nuclear engineering and textile engineering. The students were divided into four groups with four students in each group. Each group conducted the labs as well as the final projects together. The grade consists of lab reports, a final project and a final exam.

4.1. Classroom Instruction

Each lab module includes a mini-lecture to provide students with the background information needed to meaningfully understand the module investigations. The laboratory protocols, processes and characterization techniques are presented. Through the combined mini-lecture and laboratory investigation format, students are better prepared to learn fundamental nanoscience and the principles of the tools and techniques that they will apply in the labs.

4.2. Laboratory Modules

The lab modules are carefully designed to cover various aspects of nanotechnology such as synthesis of nanomaterials, micro/nano-fabrication, nanoscale property characterization, and development of nano devices. All the lab modules emphasize the concept of bottom-up meeting top-down, and some of the lab modules are closely related to each other. In addition to learning fundamental nanoscience, students gain experience in operating advanced instruments for nanoscale fabrication, property characterization and device measurement.

4.2.1. Module #1–Gold Nanoparticles: Synthesis, Optical Properties and Sensor Application

Au nanoparticles (NPs) are of interest in many fields due to their surface plasmon resonance (SPR) in the visible spectrum. The SPR is an oscillation of the conduction electrons in Au in response to the electric field of light, resulting in absorption and scattering of light of a particular wavelength. The SPR wavelength of uncoupled, well-dispersed, spherical Au NPs is 520 nm, which gives solutions of Au NPs a red color. If the NPs agglomerate, the SPR wavelength shifts to the red, resulting in a pink-purple hue (Fig. 2).

A wide range of applications utilize Au NPs. For example, Au NPs can have much greater catalytic activity than

Fig. 2. Photographs of Au NP solutions and demonstration of sensing: (left) well-dispersed Au nanoparticles and (right) agglomerated Au nanoparticles after adding NaCl.

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bulk Au and are particularly useful for decomposing environmental pollutants. Plasmonic NPs have also been used to enhance the photovoltaic efficiency of solar cells and the emission efficiency of light-emitting diodes. Au NPs provide strongly enhanced sensitivity for surface enhanced Raman spectroscopy (SERS), which facilitates ultrasensitive detection of molecules. Au NPs are also of interest for agglomeration-based biosensing if the NPs surfaces are engineered to drive agglomeration in the presence of an analyte. The color change that accompanies agglomeration is often discernible by eye, and agglomeration of Au NPs is the mechanism of the color change employed in some pregnancy test kits (Bangs, 1996). In some instances, the SPR shift can also be calibrated to measure the distance between NPs, which is known as a plasmon ruler (Jain et al., 2007; Sönnichsen et al., 2006).

In this lab module, students perform an aqueous-phase synthesis of Au NPs, where Au(III) in $HAuCl_4$ is reduced to Au(0) by sodium citrate, and Au(0) atoms nucleate and grow into NPs (Frens, 1973; McFarland et al., 2004). The nucleation rate is controlled by the amount of sodium citrate added, which controls the reduction rate. Faster nucleation gives more nuclei, resulting in smaller final NP sizes. The products are characterized by optical absorbance spectroscopy to measure the SPR, and transmission electron microscopy (TEM) is performed to analyze the NP sizes. Agglomeration of the NPs is demonstrated by adding $NaCl_{(aq)}$, which causes a shift in the SPR wavelength that is also measured by optical absorbance spectroscopy.

Student Learning Objectives: (1) to understand the concepts of nucleation and growth during nanoparticle synthesis; (2) to become familiar with optical absorbance spectroscopy and TEM; (3) to understand the SPR and its application for sensing.

4.2.2. Module #2–ZnO Nanowires: Synthesis and Characterization

One-dimensional (1D) materials represent one of the most important building blocks of nanotechnology. With reduction in size, novel electrical, mechanical, chemical and optical properties are realized. ZnO is an important semiconducting and piezoelectric material with a large exciton binding energy and a wide band gap. As such, ZnO nanowires (NWs) have received much attention due to their potential applications in electronics, photonics energy harvesting and sensing (Wang, 2004).

Semiconductor NWs are commonly synthesized by the vapor–liquid–solid (VLS) approach at high temperature. For ZnO NWs grown via the VLS process, a common catalyst is Au NPs, as shown in Figure 3(a). The liquid droplet serves as a preferential site for absorption of gas-phase reactants and, when supersaturated, as the nucleation site for crystallization. NW growth begins after the liquid becomes supersaturated with the reactants and continues as long as the catalyst alloy remains in a liquid state

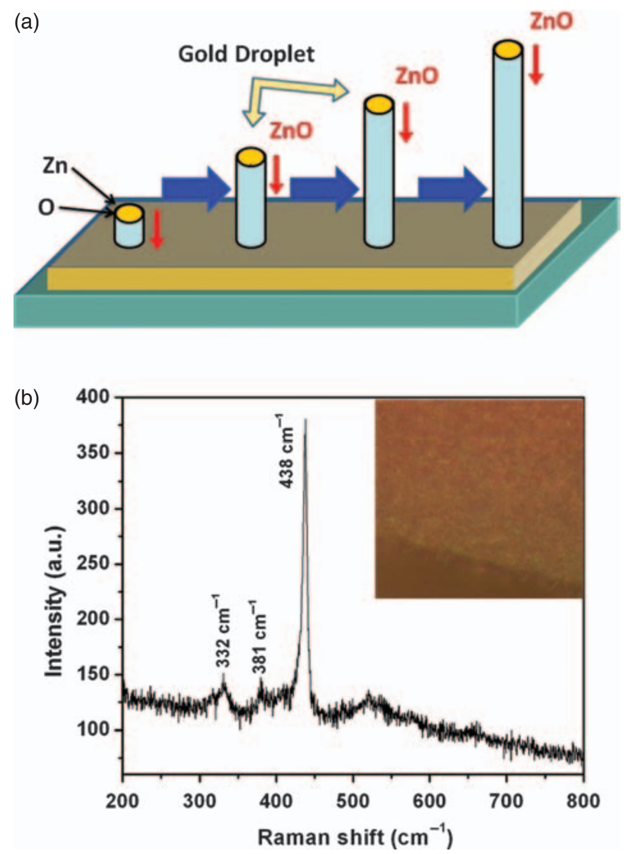

Fig. 3. (a) Schematic of the VLS growth. (b) Raman spectrum of ZnO NWs. Inset is an optical image of the as-synthesized ZnO NWs.

and the reactant is available. During growth, the catalyst droplet directs the growth direction of NW and defines their diameter (Xu et al., 2010).

Raman spectroscopy provides information about molecular vibrations that can be used for chemical identification, characterization of molecular structures, effects of bonding, and stress on the sample. The technique involves shining a monochromatic light source (i.e., laser) on a sample and detecting the scattered light. A very small amount of the scattered light (*ca.* 10^{-5} of the incident light intensity) is shifted in energy from the laser frequency due to interactions between the incident electromagnetic waves and the vibrational energy levels of the molecules in the sample. Plotting the intensity of this "shifted" light versus frequency results in a Raman spectrum of the sample (Soudi et al., 2009).

In this lab module, students synthesize ZnO NWs using the VLS method and characterize their Raman spectrum. The synthesis processes are usually carried out in a horizontal tube furnace (Manoharan et al., 2008). ZnO powder (Alfa Aesar, 99.99%) and graphite powder (Alfa Aesar, 99.99%) are mixed in 1:1 by weight ratio as the source material. A thin layer of Au (~20 nm thick) deposited on top of a Si substrate is used as the catalyst. Argon gas at a flow rate of 20 sccm is the carrier gas. The synthesis

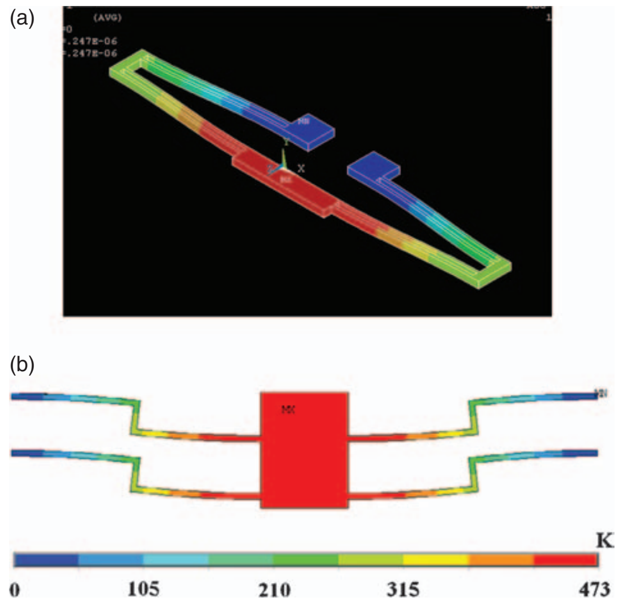

Fig. 4. Simulation models for (a) a micro folded spring and (b) a Z-shaped thermal actuator.

process takes place at at ~1000 °C for about 45 minutes. A LabRAM HR system (Horiba Scientific) is used to acquire the Raman spectrum of ZnO NW samples. The internal laser with the wavelength of 632 nm is selected as the laser source.

Student Learning Objectives: (1) to understand the growth mechanism of semiconductor NWs; (2) to understand the operating principle of Raman spectroscopy; and (3) to learn how to operate a tube furnace system and a Raman spectroscopy.

4.2.3. Module #3–MEMS/NEMS Design and Simulation

MEMS and NEMS devices play important roles in nanotechnology. Many of such devices are used in our daily lives, such as micro-switches in cell phones and accelerometers vehicles. Design of M/NEMS devices typically involves interplay of multiple (electric, mechanical, thermal and etc) domains. In this lab module, a folder spring structure and a Z-shaped thermal actuator (Guan & Zhu, 2010) are used as the case-study examples for students to practice device design and simulation. Multiphysics modeling is used to characterize the designed devices, so as to validate design objectives and optimize device design before moving to the expensive fabrication stage.

In this lab, students start with CAD design of a MEMS device, and perform multiphysics modeling using a commercial package, ANSYS, to validate design objectives from theoretical analysis. The procedure includes creating the solid model using CAD, setting up material properties and boundary conditions, meshing the model, performing static/dynamic analyses. Students then evaluate the performance of the MEMS device (e.g., mechanical stiffness, displacement, temperature distribution, etc.) and verify design objectives.

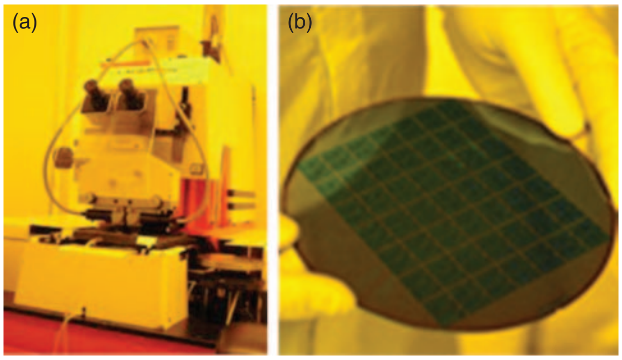

Fig. 5. (a) Overview of a mask aligner. (b) Fabricated photoresist pattern on a silicon wafer.

Student learning objectives: (1) to understand the design principles of M/NEMS devices; (2) to learn multiphysics modeling and simulation procedures; and (3) to apply multiphysics modeling for design of N/MEMS devices.

4.2.4. Module #4–MEMS/NEMS Fabrication

Micro/nano fabrication involves several key processes including lithography, deposition, and etching. In photolithography, micro/nanoscale patterns are transferred from a mask to a light sensitive photoresist. A deposition process deposits desired materials onto a device, and an etching process removes a selected portion of material from a device. By combining these three processes together repeatedly, micro/nano devices can be fabricated from different functional materials. In this lab, students fabricate a simple comb-drive actuator by going through the major fabrication processes.

During this lab, students have the opportunity to work inside a cleanroom at the NCSU Nanofabrication Facility. They go through photolithography and deep reactive ion etching (DRIE) processes to fabricate a comb-drive-based MEMS probing device. A photomask is provided to students, and students work in groups to make patterns from the photomask on a Karl Suss MJB6 Mask Aligner. Students gain experience in photolithography, including wafer cleaning, spin coating photoresist, exposure and developing, and sample inspection in a microscope. On these samples, photoresist layer is patterned as etching mask for the following DRIE process. The fabricated devices are inspected in an optical and a scanning electron microscopy (SEM).

Student learning objectives: (1) to understand the basic principle of micro/nano fabrication; (2) to obtain clean room experience for microfabrication; and (3) to become familiar with the major fabrication processes and the fabrication flow for a M/NEMS device.

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4.2.5. Module #5–MEMS/NEMS Testing and Characterization

It is not trivial to measure temperature with micrometer spatial resolution. As mentioned in module #2, Raman spectroscopy measures the scattered light caused by the interaction between a laser and the sample. Using the Raman spectroscope's ability to detect light scattering due to phonon vibrational energies allows one to correlate the Raman spectrum data with the temperature of the sample. Several characteristic changes occur at the Raman spectrum with changing temperature. Of particular interest to this lab, increased temperature shifts the Raman peaks towards larger wavenumbers (lower photon energies) (Kearney et al., 2006; Qin & Zhu, 2012). For silicon, the change in the peak position can be converted to the temperature rise,

$$\Delta T = \frac{\Omega - \Omega_0}{-0.0242} \frac{\mathrm{K}}{\mathrm{cm}^{-1}} \tag{1}$$

where Ω_0 and Ω are the measured peak positions at the laboratory temperature of 296 K and at the operating temperature, respectively.

This lab module consists of two activities performed on a Z-shaped thermal actuator (Fig. 6): (1) displacement and resistance measurement in a probe station; and (2) temperature measurement via Raman spectroscopy (Raman thermometry). Note that the Z-shaped thermal actuator was simulated in lab module #3. When a voltage is applied across the actuator, the Joule heating effect generates heat and temperature rise in the kinked beams. Due to the overall symmetry, the Z-shaped beam deflects and moves the central shuttle forward (downwards in Fig. 6(a)). Students are required to estimate the average temperatures in the thermal actuator using the displacement data and resistance data (Guan & Zhu, 2010), respectively. Following Eq. (1), localized temperatures can be calculated and compared with the average temperatures estimated from the displacement and resistance measurements.

Student learning objectives: (1) to understand the mechanism of temperature measurement using Raman spectroscopy; (2) to operate M/NEMS devices in a probe station and perform simple structural and electric measurements.

4.2.6. Module #6–Microsphere Self-Assembly and Nanolithography

Self-assembly (SA) is the autonomous organization of components into patterns or structures without human intervention (Whitesides & Grzybowski, 2002). SA is a thermodynamically-driven process that minimizes the Gibbs free energy at constant temperature and pressure. Uncontrolled agglomeration is a related process that lacks the order of self-assembled structures. SA requires weak interactions that exhibit some degree of reversibility or

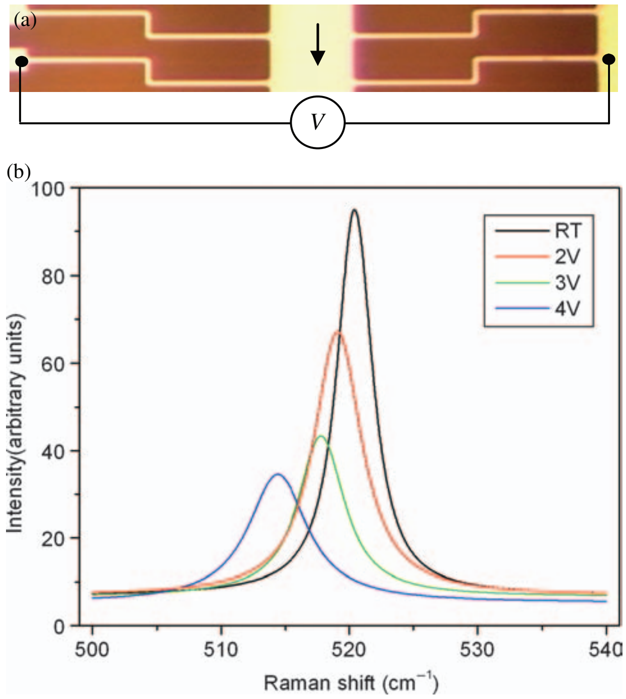

Fig. 6. (a) An optical image of the Z-shaped thermal actuator. (b) Representative Raman spectra of the Z-shaped thermal actuator at room temperature and different actuation voltages.

adjustability, which enables self-correction of errors during the assembly process. SA is ubiquitous in nature and describes process such as crystallization and cell membrane, protein, and nucleic acid function (Whitesides & Boncheva, 2002).

When a concentrated solution of polymer microspheres dries under certain conditions, a close-packed monolayer of microspheres forms. This microsphere monolayer can serve as a mask for the deposition of metals in the interstitial sites. After performing lift off by rinsing with solvent to remove the microspheres, a patterned array of metal islands remains. This technique of nanofabrication is known as microsphere nanolithography (Haynes & van Duyne, 2001). The island size and spacing directly depend upon the microsphere size. Metal islands produced in this manner have been particularly useful for sensing applications such as surface-enhanced Raman spectroscopy (SERS) and catalysis.

In this lab module, students investigate the self-assembly of commercially-obtained polystyrene microspheres with diameters of 0.5–3.0 μm into monolayers through dropcasting of an aqueous suspension. Monolayers deposited onto glass are imaged by optical microscopy, and ~50 nm thick layers of Au are thermally evaporated or sputtered onto microsphere monolayers deposited on Si substrates. After depositing Au, the microspheres that served as a mask are lifted off by rinsing with water, followed by acetone to accelerate drying. The remaining Au islands are then imaged and measured using scanning electron microscopy (Fig. 7). In the lab reports, students discuss how the sizes of the Au islands and the spacings between islands correlate with the microsphere size.

Student learning objectives: (1) to understand the concept self-assembly; (2) to become familiar with optical and scanning electron microscopies; and (3) to gain proficiency at formation of microsphere monolayers and microsphere nanolithography.

4.2.7. Module #7–Applications: Energy Harvesting and Biosensing

Piezoelectric energy harvesting: Energy harvesting is an alternative approach to reclaim energy from available sources in the M/NEMS environment and to convert it into electrical energy to power the M/NEMS. Mechanical vibration sources exist abundantly in the ambient environment of M/NEMS. Piezoelectric transducers play an important role in vibration power harvesting. Extensive nanotechnology research on piezoelectric nanostructures aims to achieve more efficient vibration energy harvesting.

In this sub-module, students investigate vibration energy harvesting in groups using piezoelectric transducers. Each group of students is given a cantilever transducer. They mount the mass and the transducer onto a vibration platform, adjust the vibration input and record the output power by measuring the output voltage and the current through a resistive load. The energy harvesting efficiency is then calculated and compared with reported results. Figure 8 shows the experimental setup for harvesting vibration energy.

Student learning objectives: (1) to understand the working principles of vibration energy harvesting; (2) to became familiar with piezoelectric transducer; and (3) to learn how to calculate energy harvesting conversion efficiency.

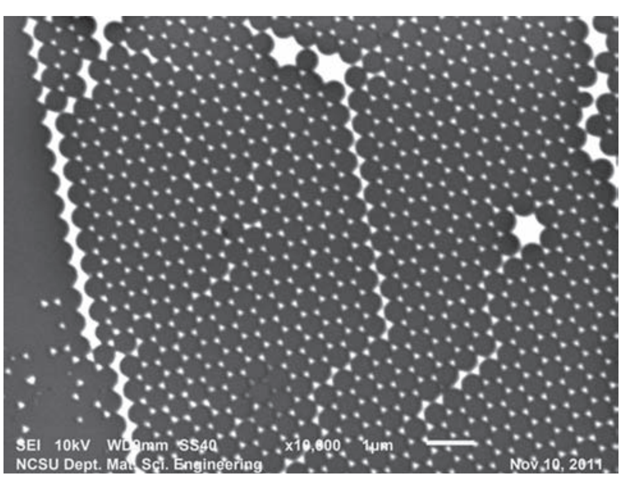

Fig. 7. SEM image of the pattern of Au islands obtained through microsphere nanolithography using 0.5 μm polystyrene microspheres.

Cantilever-based biosensing: Micro/nano cantilevers have been extensively used in nanoscale sensing application such as physical, chemical, and biological sensing. A resonant frequency shift resulting from biochemical absorption, change in stiffness, or added mass can be measured with high signal-to-noise using piezoelectric micro/nano cantilever sensors (Fig. 9). New developments in nanomaterials, nanostructures and nanofabrication techniques will further advance micro/nano cantilever sensor technology, which is a good example for students to learn how nanotechnology enables advanced sensors.

In this sub-module, students employ piezoelectric cantilever sensors with different feature sizes for precise mass detection, which is critical in sensitive biosensing applications. Students position a metal mass onto the tip surface of the cantilever (to mimic biosensing), and record the resonant frequency of the piezoelectric cantilever sensor before and after loading using a HP 4294A impedance analyzer. By relating the resonant frequency shift to the added mass, students can calculate the sensitivity of each cantilever sensor.

Student learning objectives: (1) to understand the working principles of cantilever sensors and piezoelectric read-out methods; (2) to operate impedance analyzer for resonant frequency recording; and (3) to understand the relationship between the cantilever feature sizes and the sensitivity through the sensitivity analysis.

4.3. Final Projects

The final projects build upon the knowledge and skills that students have learned from the lab modules. Each group of four students identified a problem of interest through discussions with the course instructors. Topics for the final projects came from the course instructors, other faculty members, local industries, or student suggestions.

One objective of this course was for students to improve their communication and presentation skills for educating the public about nanotechnology. To help develop these abilities, we experimented with an innovative format for the final projects. The students were required to give a 15 minute presentation with an interactive component to a local high school physics class (Raleigh Charter High School). The students were required to develop presentations that were interactive through the use of models or mini-labs, to demonstrate effective communication skills (eye contact, voice projection), and to deliver accurate technical information at an appropriate content level for the audience.

Development of Student Projects. Since many of the students had never taught a class or presented technical information to the public, the students were supplied with a checklist that noted the important aspects of communication and a rubric that was designed to capture the

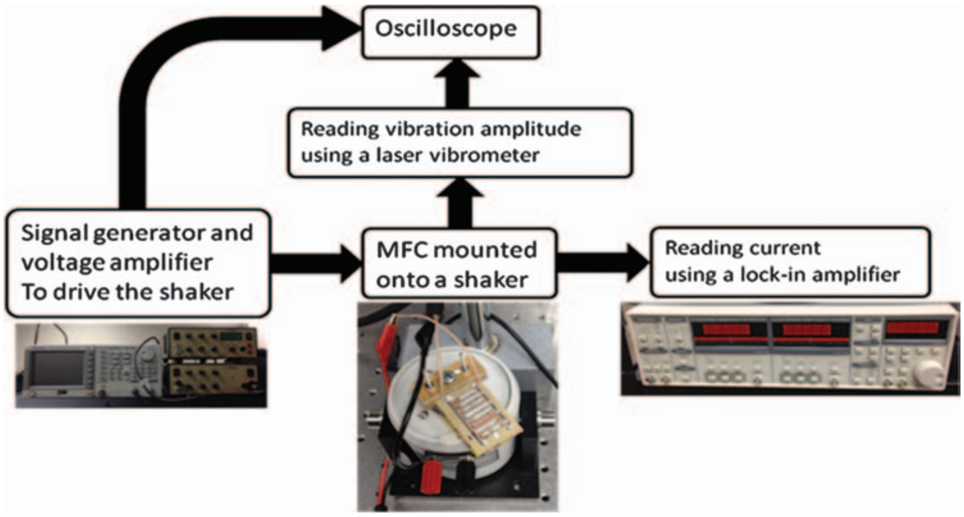

Fig. 8. Experimental setup for vibration energy harvesting tests. Piezoelectric macro-fiber composite transducer with inter-digital-electrode was used for vibration energy harvesting.

effectiveness of their presentation and the delivery of technical information to high school students. Once the students developed their presentations, they were required to practice their presentation with science educators before presenting to the high school students.

The students presented their projects to a class of ~25 high school physics students. Science educators, nanotechnology professors, the high school physics teacher, and high school students were provided a rubric designed to evaluate communication skills, the delivery of technical content at an appropriate level, and the interactive component of the presentations

Student Project Examples. One group of students created a presentation called "Tiny Science." The group introduced the concept of CNTs and discussed the application of CNTs in batteries. They created an interactive quiz designed to engage the students in thinking about the size and scale of objects and the use of CNTs in batteries.

Another group demonstrated the materials and methods used to build flexible electronics. The students discussed the possible applications of flexible electronics in cancer diagnosis and treatment, portable electronics, and flexible solar cells. To actively engage the high school students, the group demonstrated the concept of flexible electronics by having students build a model with a rope, a rubber band, and glue.

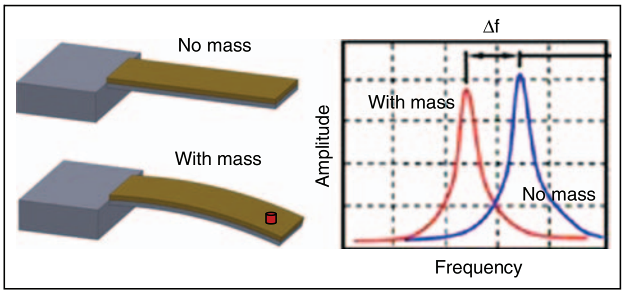

Fig. 9. Schematic of mass sensing based on frequency shift.

Student Feedback on the Projects. Students were asked if they thought they are better able to educate the public about nanotechnology as a result of taking the class and doing the presentations at the high school. Students were very supportive of the projects and noted that they enjoyed working together to design and implement their presentations. One student stated that he "[planned to return to his own high school] to duplicate what we are doing at the high school for this class." Although some of the students stated that it was difficult to communicate the technical aspects of nanotechnology to the general public, many students responded positively stating that they are better able to describe nanotechnology applications to others as a result of the projects and the class.

5. EVALUATION-ASSESSING THE COURSE IMPACT

Students' perceptions of the nanotechnology class were assessed with written evaluations at the end of the course. The assessment included 24 items that included questions related to each of the seven laboratory modules. There were 16 students (2 females, 14 males) in the class from a range of engineering majors that included 2 materials science engineering, 10 mechanical engineering, 1 textile engineering, and 1 nuclear engineering, and 2 electrical engineering). The mean pre-instruction score was 51.95 and the mean post-instruction score was 79.14. Analysis with a t-test showed that the differences from pre to post were statistically significant ($t(14) = -7.98$, $p < .001$).

There were open-ended items on the evaluation that asked students to comment on the various components of the class and the instruction. When asked about the most useful part of the class the responses were varied

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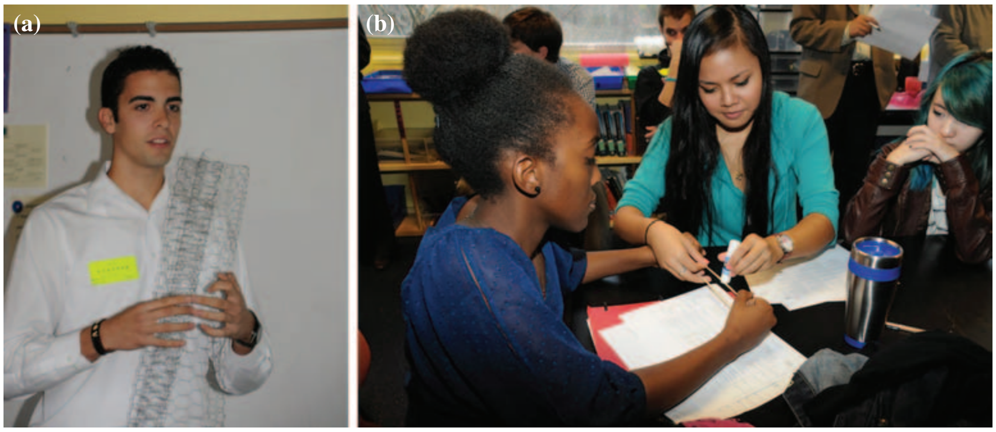

Fig. 10. (Left) A student demonstrating a CNT model in front of high school students. (Right) High school students are making "flexible electronics" using ropes, rubber bands and glue.

and included learning new laboratory techniques, making new nanomaterials (such as nanoparticles) and seeing different nanodevices and how they functioned, as well as the interdisciplinary nature of nanotechnology. Criticisms of the course included a lack of time to explore concepts and techniques more deeply, having multiple instructors, and having to apply subjects outside of their disciplinary engineering field (e.g., during the final projects).

Students were asked how their knowledge of nanotechnology changed from the beginning to the end of the class. Responses included comments about increased interest in nanotechnology, a deeper understanding of the interdisciplinary nature of nanotechnology, and a deeper understanding of the variety of processes used in nanoengineering. One of the evaluation questions asked participants if there were new ideas of interest to them as a result of taking the class. Students noted they were more interested in applications of nanotechnology in making new products, such as nanospheres, flexible electronics, energy harvesting, and the potential of nanostructures.

One of the implicit goals of the course was to increase students' interest in pursuing additional coursework in nanotechnology and to consider a future career in nanoscience or engineering. The majority of the students indicated that they had already chosen a career pathway other than nanotechnology and had not changed their career plans. Several of the students noted that they would pursue additional courses that would integrate nanotechnology into their current field of study.

When asked if they felt better able to educate the public about nanotechnology as a result of taking this class, all of the students indicated that they could now explain nanotechnology better. For example, one student said, "Yes, I was telling my girlfriend and parents about nanotechnology and I do feel better equipped (to discuss the topic)." Another said, "I have a better understanding of simple devices we use everyday. I would not have known that they had nanotech devices in them without taking this class."

In summary, the students in the class made significant improvements in their knowledge of nanotechnology laboratory techniques and applications. The course was viewed as a positive experience that increased students' interest of nanoscale engineering. The final projects were reported as helpful to students in communicating about nanotechnology to others. Furthermore, students reported that as a result of taking the class they had a better understanding of the interdisciplinary nature of nanotechnology.

6. CONCLUDING REMARKS

This paper describes our efforts to teach the first multidisciplinary undergraduate nanotechnology laboratory course in the College of Engineering at NCSU. A highlight of this course is the seven carefully designed lab modules that bridge the major "pillars" of nanotechnology–nanomaterials, nanofabrication, nanoscale characterization, and nanodevices. In addition, the final projects employed an innovative format; students were required to present their projects in an interactive manner to high school students. The final projects provided a means for students to improve their communication and presentation skills for educating the public about nanotechnology, in addition to conduct nanotechnology research through problem-based learning.

Evaluation results showed that this class significantly improved the students' knowledge and skills in nanotechnology. The most useful part of the class from the student's perspective included learning new laboratory techniques, making new nanomaterials and seeing different nanodevices and how they functioned, as well as the interdisciplinary nature of nanotechnology. Criticisms of the course included a lack of time to explore concepts and techniques more deeply, having multiple instructors, and having to apply subjects outside of their engineering field. Based on these results, the authors will continue teaching the course with these lab modules. Improvements will include adding more mini-lectures, better coordination among the instructors and, where possible, to create opportunities for students to explore topics in depth. We envision that a critical mass will be reached to create an undergraduate concentration in nanotechnology at NCSU, especially with the recent establishment of a Nanosystem Engineering Research Center at NCSU.

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