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IMPACTING UNDERGRADUATE NANOSCIENCE AND NANOENGINEERING EDUCATION

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ABSTRACT

This National Science Foundation supported Nanotechnology Undergraduate Education (NUE) project takes into account the need for a better integration of theory, experiment, and applications. We have reported three different approaches toward enhancing undergraduate nanoscience and engineering education with an emphasis on devices and systems. We are using the practical approach of direct engagement of the students in ongoing research in our advanced materials laboratories. Our first activity for enhancing nanoscience and nanoengineering education was to introduce simple concepts of nanoscience and technology into existing required undergraduate engineering courses. Introducing the concepts of nanoscience and engineering at this early stage of undergraduate education was found to positively impact student interest in registering for a technical elective nanotechnology course that we developed as our second initiative. Under our third initiative, a limited number of undergraduates well-imbued with this foundational perspective were recruited and financially supported to engage in a semester-long research project related to nanotechnology. The efforts made by the NUE team have befitted mechanical undergraduate students at sophomore, junior and senior levels. While the Nanotechnology-I and nanotechnology-II course have jointly attracted enrollments of more than 30 per year, the introduction of basic concepts in existing course has impacted all the mechanical engineering undergraduates (over 200) for the last two years. NUE fund has also been used to support financially over 15 undergraduates students via stipend, wages, and REU programs. One of the students taking nanotechnology was selected and sent to Hannover Medical School, Germany as a part to provide international experience in the area of nano-biotechnology. To study the efficacy of the 'Nanotechnology-I course (MEEN 530.1: Fundaments of Nanoscience and Engineering), a mixed-method design is being used for the second time. With IRB approval, undergraduate students were asked to complete content-specific, pre-/post-tests inventory-surveys and participate in an exit interview at the end of the semester. The inventory was developed by NUE team members with expertise in nanotechnology undergraduate education. Inventory items are clustered across five domains, including: (a) Nanoscale dimension and basics, (b) Synthesis methods, (c) structural characterization, (d) Carbon-nanostructure and Bioengineering, and (e) Device applications. The exit interview was recorded and is in the process of being transcribed. A preliminary comparison of the pre- and post- data review of pre-/post- assessment data suggests that students experienced positive change-in-learning related to course content in all the five categories.

INTRODUCTION

The design and development of advanced materials, devices and systems for the 21st century is starting to be dominated by the convergence of several rapidly-evolving advanced technologies such as nanotechnology, microelectronics, information technology and biotechnology (Healy, 2009). With the steady erosion of the traditional manufacturing base within the United States, it is imperative to maintain the country's traditional lead role in basic scientific and engineering research in the high-tech areas that will drive the economy of the future (National Research Council, 2002; Stix, 2001; Alivisatos, 2001). The nation's commitment to this is amply demonstrated in the high level of funding for basic research from lead governmental agencies such as NSF and the Department of Energy. The need for qualified nanotechnology workers for the next two decades is estimated to be in the millions (Rocco, 2003). Broad impact can be achieved by curricular enhancement and reform at the undergraduate level (Winkelman, 2009). Curricular enhancement, if it aims to be comprehensive, needs to ensure that students are exposed to the technical aspects as well as social, economic and ethical impacts of nanotechnology that numerous researchers are exploring seriously (Tomasik,2009). This paper reports activities and findings of a team of engineering, science, and education faculty members, who are actively involved in nanomaterials-based research and have been collaborating with each other for the past several years to enhance undergraduate nanoscience and engineering education in the area of devices and systems. They have engaged undergraduate students directly in the advanced laboratories and ongoing research projects. This approach has enable/empowered the students more effectively with the knowledge of the fundamentals of nanoscience and engineering and proficiency to conduct research and develop economically-viable nano-devices with innovative applications in all spheres of daily life.

The stronger effectiveness of our approach arises from a better marriage between theory, experiment and applications. More hands-on exposure is provided to students in the areas of synthesis, processing and manufacturing of nano-components and nano-systems; characterization and measurement of nanostructured systems and devices; and the design, analysis and simulation of nanostructures and nano-devices. This is accomplished by providing students with classroom instruction heavily aided by hands-on laboratory learning, with a systems emphasis. An interdisciplinary nanotechnology course (Nanotechnology I) with a significant hands-on laboratory component has been developed as a preparatory course. This course is offered as a junior-level technical elective and is open to all engineering majors. Secondly, a few undergraduates well-imbued with this foundational perspective on nanotechnology are recruited to engage in a semester-long nanomaterials research project (Nanotechnology II). The students have the option to receive "Independent Study" or "Independent Research" course credit for this systematically mentored and monitored team activity. The team set-up is carefully designed to inspire the students to bring out their individual strengths and innovative abilities and contribute meaningfully to the team goals in a way that helps them find self-worth. Each Faculty and Student Team (FaST) consisted of two students (one graduate and one undergraduate) and one NUE faculty member. Working in this type of team set-up has been found to promote the development of student-faculty interaction and student-student communication.

The NUE efforts have provided a significant number of underrepresented minority students with training and mentoring focused on the economic and intellectual powerhouse area of nanotechnology. Besides the obvious benefit of attracting the best undergraduates into graduate research, our students are also engaged in passing on the learning downstream through helping with summer camps for K-12 educators and school visitations to help attract the enrollment of high-quality students from across the nation. The proposed Nanotechnology I course is expected to serve as a major (but not necessarily exclusive) feeder of talent to the semester-long team research experience. The students impacted by one and/or both of these initiatives are expected to form an excellent talent pool for traditional graduate engineering programs, as well as nontraditional graduate programs planned for the near future at our university, such as the graduate programs of the ERC-supported Bioengineering Department and/or Joint School of Nanoscience and Nanoengineering. The content organization of the paper is as follows: (a) Nanotechnology-I: Development of an interdisciplinary nanotechnology theory-cum-laboratory course, (b) Nanotechnology-II: Development of an semester-long hands-on research-based course, (c) Nanotechnology modules in existing undergraduate courses, (d) REU activities, and (e) Special opportunity for an NUE student to visit an international laboratory.

A. NANOTECHNOLOGY-I: DEVELOPMENT OF AN INTERDISCIPLINARY NANOTECHNOLOGY THEORY-CUM-LABORATORY COURSE: This course was developed to provide more practical exposure to undergraduate students in the areas of synthesis, processing and manufacturing of nano-components and nano-systems, characterization and measurements of nanostructured systems and devices. The course is named 'Fundamentals of Nanoscience and Engineering.' The NUE project refers to this course as Nanotechnology-I. The Nanotechnology-I, offered as a special topics course in the first year of project, has now become a regular course in the department of Mechanical Engineering with the aforementioned course title. This course is now planned to be offered every fall semester in the Department of Mechanical Engineering.

A.1. Description Nanotechnology-I Course: This course offers a fundamental perspective in areas related to the structure, stability and functional characteristics of nanoscale materials and interpretation of results with the help of available theoretical models, with an emphasis on the interrelationship between materials properties and processing. This classroom instruction was also aided by relevant hands-on laboratory learning. Some of the pertinent topics of this course could be listed as: Top-down and bottom-up approaches for nanoparticle synthesis, characterization of nano-materials, nanofabrication by self-assembly and self-organization, bio-inspired self-assembly of nanostructure, molecular electronics, geometry, synthesis and properties of nanoscale carbon. The outcome of the course was broader understanding of nanoscience and engineering among undergraduate students. The students have acquired practical skills of nanomaterials synthesis and characterization after taking this course. The demographics of the class for Fall 2011 and Spring 2011 are shown in Figure 1 and Figure 2, respectively.

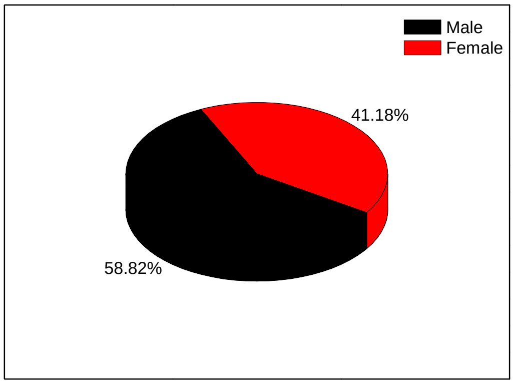


Fig. 1. Demographics of Fall 2011 Nanotechnology–I class. Total no of students: 18

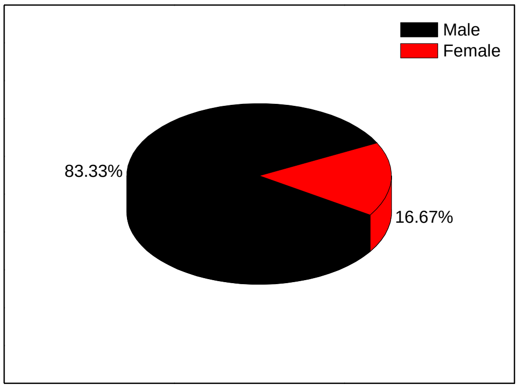


Fig. 2. Demographics of Spring 2010 Nanotechnology–I class. Total no of students: 12

A.2. Assessment of Nanotechnology-I Course: To study the efficacy of Nanotechnology-I course, a mixed-method design was proposed. Undergraduate students completed content-specific, pre-/post-tests. Researchers in the nanotechnology domain have developed these content-specific assessment items, thus establishing beginning inventory face validity. In spring 2010 the inventory was piloted. There were 25 items, clustered across five domains, including: (a) Nanoscale Dimension and Basics (6 items); (b) Synthesis Methods (5 items); (c) Structural Characterization (7 items); (d) C-nanostructure and Bioengineering (4 items); and (e) Device Applications (3 items). An analysis of pre-assessment response rates between 2010 (*n=12*) and 2011 (*n=25*) cohorts (by domain) suggested acceptable reliability with coefficients ranging from 0.69 to 0.98. (Fig. 3).

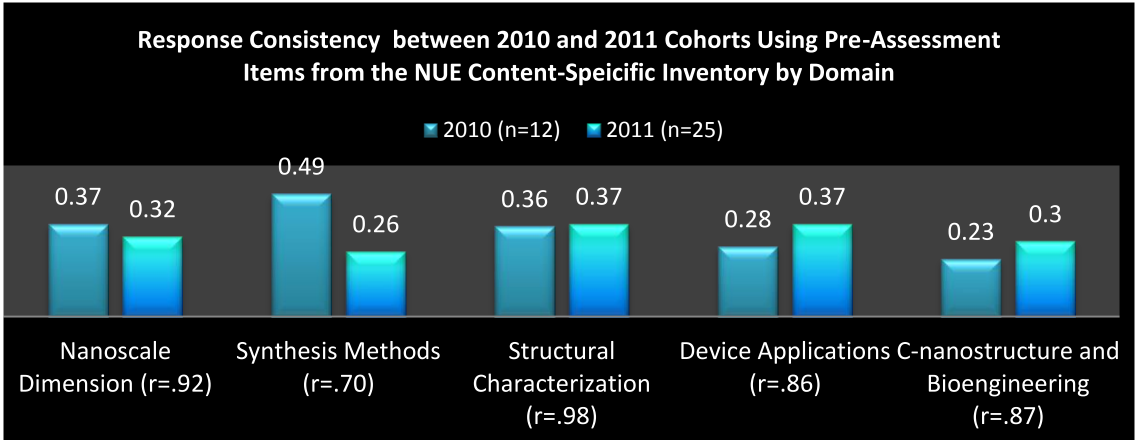
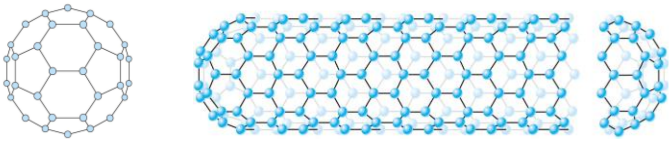


Fig.3. Response Consistency between 2010 and 2011 Cohorts in Pre-Assessment Items by Domain

A full copy of the inventory is presented in our 2011 NUE Annual Report to the Engineering Education and Centers (EEC) Division of the NSF. A representative question from each of this category is presented in Table 1.

Table 1: Representative questions from course concept inventory

Category	**Examples Question**
Nanoscale dimensions and basics	The correct nanometer size scale in increasing order (smallest to largest) in terms of well-known species is (a) DNA, virus, proteins, bacteria (b) Proteins, DNA, virus, bacteria (c) bacteria, virus, proteins, DNA (d) DNA, proteins, virus, bacteria
Synthesis Methods	Which nanomanufacturing category do Pulsed Laser Deposition (PLD) and mechanical attrition (MA) fall under? a. PLD: Top Down, MA: Bottom-up b. PLD: Bottom-up, MA: Top-down c. Both PLD and MA: Top-down d. Both PLD and MA: Bottom-up
Structural Characterization	Atomic force microscopy (AFM) is the most widely used form of scanning probe microscopy for the characterization of nanomaterials, since it requires: (a) electrically conductive and optically transparent samples (b) neither electrically conductive nor optically transparent samples (c) electrically conductive and optically non-transparent samples

	(d) good vacuum
Carbon-Nanostructure and Bioengineering	What are the characteristics of C_{60} fullerene molecules that are used as capping materials for the two ends of a tube made from rolling a single sheet of graphite to make carbon nanotubes:  (a) They are solid spherical clusters of sixty carbon atoms with 20 hexagons and 12 pentagons with no two pentagons having a common side (b) They are hollows spherical clusters of sixty carbon atoms with 20 hexagons and 12 pentagons with both hexagons and pentagons having a common side (c) They are hollow spherical clusters of sixty carbon atoms with 20 hexagons and 12 pentagons with no two hexagons having a common side (d) They are hollow spherical clusters of sixty carbon atoms with 20 hexagons and 12 pentagons with two pentagons having a common side
Device Applications	The two main conditions for observing the quantum effect between two metallic nanodots due to the discrete nature of charge are: (a) barrier resistance (R_t) >> charging energy ($E_c = e^2/C$) and E_c >> thermal energy (k_BT), (b) R_t >> E_c and E_c << thermal energy (c) R_t << E_c and E_c << thermal energy (d) $R_t = E_c$ and E_c = thermal energy

A. 3. Other Developments in the Area of Assessment: Pre-assessment responses between 2010 and 2011 cohorts were analyzed to determine NUE Content-Specific Inventory internal consistency. As indicated in Figure 4, adequate reliability among items and across domains was established, as follows: Nanoscale Dimension (*r=0.*92); Synthesis Methods (*r=0.*70); Structural Characterization (*r=0.*98); Device Applications (*r=0.86*); C-nanostructure and Bioengineering (*r=0.87*). Subsequently and using the NUE Content-Specific Inventory, assessment data were collected to determine change in understanding and learning among 2011 (*n*=25) nanotechnology students. The inventory was administered at the beginning of the semester (pre-

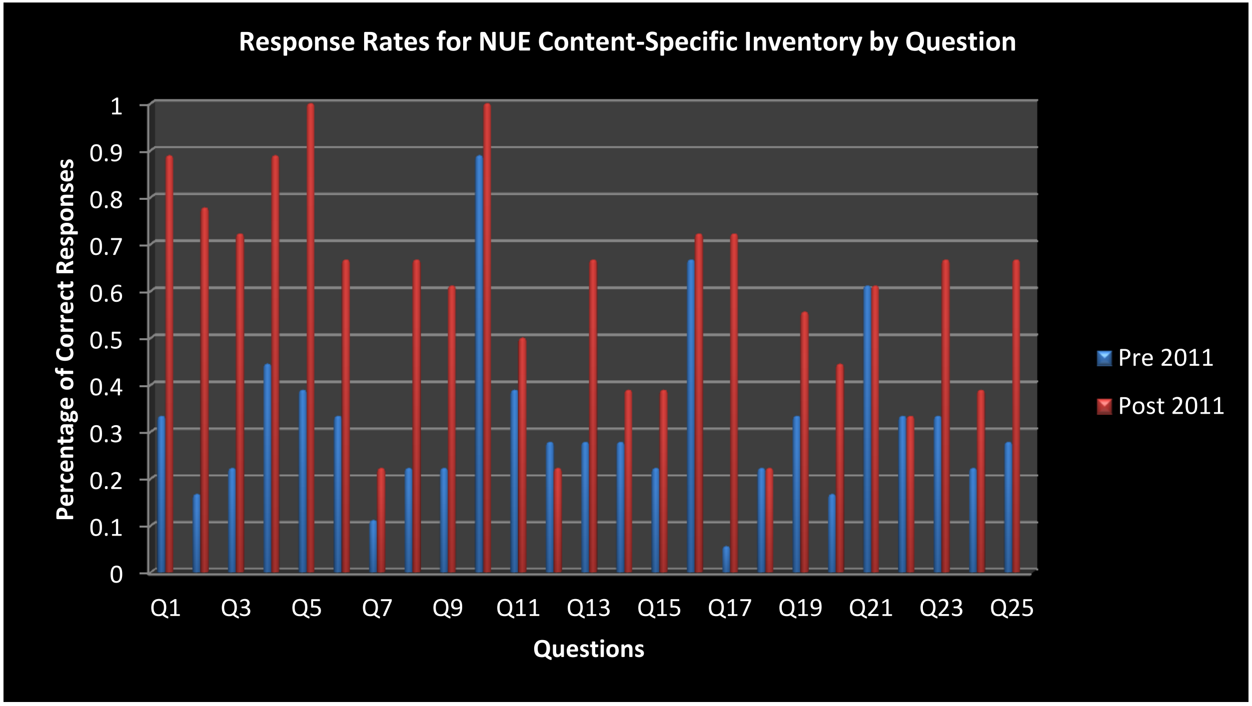


Fig.4. Response Rates for NUE Content-Specific Inventory by Question (2011)

assessment) and at the end of the semester (post-assessment). A review of these data both by domain and across questions indicated a positive change in understanding related to nanotechnology content. Figure 5 demonstrates differences (pre-/post) in overall percentages of correct responses across questions. Students showed growth in their understanding of nearly all questions except Question 12 (Structural Characterization). The most growth was for Question 17 (Device Applications) and Question 2 (Nanoscale Dimension Basics). Similarly, Figure 5 depicts differences (pre-/post) in overall percentages of correct responses by domain. In this case, students showed the most growth in Nanoscale Dimension and Basics and Structural Characterization. It is notable that similar pre-/post-assessment data were collected in 2010. Though NUE Content-Specific Inventory reliability had not yet been established, similar results by question and domain were obtained. Thus, it is reasonable to suggest that positive change in understanding related to nanotechnology content also occurred with the 2010 cohort.

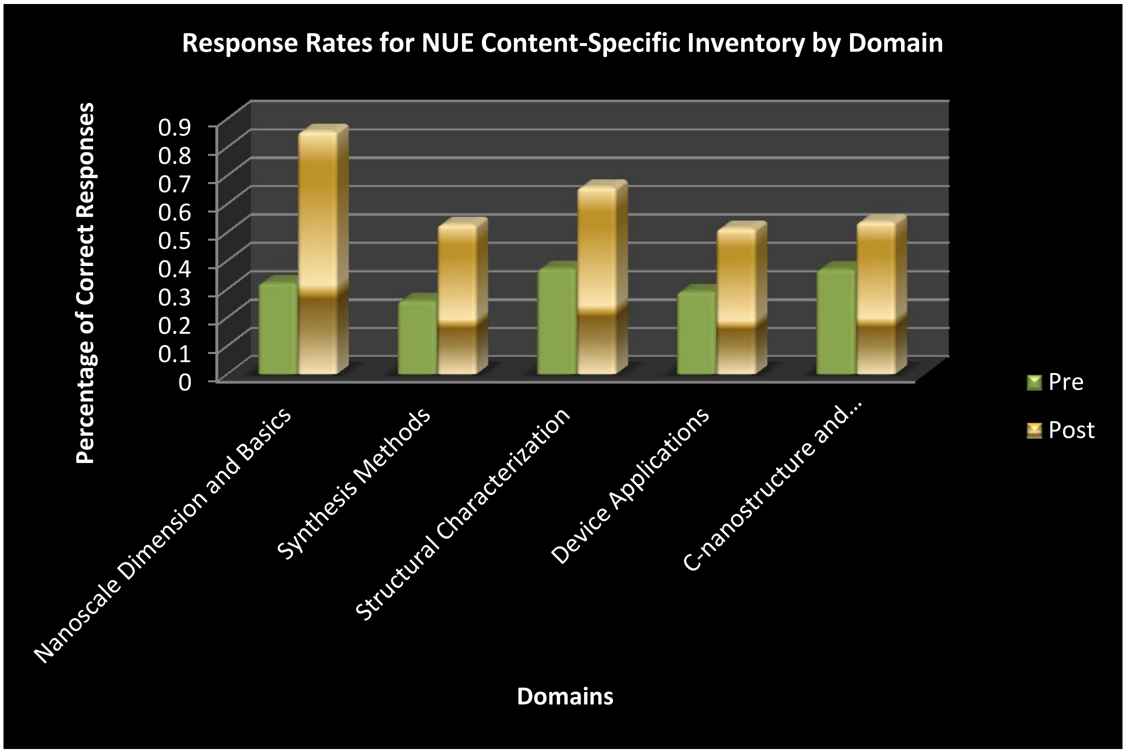


Fig. 5. Response Rates for NUE Content-Specific Inventory by Domain

As well and to continue the inventory validation process, qualitative information was gathered through exit focus groups. There was positive change in understanding and learning among fall 2011 students. In particular, descriptive data from the exit focus groups informed student excitement and continued interest in nanotechnology and related course content. Students indicated that it would be helpful to have more information on how nanotechnology concepts relate to their academic and career goals.

B. NANOTECHNOLOGY II: DEVELOPMENT OF AN SEMESTER-LONG HANDS-ON RESEARCH-BASED COURSE: This course was offered for the first time during the Spring 2011 semster in the department of Mechancial Engineering. The course was designed to enhance student participation in research conducted by NUE faculty members in the area of nanoscience and nanoengineering. Topics were both analytical and experimental in nature. The course also encouraged the students to engage in independent studies. The course required the submission of a written report by each student at the end of the semester. The course was offered as MEEN 596.001: Independent Study. The course prerequisite was senior standing and consent of instructor. The student learning objectives were: (i) to develop abilities to explain relationship between nanomaterial structures and their properties and to understand the working principles of various nanomaterials synthesis and characterization methods and (ii) to provide hands-on working experience on selected state-of-the-art nanomaterials synthesis and charactrization equipment. Students enrolled in this class received "P" for "Satisfactory" or "F" for "Unsatisfactory" grades.

B.1. Deliverables of Nanotechnology-II course: Each student was required to make a mid-semester 15-minute PowerPoint presentation reporting his/her mid-term progress on an assigned project to a panel of 3-5 faculty members. At the end of the semester, each student was required to submit a written report (minimum 30 pages, double spaced), a poster documenting his/her work, and to make a 20-minute PowerPoint presentation to the same panel. The students enrolled in this course were also required to attend a weekly ERC seminar.

B.2. Assignments & Academic Calendar

January:
- Selection of research projects
- Assignment of respective supervisor from the panel of co-instructors
- **Friday, 1/21/11,** Submission of one page research plan
- Weekly assessment by assigned supervisor

February:
- Weekly assessment by supervisor
- **Friday, 2/25/11**, Panel Evaluation of project progress: 5 minute-PowerPoint presentation

March:
- Weekly assessment by supervisor
- **Friday, 3/25/11**, Mid-semester 15-minute PowerPoint presentation to the panel reporting his/her mid-term progress on an assigned project to the panel of co-instructors

April:
- Weekly assessment by supervisor
- Evaluation of project progress: 5-minute PowerPoint presentation
- **Friday, 4/20/11**, Submission of a final a written report (minimum 30 pages, double space), a poster documenting his/her work

May
- **Friday, 5/6/11**, a 20-minute PowerPoint final presentation to the panel consisting of all the instructors

B.3. Student Enrollment: This course has a cap of 5 undergraduate students per semester. This cap has been set to ensure sufficient supervision and personal guidance to each undergraduate student and to ensure that each project makes significant progress in the given time and lab facilities. In order to impact more students with the NUE project, we have planned to offer this course for the next two semesters: Spring 2012, and Fall 2012. The number of students enrolled for the Spring 2011 semester was four.

B.4. Example Project Enabling and Empowering the students more effectively

Fabrication, characterization of titanium nitride nanowires: TiN has a number of outstanding physical, chemical, and biological properties. It is a very well-known material, which possesses high hardness, low wear, low electrical resistivity, high corrosion resistance, and very efficient diffusion barrier characteristic. The coatings of TiN are normally free from any type of thermal irritation, acute toxicity or cytotoxicity. While there are abundant reports about the growth of TiN in thin film form, there are scarce reports to date on the growth of TiN in nanowire form. It has been shown that several materials in nanowire form depict great promise as multifunctional components in a wide number of promising device technologies. Since the discovery of carbon nanotubes, the synthesis of one dimensional (1-D) structure like nanowires, nanobelts, and nanorods has attracted more focus in biological, electronic, and photonic field in recent times. This work was able develop a firsthand fabrication method of vertically aligned TiN nanowires using a physical vapor deposition (PVD) based bottom-up method. TiN nanowires are expected to play important roles in the fabrication of new electronic and biological devices or fabrication of existing devices with improved characteristics. For an example, vertically aligned TiN nanowires can serve as columnar defects in high temperature superconducting thin films that may result in the substantial improvement in current carrying capabilities of the superconducting films, especially in an applied magnetic field. Due to size compatibility, TiN nanowire could also be easily integrated with biological molecules for new biological applications. The ends and sidewalls of TiN nanowires can provide a very high surface area, and consequently, a very high number of biological binding sites. This high density of binding sites may increase the detection sensitivity of DNA, glucose, and other biological molecules via a device shown in Fig. 6.

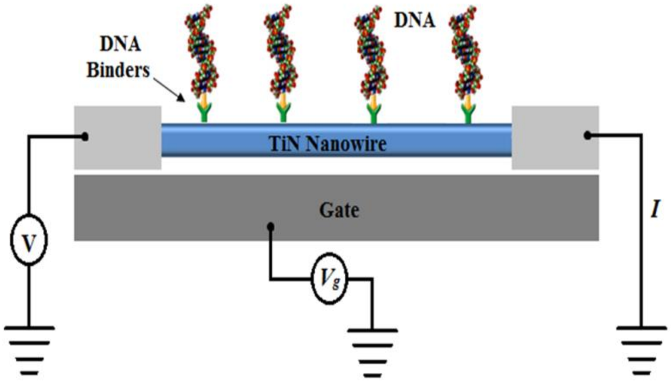


Fig. 6. Schematic of possible use of a biologically modified TiN nanowire between a source and drain in the fabrication of a sensing device.

C. NANOTECHNOLOGY MODULES IN EXISTING UNDERGRADUATE COURSES: Our first educational activity as part of the NUE project was to introduce simple concepts of nanoscience and technology into existing required courses (Table 2) at undergraduate levels within the College of Engineering. These modules covered the core concepts of nanomaterials and unique phenomena at the nanoscale. Introducing the concepts of nanoscience and engineering at this early stage of undergraduate education was found to impact the students' interest in registering for the technical elective nanotechnology courses described in section II.

All of these courses are offered during both Spring and Fall semesters and have enrollments in the range of 20-30. Thus the modules developed to introduce the concepts of nanoscience and engineering in courses cumulatively benefit a large number of engineering undergraduate students. The students impacted by these courses are attracted to the new course that we have developed under the new NUE grant at our university.

Table 2: Courses in which modules introducing the concepts of nanotechnology were introduced

Course	Semester and Year	No. of students	Concepts introduced using two lectures
MEEN 260:Materials Science Major: Industrial and Chemical	Spring 2011	21	Nanoscale dimension and associated novel properties, Scaling law
	Fall 2011	18	
MEEN 360: Fundamentals of Materials Science Major: Mechanical	Spring 2011	33	Nanoscale dimension and associated novel properties, Nanotubes and nanowires
	Fall 2011	28	
MEEN 460: Modern Engineering Materials Major: Mechanical	Spring 2011	25	Artificial atoms, magic numbers, carbon nanotubes
	Fall 2011	22	
MEEN 446: Manufacturing Processes Major: Mechanical	Fall 2011	24	Nanomanufacturing, top-down and bottom-up methods

D. REU ACTIVITIES: Under the REU activities carried out under NUE program, undergraduate students from our home institution as well external institutions were provided opportunities to work on nano-bio related projects during the summer. The undergraduate students are paired with graduate students working under the supervision of NUE PI and CoPIs. There are presently three undergraduate students being supported by the NUE project. These students are working on a semester-long projects related to nanofabrication and devices. Two of these students have taken Nanotechnology-I as well Nanotechnology-II course offered in 2011 under the NUE project. These two students have been given additional opportunities based on their performances in these courses and their interest in enhancing further their knowledge of nanoscience and nanoengineering.

E. SPECIAL OPPORTUNITY FOR AN NUE STUDENT TO VISIT AN INTERNATIONAL LABORATORY: One undergraduate student (Ms. Crystal Jessamy) was given an opportunity to spend two weeks in the lab of Dr. Frank Witte at the Hannover Medical School, Germany. During the visit, the student was exposed to the theory and process behind cell adhesion. The first procedure she was shown and worked through with was the MTT Assay. This procedure allows one to measure the activity of enzymes released from cells on sample surfaces.

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